Arithmetic: A Programmatic Approach

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Introduction

Procedural mathematics is a method of doing mathematics that stemmed from my dissatisfaction with classical logic and in particular, universal quantification. My intuitive understanding of universal quantification is as an infinite conjunction, i.e. $P_1 \wedge P_2 \wedge P_3 \wedge \cdots$. My uneasiness with the proposition is not deep, it's simply that the proposition's end has always felt inaccessible, out of reach, rarefied. Perhaps my discomfort stems from the fact that I was programming for nearly a decade before learning university-level mathematics, and so I had implicitly/intuitively developed a different more syntactical and restrained understanding of program correctness over an unbounded domain. Procedural mathematics is my attempt at articulating this programmatic understanding.

Background of Procedural Mathematics

Perhaps it would be easier to describe procedural mathematics by first contrasting it to its alternatives. One method of doing mathematics is through argumentation. In this method, the objects under consideration are first defined, then a statement called a theorem is made, then a deductive argument for why the theorem holds called a proof is provided. Here, proofs can use theorems that have been proven earlier and likewise for definitions. This method is perfectly valid and is underpinned by such concepts as universal quantification for expressing generality, existential quantification for expressing existence, the domains over which they apply, and the logical rules governing their interactions with other logical operators such as conjunction and disjunction. The fact that this so far has been the only known general method for doing mathematics has, I believe, led to a situation where it has been applied in contexts (especially in education and technology) where alternative approaches may have been suitable.

Another method for doing mathematics, albeit incomplete, goes by various names including Transparent Proofs, Transparent Pseudo Proofs, and Gneric Proofs. This method is essentially a specialization of the argumentation method presented above except that instead of giving a deductive argument for why the theorem holds, a deductive argument for why a particular case of a theorem holds is presented in such a way that the main ideas for the proof of the general case are communicated. The benefit of this method is that universal and existential quantification, domains of discourse, and the apparatus of mathematical logic are temporarily backgrounded whilst the techniques specific to the given proof are given center stage. The drawback of this method is that the outcome is not actually a proof because the line between the main ideas of the general proof and the ideas incidental to the particular case is not made explicit. And as soon as this line is made clear, the Transparent Pseudo Proof reverts to being an ordinary proof. Hence in the end, this method only tends to be used in brief proof sketches.

Yet another incomplete method of doing mathematics goes by the name of Proof Without Words. A proof without words is understood to be a theorem statement followed by a diagram or a picture that demonstrates it to be self-evident. It is convenient to extend this definition to include unexplained algorithms because their persuasive effect can be similar to that of diagrams and pictures. Similar to the Transparent Pseudo Proofs mentioned above, this method of doing mathematics excels in emphasizing the content of a proof over its form. Unfortunately Proof Without Words are not quite proofs because the link between the "picture" and the theorem to be proved is necessarily implicit. That something is missing in these kinds of proofs is evidenced by the tendency for their authors to caption diagrams and pictures, and write proofs of correctness for unexplained algorithms so as to "complete" them. What is sought then is a method for doing proof based mathematics that does not depend on the concepts of mathematical logic, nor consequently, argumentation, and yet can scale enough to communicate topics like number theory, real and complex analysis, and linear algebra.

Description of Procedural Mathematics

Overall, this method replaces proving stated mathematical theorems with inventing correct procedures to realize stated objectives. To achieve this, the first part of this method calls for the elucidation of the mathematical semantic rules being followed; their adherence is the criterion for “correctness”. Rules whose adherence is known to guarantee that procedure implementations meet stated objectives in practice (like those of elementary algebra) are what would typically be chosen here. The use of semantic rules in this method is similar to its use in computer science, though the types of rules are markedly different. There, type systems and ownership systems are the most common semantic rules and they serve to prevent syntactically valid programs from compiling when objects of an incorrect type are found in certain contexts within the source code or when object access patterns in the source code are incorrect respectively. The key point of semantic rules is that they serve to rule out grammatically correct instructions before they are even “executed”.

So far with our semantic rules we have enough to “prove” “theorems” true in a programmatic manner. But just like machine code is hard to read and write for programmers, our newfangled “proofs” would be hard to read and write for mathemticians. The next parts of this method are about using commonplace software engineering techniques to structure our “proofs” better and hence allow them to scale enough to realize complex objectives. The second part of this method is the declaration of terminology that will later be used. Declarations are more similar to their namesake in computer programming than they are to definitions in proof-based mathematics. Their purpose is to simplify/make concise instructions that involve manipulating complex structures, just like in computer programming. Nevertheless, the conceptual role of declarations is analogous to that of definitions in mathematics: they give single a name to a group of related ideas; and this in turn enables comprehension of more complex structures.

The third part of this method is announcement of the mathematical objective to be achieved. Some reasonable objectives might be to show that an arithmetical equality holds, construct an object with certain properties, or construct another procedure with a potentially different objective. Again, objectives are more similar to the comments that one might see above a procedure in a computer program’s source code than they are to a theorem statement in proof-based mathematics. Their purpose is to enable readers to understand more complex proofs by sometimes getting them to see certain parts of proofs as black boxes that have the effect given by their objective. For this reason procedure objectives could be said to play a role analogous to theorem statements in proof-based mathematics. However there are some conceptual differences: unlike the theorem statement of a proof, a procedure objective is not a fact nor is it a logical consequence of a group of axioms; rather it is merely a description of the intent of the associated implementation.

The last part of this method is the implementation of a semantically valid procedure for achieving the stated objective. This procedure might in turn use previous procedures or even the current procedure (in which case, the procedure is said to be recursive) to achieve sub-objectives. Semantically valid procedures are very similar to source code written in a statically typed programming language because both comprise an unambiguous set of instructions that can be carried out by a practitioner and both are constructed according to some agreed upon some set of semantic rules. Their dissimilarity is that semantically valid procedures would usually be written in a natural language grammar for a human audience whereas source code is usually written in an artificial grammar primarily for execution on a computer. Semantically valid procedures are also similar to deductive proofs in that both are constructed according to rules which serve to bestow correctness upon the proof; however they are crucially different in that one is instructional whilst the other is argumentative in nature.

Comparing Procedural Mathematics

	Classical Mathematics	**Transparent / Wordless Proofs**	**Procedural Mathematics**
Grammatical Mood	Factual because proofs establish theorems, which are facts about abstract objects. For example, claims that a proposition holds on every member of a domain are valid.	Factual because the theorems being proved are identical to their equivalents in classical mathematics.	Intentional because procedures are labelled only with their intent. I.e. no claim is made that procedures achieve the objectives on every member of a domain.
Generality	Full. Universal quantifiers are used to express the generality of propositions over infinite domains.	None becuase a theorem is proven for only one well-chosen case. That being said, most readers should be able to generalize proof to other cases.	Full. Symbols are used to indicate values that are only known at "run-time". At "run-time" these symbols take on a single value, rather than ranging over a set.
Transparency	Optional because the logical and object language can be inseparably mixed. For example, a non-constructive arithmetical proof generally cannot be put in purely arithmetical terms.	More than in classical mathematics because theorems are proven only on explicitly selected objects. I.e. transparent proofs enforce more terms in the object language than classical proofs.	Full because procedural mathematics is about providing instructions to do mathematics rather than "doing" mathematics. Hence procedure execution yields artifacts purely in the object language.
Correctness Criterion	All inferences leading to theorem must originate from stated inference rules and must trace back to stated axioms.	Almost the same as classical mathematics, but the generalization steps are not made explicit.	Adherence of procedure implementations to well-chosen mathematical semantic rules with the objective in a "conclusive" position.
Expressiveness	Full. Sufficient for doing pure and applied mathematics and includes topics like transfinite set theory.	Subset of classical mathematics where existential statements have witnesses because proofs are done on explicitly chosen witnesses.	Subset of classical mathematics. Captures topics like trigonometry and calculus. Fails to express topics like transfinite set theory.
Imports	Universal and existential quantification, transfinite set theory, inference rules, axioms.	Inference rules and axioms. Universal and existential quantification are made implicit.	Data structures, procedures, lambdas, recursion, static analysis.
Treatment of Contradictions	The derivation of a contradiction from an assumption implies that the assumption is false. Justified by the law of noncontradiction.	Largely outside the scope of transparent / wordless proofs. Where they do occur, interpretation is the same as that of classical mathematics.	Sentences are shown to be "impossible" by providing a procedure (with an effectively empty domain) to transform it into a more obviously "impossible" sentence.

The above table shows the similarities and differences between the four methods of doing mathematics presented above. Note that they are not all trying to do exactly the same thing, as is evidenced by the variations in their grammatical moods. Also note that while procedural mathematics is strictly less expressive than classical mathematics, it may just be expressive enough to conduct most fields of applied mathemtics within.

Methodology of Mathematical Experiment

Above I have described a general method for doing mathematics but did not provide evidence that it is workable. The rest of this book intends to prove that this approach is indeed generally usable by reformulating the elementary parts of number theory, hard analysis, calculus, and linear algebra using the tools of procedural mathematics. So, while formal mathematics usually takes the format of definition-theorem-proof, this project has the format of declaration-procedure objective-procedure implementation. So where there usually would have been a statement and proof of Euler's totient theorem, procedure I:72 is provided, and where there would have been a definition of Euler's totient function, declaration I:28 is provided. Perhaps not surprisingly, software programming tools and concepts like lambdas, procedures, recursion, and modularity have turned out to be instrumental in rendering intelligable what could have been an indecipharable network of instructions/operations.

Contents

Declarations

Part I

Integer Arithmetic

Chapter 1

Integer Arithmetic

Declaration I:0(1.22)

The phrase "integer" will be used as a shorthand for an ordered pair of natural numbers.

Declaration I:1(1.23)

The phrase "the positive part of a" and the notation $\mathrm{po}(a)$, where a is an integer, will be used as a shorthand for the first entry of a.

Declaration I:2(1.24)

The phrase "the negative part of a" and the notation $\mathrm{ne}(a)$, where a is an integer, will be used as a shorthand for the second entry of a.

Declaration I:3(1.25)

The phrase "$a = b$", where a, b are integers, will be used as a shorthand for "$\mathrm{po}(a) + \mathrm{ne}(b) = \mathrm{ne}(a) + \mathrm{po}(b)$".

Procedure I:0(1.65)

Objective

Choose an integer a. The objective of the following instructions is to show that $a = a$.

Implementation

1. **Show that $a = a$ using declaration I:3 given that $\mathrm{po}(a) + \mathrm{ne}(a) = \mathrm{ne}(a) + \mathrm{po}(a)$.**

Procedure I:1(1.66)

Objective

Choose two integers a, b such that $a = b$. The objective of the following instructions is to show that $b = a$.

Implementation

1. **Using declaration I:3, show that $b = a$**
   (a) given that $\mathrm{po}(b) + \mathrm{ne}(a) = \mathrm{ne}(b) + \mathrm{po}(a)$
   (b) given that $\mathrm{po}(a) + \mathrm{ne}(b) = \mathrm{ne}(a) + \mathrm{po}(b)$
   (c) given that $a = b$.

Procedure I:2(1.67)

Objective

Choose three integers a, b, c such that $a = b$ and $b = c$. The objective of the following instructions is to show that $a = c$.

Implementation

1. Show that $\mathrm{po}(a) + \mathrm{ne}(b) = \mathrm{ne}(a) + \mathrm{po}(b)$ using declaration I:3.
2. Show that $\mathrm{po}(b) + \mathrm{ne}(c) = \mathrm{ne}(b) + \mathrm{po}(c)$ using declaration I:3.
3. **Hence show that $a = c$**
   (a) given that $\mathrm{po}(a) + \mathrm{ne}(c) = \mathrm{ne}(a) + \mathrm{po}(c)$
   (b) given that $\mathrm{po}(a) + \mathrm{ne}(b) + \mathrm{po}(b) + \mathrm{ne}(c) = \mathrm{ne}(a) + \mathrm{po}(b) + \mathrm{ne}(b) + \mathrm{po}(c)$.

Declaration I:4(1.26)

The notation $a + b$, where a, b are integers, will be used as a shorthand for the pair $\langle \text{po}(a) + \text{po}(b), \text{ne}(a) + \text{ne}(b) \rangle$.

Procedure I:3(1.68)

Objective

Choose four integers a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $a + b = c + d$.

Implementation

1. Show that $\text{po}(a) + \text{ne}(c) = \text{ne}(a) + \text{po}(c)$ using declaration I:3.
2. Show that $\text{po}(b) + \text{ne}(d) = \text{ne}(b) + \text{po}(d)$ using declaration I:3.
3. Hence using declaration I:4, show that $a + b$

(a) $= \langle \text{po}(a), \text{ne}(a) \rangle + \langle \text{po}(b), \text{ne}(b) \rangle$

(b) $= \langle \text{po}(a) + \text{po}(b), \text{ne}(a) + \text{ne}(b) \rangle$

(c) $= \langle \text{po}(a) + \text{po}(b) + \text{ne}(c) + \text{ne}(d), \text{ne}(a) + \text{ne}(b) + \text{ne}(c) + \text{ne}(d) \rangle$

(d) $= \langle (\text{po}(a) + \text{ne}(c)) + (\text{po}(b) + \text{ne}(d)), \text{ne}(a) + \text{ne}(b) + \text{ne}(c) + \text{ne}(d) \rangle$

(e) $= \langle (\text{ne}(a) + \text{po}(c)) + (\text{ne}(b) + \text{po}(d)), \text{ne}(a) + \text{ne}(b) + \text{ne}(c) + \text{ne}(d) \rangle$

(f) $= \langle \text{ne}(a) + \text{ne}(b) + \text{po}(c) + \text{po}(d), \text{ne}(a) + \text{ne}(b) + \text{ne}(c) + \text{ne}(d) \rangle$

(g) $= \langle \text{po}(c) + \text{po}(d), \text{ne}(c) + \text{ne}(d) \rangle$

(h) $= \langle \text{po}(c), \text{ne}(c) \rangle + \langle \text{po}(d), \text{ne}(d) \rangle$

(i) $= c + d$.

Procedure I:4(1.69)

Objective

Choose three integers a, b, c. The objective of the following instructions is to show that $(a + b) + c = a + (b + c)$.

Implementation

1. Using declaration I:4, show that $(a + b) + c$

(a) $= \langle \text{po}(a) + \text{po}(b), \text{ne}(a) + \text{ne}(b) \rangle + \langle \text{po}(c), \text{ne}(c) \rangle$

(b) $= \langle (\text{po}(a) + \text{po}(b)) + \text{po}(c), (\text{ne}(a) + \text{ne}(b)) + \text{ne}(c) \rangle$

(c) $= \langle \text{po}(a) + (\text{po}(b) + \text{po}(c)), \text{ne}(a) + (\text{ne}(b) + \text{ne}(c)) \rangle$

(d) $= \langle \text{po}(a), \text{ne}(a) \rangle + \langle \text{po}(b) + \text{po}(c), \text{ne}(b) + \text{ne}(c) \rangle$

(e) $= a + (b + c)$.

Procedure I:5(1.70)

Objective

Choose two integers a, b. The objective of the following instructions is to show that $a + b = b + a$.

Implementation

1. Using declaration I:4, show that $a + b$

(a) $= \langle \text{po}(a) + \text{po}(b), \text{ne}(a) + \text{ne}(b) \rangle$

(b) $= \langle \text{po}(b) + \text{po}(a), \text{ne}(b) + \text{ne}(a) \rangle$

(c) $= b + a$.

Declaration I:5(1.27)

The notation a, where a is a natural number, will contextually be used as a shorthand for the pair $\langle a, 0 \rangle$.

Procedure I:6(1.71)

Objective

Choose an integer a. The objective of the following instructions is to show that $0 + a = a$.

Implementation

1. Using declaration I:4, show that $0 + a$

(a) $= \langle 0, 0 \rangle + \langle \text{po}(a), \text{ne}(a) \rangle$

(b) $= \langle 0 + \text{po}(a), 0 + \text{ne}(a) \rangle$

(c) $= \langle \text{po}(a), \text{ne}(a) \rangle$

(d) $= a$.

Declaration I:6(1.28)

The notation $-a$, where a is an integer, will be used as a shorthand for the pair $\langle \text{ne}(a), \text{po}(a) \rangle$.

Procedure I:7(1.72)

Objective

Choose two integers a, b such that $a = b$. The objective of the following instructions is to show that $-a = -b$.

Implementation

1. Show that $\mathrm{po}(a) + \mathrm{ne}(b) = \mathrm{ne}(a) + \mathrm{po}(b)$ using declaration I:3.
2. Hence using declaration I:6, show that $-a$
   (a) $= \langle \mathrm{ne}(a), \mathrm{po}(a) \rangle$
   (b) $= \langle \mathrm{ne}(a) + \mathrm{po}(b), \mathrm{po}(a) + \mathrm{po}(b) \rangle$
   (c) $= \langle \mathrm{po}(a) + \mathrm{ne}(b), \mathrm{po}(a) + \mathrm{po}(b) \rangle$
   (d) $= \langle \mathrm{ne}(b), \mathrm{po}(b) \rangle$
   (e) $= -b$.

Procedure I:8(1.73)

Objective

Choose an integer a. The objective of the following instructions is to show that $-a + a = 0$.

Implementation

1. Using declaration I:4, show that $-a + a$
   (a) $= (-a) + a$
   (b) $= \langle \mathrm{ne}(a), \mathrm{po}(a) \rangle + \langle \mathrm{po}(a), \mathrm{ne}(a) \rangle$
   (c) $= \langle \mathrm{ne}(a) + \mathrm{po}(a), \mathrm{po}(a) + \mathrm{ne}(a) \rangle$
   (d) $= \langle 0, 0 \rangle$
   (e) $= 0$.

Declaration I:7(1.29)

The notation ab, where a, b are integers, will be used as a shorthand for the pair $\langle \mathrm{po}(a)\,\mathrm{po}(b) + \mathrm{ne}(a)\,\mathrm{ne}(b), \mathrm{po}(a)\,\mathrm{ne}(b) + \mathrm{ne}(a)\,\mathrm{po}(b) \rangle$.

Procedure I:9(1.74)

Objective

Choose four integers a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $ab = cd$.

Implementation

1. Show that $\mathrm{po}(a) + \mathrm{ne}(c) = \mathrm{ne}(a) + \mathrm{po}(c)$ using declaration I:3.
2. Show that $\mathrm{po}(b) + \mathrm{ne}(d) = \mathrm{ne}(b) + \mathrm{po}(d)$ using declaration I:3.
3. Hence using declaration I:7, show that ab
   (a) $= \langle \mathrm{po}(a)\,\mathrm{po}(b) + \mathrm{ne}(a)\,\mathrm{ne}(b), \mathrm{po}(a)\,\mathrm{ne}(b) + \mathrm{ne}(a)\,\mathrm{po}(b) \rangle$
   (b) $= \langle \mathrm{po}(a)\,\mathrm{po}(b) + \mathrm{ne}(a)\,\mathrm{ne}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d), \mathrm{po}(a)\,\mathrm{ne}(b) + \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (c) $= \langle \mathrm{po}(a)(\mathrm{po}(b) + \mathrm{ne}(d)) + \mathrm{ne}(a)\,\mathrm{ne}(b) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d), \mathrm{po}(a)\,\mathrm{ne}(b) + \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (d) $= \langle \mathrm{po}(a)(\mathrm{ne}(b) + \mathrm{po}(d)) + \mathrm{ne}(a)\,\mathrm{ne}(b) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d), \mathrm{po}(a)\,\mathrm{ne}(b) + \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (e) $= \langle (\mathrm{po}(a) + \mathrm{ne}(c))\,\mathrm{po}(d) + \mathrm{ne}(a)\,\mathrm{ne}(b) + \mathrm{po}(c)\,\mathrm{ne}(d), \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (f) $= \langle (\mathrm{ne}(a) + \mathrm{po}(c))\,\mathrm{po}(d) + \mathrm{ne}(a)\,\mathrm{ne}(b) + \mathrm{po}(c)\,\mathrm{ne}(d), \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (g) $= \langle \mathrm{ne}(a)(\mathrm{po}(d) + \mathrm{ne}(b)) + \mathrm{po}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d), \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (h) $= \langle \mathrm{ne}(a)(\mathrm{po}(b) + \mathrm{ne}(d)) + \mathrm{po}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d), \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (i) $= \langle (\mathrm{ne}(a) + \mathrm{po}(c))\,\mathrm{ne}(d) + \mathrm{po}(c)\,\mathrm{po}(d), \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (j) $= \langle (\mathrm{po}(a) + \mathrm{ne}(c))\,\mathrm{ne}(d) + \mathrm{po}(c)\,\mathrm{po}(d), \mathrm{po}(a)\,\mathrm{ne}(d) + \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (k) $= \langle \mathrm{ne}(c)\,\mathrm{ne}(d) + \mathrm{po}(c)\,\mathrm{po}(d), \mathrm{ne}(c)\,\mathrm{po}(d) + \mathrm{po}(c)\,\mathrm{ne}(d) \rangle$
   (l) $= cd$.

Procedure I:10(1.75)

Objective

Choose three integers a, b, c. The objective of the following instructions is to show that $(ab)c = a(bc)$.

Implementation

1. Using declaration I:7, show that $(ab)c$

   (a) $= \langle \operatorname{po}(a)\operatorname{po}(b) + \operatorname{ne}(a)\operatorname{ne}(b), \operatorname{po}(a)\operatorname{ne}(b) + \operatorname{ne}(a)\operatorname{po}(b)\rangle\langle \operatorname{po}(c), \operatorname{ne}(c)\rangle$

   (b) $= \langle(\operatorname{po}(a)\operatorname{po}(b) + \operatorname{ne}(a)\operatorname{ne}(b))\operatorname{po}(c) + (\operatorname{po}(a)\operatorname{ne}(b)+\operatorname{ne}(a)\operatorname{po}(b))\operatorname{ne}(c), (\operatorname{po}(a)\operatorname{po}(b)+\operatorname{ne}(a)\operatorname{ne}(b))\operatorname{ne}(c) + (\operatorname{po}(a)\operatorname{ne}(b) + \operatorname{ne}(a)\operatorname{po}(b))\operatorname{po}(c)\rangle$

   (c) $= \langle \operatorname{po}(a)(\operatorname{po}(b)\operatorname{po}(c) + \operatorname{ne}(b)\operatorname{ne}(c)) + \operatorname{ne}(a)(\operatorname{po}(b)\operatorname{ne}(c)+\operatorname{ne}(b)\operatorname{po}(c)), \operatorname{po}(a)(\operatorname{po}(b)\operatorname{ne}(c)+\operatorname{ne}(b)\operatorname{po}(c)) + \operatorname{ne}(a)(\operatorname{po}(b)\operatorname{po}(c) + \operatorname{ne}(b)\operatorname{ne}(c))\rangle$

   (d) $= \langle \operatorname{po}(a), \operatorname{ne}(a)\rangle\langle \operatorname{po}(b)\operatorname{po}(c) + \operatorname{ne}(b)\operatorname{ne}(c), \operatorname{po}(b)\operatorname{ne}(c) + \operatorname{ne}(b)\operatorname{po}(c)\rangle$

   (e) $= a(bc)$.

Procedure I:11(1.76)

Objective

Choose two integers a, b. The objective of the following instructions is to show that $ab = ba$.

Implementation

1. Using declaration I:7, show that ab

   (a) $= \langle \operatorname{po}(a)\operatorname{po}(b) + \operatorname{ne}(a)\operatorname{ne}(b), \operatorname{po}(a)\operatorname{ne}(b) + \operatorname{ne}(a)\operatorname{po}(b)\rangle$

   (b) $= \langle \operatorname{po}(b)\operatorname{po}(a) + \operatorname{ne}(b)\operatorname{ne}(a), \operatorname{po}(b)\operatorname{ne}(a) + \operatorname{ne}(b)\operatorname{po}(a)\rangle$

   (c) $= ba$.

Procedure I:12(1.77)

Objective

Choose an integer a. The objective of the following instructions is to show that $1a = a$.

Implementation

1. Using declaration I:7, show that $1a$

   (a) $= \langle 1, 0\rangle\langle \operatorname{po}(a), \operatorname{ne}(a)\rangle$

   (b) $= \langle 1\operatorname{po}(a) + 0\operatorname{ne}(a), 1\operatorname{ne}(a) + 0\operatorname{po}(a)\rangle$

   (c) $= \langle \operatorname{po}(a), \operatorname{ne}(a)\rangle$

   (d) $= a$.

Procedure I:13(1.78)

Objective

Choose three integers a, b, c. The objective of the following instructions is to show that $a(b + c) = ab + ac$.

Implementation

1. Using declaration I:4 and declaration I:7, show that $a(b + c)$

   (a) $= \langle \operatorname{po}(a), \operatorname{ne}(a)\rangle\langle \operatorname{po}(b)+\operatorname{po}(c), \operatorname{ne}(b)+\operatorname{ne}(c)\rangle$

   (b) $= \langle \operatorname{po}(a)(\operatorname{po}(b) + \operatorname{po}(c)) + \operatorname{ne}(a)(\operatorname{ne}(b) + \operatorname{ne}(c)), \operatorname{po}(a)(\operatorname{ne}(b) + \operatorname{ne}(c)) + \operatorname{ne}(a)(\operatorname{po}(b) + \operatorname{po}(c))\rangle$

   (c) $= \langle(\operatorname{po}(a)\operatorname{po}(b) + \operatorname{ne}(a)\operatorname{ne}(b)) + (\operatorname{po}(a)\operatorname{po}(c) + \operatorname{ne}(a)\operatorname{ne}(c)), (\operatorname{po}(a)\operatorname{ne}(b) + \operatorname{ne}(a)\operatorname{po}(b)) + (\operatorname{po}(a)\operatorname{ne}(c) + \operatorname{ne}(a)\operatorname{po}(c))\rangle$

   (d) $= \langle \operatorname{po}(a)\operatorname{po}(b) + \operatorname{ne}(a)\operatorname{ne}(b), \operatorname{po}(a)\operatorname{ne}(b) + \operatorname{ne}(a)\operatorname{po}(b)\rangle + \langle \operatorname{po}(a)\operatorname{po}(c) + \operatorname{ne}(a)\operatorname{ne}(c), \operatorname{po}(a)\operatorname{ne}(c) + \operatorname{ne}(a)\operatorname{po}(c)\rangle$

   (e) $= ab + ac$.

Procedure I:14(1.91)

Objective

Choose an integer a. The objective of the following instructions is to show that $(-1)^{2a} = 1$ and $(-1)^{2a+1} = -1$.

Implementation

1. Show that $(-1)^2 = (-1)(-1) + 1 + (-1) = (-1)((-1) + 1) + 1 = (-1)0 + 1 = 1$.

2. **Hence show that** $(-1)^{2a} = ((-1)^2)^a = 1^a = 1$**.**

3. **Also show that** $(-1)^{2a+1} = (-1)^{2a}(-1) = 1(-1) = -1$**.**

Declaration I:8(1.30)

The phrases "$a < b$" and "$b > a$", where a, b are rational numbers, will be used as a shorthand for "$\text{po}(a) + \text{ne}(b) < \text{ne}(a) + \text{po}(b)$".

Procedure I:15(1.79)

Objective

Choose four integers a, b, c, d such that $a < b$, $a = c$ and $b = d$. The objective of the following instructions is to show that $c < d$.

Implementation

1. Show that $\text{po}(a) + \text{ne}(c) = \text{ne}(a) + \text{po}(c)$ using declaration I:3.
2. Show that $\text{po}(b) + \text{ne}(d) = \text{ne}(b) + \text{po}(d)$ using declaration I:3.
3. Show that $\text{po}(a) + \text{ne}(b) < \text{ne}(a) + \text{po}(b)$ using declaration I:8.
4. Hence show that $\text{po}(c) + \text{ne}(d)$
   (a) $= (\text{ne}(a) + \text{po}(c)) + (\text{po}(b) + \text{ne}(d)) - \text{ne}(a) - \text{po}(b)$
   (b) $= (\text{po}(a) + \text{ne}(c)) + (\text{ne}(b) + \text{po}(d)) - \text{ne}(a) - \text{po}(b)$
   (c) $= (\text{po}(a) + \text{ne}(b)) + \text{ne}(c) + \text{po}(d) - \text{ne}(a) - \text{po}(b)$
   (d) $< (\text{ne}(a) + \text{po}(b)) + \text{ne}(c) + \text{po}(d) - \text{ne}(a) - \text{po}(b)$
   (e) $= \text{ne}(c) + \text{po}(d)$.
5. **Hence show that $c < d$ using declaration I:8.**

Procedure I:16(1.80)

Objective

Choose three integers a, b, c such that $a < b$. The objective of the following instructions is to show that $a + c < b + c$.

Implementation

1. Show that $\text{po}(a) + \text{ne}(b) < \text{ne}(a) + \text{po}(b)$ using declaration I:8.
2. Hence show that $\text{po}(a + c) + \text{ne}(b + c)$
   (a) $= \text{po}(a) + \text{po}(c) + \text{ne}(b) + \text{ne}(c)$
   (b) $= (\text{po}(a) + \text{ne}(b)) + \text{po}(c) + \text{ne}(c)$
   (c) $= (\text{ne}(a) + \text{po}(b)) + \text{po}(c) + \text{ne}(c)$
   (d) $= \text{ne}(a) + \text{ne}(c) + \text{po}(b) + \text{po}(c)$
   (e) $= \text{ne}(a + c) + \text{po}(b + c)$.
3. **Hence show that $a + c < b + c$ using declaration I:8.**

Procedure I:17(1.81)

Objective

Choose two integers a, b. The objective of the following instructions is to show that $a < b$, $a = b$ and $a > b$.

Implementation

1. Show that either
   (a) $\text{po}(a) + \text{ne}(b) < \text{ne}(a) + \text{po}(b)$
   (b) $\text{po}(a) + \text{ne}(b) = \text{ne}(a) + \text{po}(b)$
   (c) $\text{po}(a) + \text{ne}(b) > \text{ne}(a) + \text{po}(b)$
2. Hence show that either
   (a) $a < b$ using declaration I:8 given that $\text{po}(a) + \text{ne}(b) < \text{ne}(a) + \text{po}(b)$.
   (b) $a = b$ using declaration I:3 given that $\text{po}(a) + \text{ne}(b) = \text{ne}(a) + \text{po}(b)$.
   (c) $a > b$ using declaration I:8 given that $\text{po}(a) + \text{ne}(b) > \text{ne}(a) + \text{po}(b)$.

Procedure I:18(1.85)

Objective

Choose two integers a, b such that $0 < a$ and $0 < b$. The objective of the following instructions is to show that $0 < a + b$.

Implementation

1. Show that $\text{ne}(a) = \text{po}(0) + \text{ne}(a) < \text{ne}(0) + \text{po}(a) = \text{po}(a)$ using declaration I:8.
2. Show that $\text{ne}(b) = \text{po}(0) + \text{ne}(b) < \text{ne}(0) + \text{po}(b) = \text{po}(b)$ using declaration I:8.

3. Show that $\mathrm{po}(0) + \mathrm{ne}(a+b) = \mathrm{ne}(a+b) = \mathrm{ne}(a) + \mathrm{ne}(b) < \mathrm{po}(a) + \mathrm{po}(b) = \mathrm{po}(a+b) = \mathrm{ne}(0) + \mathrm{po}(a+b)$.
4. **Hence show that** $0 < a + b$ **given that** $\mathrm{po}(0) + \mathrm{ne}(a+b) < \mathrm{ne}(0) + \mathrm{po}(a+b)$**.**

Procedure I:19(1.86)

Objective

Choose two integers a, b such that $0 < a$ and $0 < b$. The objective of the following instructions is to show that $0 < ab$.

Implementation

1. Show that $\mathrm{ne}(a) = \mathrm{po}(0) + \mathrm{ne}(a) < \mathrm{ne}(0) + \mathrm{po}(a) = \mathrm{po}(a)$ using declaration I:8.
2. Hence show that $0 < \mathrm{po}(a) - \mathrm{ne}(a)$.
3. Show that $\mathrm{ne}(b) = \mathrm{po}(0) + \mathrm{ne}(b) < \mathrm{ne}(0) + \mathrm{po}(b) = \mathrm{po}(b)$ using declaration I:8.
4. Hence show that $0 < \mathrm{po}(b) - \mathrm{ne}(b)$.
5. **Hence show that** $0 < ab$
   (a) given that $\mathrm{po}(0) + \mathrm{ne}(ab) = \mathrm{ne}(a)\,\mathrm{po}(b) + \mathrm{po}(a)\,\mathrm{ne}(b) < \mathrm{po}(a)\,\mathrm{po}(b) + \mathrm{ne}(a)\,\mathrm{ne}(b) = \mathrm{ne}(0) + \mathrm{po}(ab)$
   (b) given that $\mathrm{ne}(a)(\mathrm{po}(b) - \mathrm{ne}(b)) < \mathrm{po}(a)(\mathrm{po}(b) - \mathrm{ne}(b))$
   (c) given that $0 < (\mathrm{po}(a) - \mathrm{ne}(a))(\mathrm{po}(b) - \mathrm{ne}(b))$.

Declaration I:9(1.34)

The notation $\|a\|$ will be used as a shorthand for the following expression:

1. $-a$ if $a < 0$
2. a if $a \geq 0$

Procedure I:20(1.87)

Objective

Choose two integers a, b. The objective of the following instructions is to show that $\|ab\| = \|a\|\|b\|$.

Implementation

1. If $a \geq 0$ and $b \geq 0$, then do the following:
   (a) **Show that** $\|ab\| = ab = \|a\|\|b\|$ **given that** $ab \geq 0$**.**
2. Otherwise if $a < 0$ and $b \geq 0$, then do the following:
   (a) **Show that** $\|ab\| = -(ab) = (-a)b = \|a\|\|b\|$ **given that** $ab < 0$**.**
3. Otherwise if $a \geq 0$ and $b < 0$, then do the following:
   (a) **Show that** $\|ab\| = -(ab) = a(-b) = \|a\|\|b\|$ **given that** $ab < 0$**.**
4. Otherwise do the following:
   (a) **Show that** $\|ab\| = ab = (-a)(-b) = \|a\|\|b\|$**.**
      i. given that $ab > 0$
      ii. given that $a < 0$ and $b < 0$.

Procedure I:21(1.88)

Objective

Choose two integers a, b. The objective of the following instructions is to show that $\|a+b\| \leq \|a\| + \|b\|$.

Implementation

1. If $a + b \geq 0$, then do the following:
   (a) **Show that** $\|a+b\| = a + b \leq \|a\| + \|b\|$
      i. given that $a \leq \|a\|$
      ii. and $b \leq \|b\|$.
2. Otherwise do the following:
   (a) **Show that** $\|a+b\| = -(a+b) = (-a) + (-b) \leq \|a\| + \|b\|$
      i. given that $-a \leq \|a\|$
      ii. and $-b \leq \|b\|$
      iii. and $a + b < 0$.

Procedure I:22(1.89)

Objective

Choose two integers a, b. The objective of the following instructions is to show that $\|a\| - \|b\| \leq \|a - b\|$.

Implementation

1. Show that $\|a\| = \|b + (a - b)\| \leq \|b\| + \|a - b\|$ using procedure I:21.
2. **Hence show that** $\|a\| - \|b\| \leq \|a - b\|$**.**

Declaration I:10(1.03)

The notation $\operatorname{sgn}(a)$ will be used as a shorthand for the following expression:

1. -1 if $a < 0$
2. 0 if $a = 0$
3. 1 if $a > 0$

Declaration I:11(sun0902201144)

The notation $\mathrm{H}(a)$ will be used as a shorthand for the following expression:

1. 0 if $a < 0$
2. 1 if $a \geq 0$

Procedure I:23(1.90)

Objective

Choose an integer a. The objective of the following instructions is to show that $a = \operatorname{sgn}(a)\|a\|$.

Implementation

1. If $a > 0$, then do the following:
   (a) **Show that** $a = 1a = \operatorname{sgn}(a)\|a\|$
      i. given that $\|a\| = a$
      ii. and $\operatorname{sgn}(a) = 1$.
2. If $a = 0$, then do the following:
   (a) **Show that** $a = 0 = \operatorname{sgn}(a)0 = \operatorname{sgn}(a)\|a\|$ **given that** $\|a\| = a = 0$**.**
3. Otherwise if $a < 0$, then do the following:
   (a) **Show that** $a = (-1)(-a) = \operatorname{sgn}(a)\|a\|$
      i. given that $\|a\| = -a$
      ii. and $\operatorname{sgn}(a) = -1$.

Chapter 2

Modular Arithmetic

Procedure I:24(1.00)

Objective

Choose an integer a and a positive integer b. The objective of the following instructions is to construct integers n and m such that $a = nb + m$ and $0 \leq m < b$.

Implementation

1. Let $n = 0$.
2. While $(n+1)b \leq a$, do the following:
   (a) Let n receive $n + 1$.
   (b) Show that $nb \leq a$.
3. While $nb > a$, do the following:
   (a) Let n receive $n - 1$.
   (b) Show that $(n+1)b > a$.
4. Hence show that $nb \leq a$ and $(n+1)b > a$.
5. Let $m = a - nb$.
6. **Now show that $b > a - nb = m \geq 0$ and $a = bn + a - nb = nb + m$.**
7. **Yield $\langle n, m\rangle$.**

Declaration I:12(1.00)

The notation $a \operatorname{div} b$ will be used to refer to the first part of the pair yielded by executing procedure I:24 on $\langle a, b\rangle$.

Declaration I:13(1.01)

The notation $a \bmod b$ will be used to refer to the second part of the pair yielded by executing procedure I:24 on $\langle a, b\rangle$.

Declaration I:14(1.02)

The notation $a \equiv b \pmod{c}$ will be used as a shorthand for "$a \bmod c = b \bmod c$".

Procedure I:25(1.01)

Objective

Choose four integers a, b, c, d and a positive integer e in such a way that $a \equiv c \pmod{e}$ and $b \equiv d \pmod{e}$. The objective of the following instructions is to show that $a + b \equiv c + d \pmod{e}$.

Implementation

1. Show that $a + b$
   (a) $\equiv (a \operatorname{div} e)e + (a \bmod e) + (b \operatorname{div} e)e + (b \bmod e)$
   (b) $\equiv (a \bmod e) + (b \bmod e)$
   (c) $\equiv (c \bmod e) + (d \bmod e)$
   (d) $\equiv (c \operatorname{div} e)e + (c \bmod e) + (d \operatorname{div} e)e + (d \bmod e)$
   (e) $\equiv c + d \pmod{e}$.

Procedure I:26(1.02)

Objective

Choose four integers a, b, c, d and a positive integer e in such a way that $a \equiv c \pmod{e}$ and $b \equiv d \pmod{e}$. The objective of the following instructions is to show that $ab \equiv cd \pmod{e}$.

Implementation

1. Show that ab
   (a) $\equiv ((a \operatorname{div} e)e + (a \bmod e))((b \operatorname{div} e)e + (b \bmod e))$
   (b) $\equiv (a \operatorname{div} e)(b \operatorname{div} e)e^2 + (a \operatorname{div} e)(b \bmod e)e + (a \bmod e)(b \operatorname{div} e)e + (a \bmod e)(b \bmod e)$
   (c) $\equiv (a \bmod e)(b \bmod e)$
   (d) $\equiv (c \bmod e)(d \bmod e)$
   (e) $\equiv (c \operatorname{div} e)(d \operatorname{div} e)e^2 + (c \operatorname{div} e)(d \bmod e)e + (c \bmod e)(d \operatorname{div} e)e + (c \bmod e)(d \bmod e)$
   (f) $\equiv cd \pmod{e}$**.**

Procedure I:27(1.03)

Objective

Choose an integer a and two positive integers b, c. The objective of the following instructions is to show that $(a \bmod bc) \bmod b = a \bmod b$.

Implementation

1. **Show that** $(a \bmod bc) \bmod b = (a - (a \operatorname{div} bc)bc) \bmod b = a \bmod b$**.**

Procedure I:28(1.04)

Objective

Choose a positive integer a and four integers b_1, b_0, c_1, c_0 such that $0 \leq b_0 < a$, $0 \leq c_0 < a$, and $b_1 a + b_0 = c_1 a + c_0$. The objective of the following instructions is to show that $b_1 = c_1$ and $b_0 = c_0$.

Implementation

1. **Show that** $b_0 = b_0 \bmod a = (b_1 a + b_0) \bmod a = (c_1 a + c_0) \bmod a = c_0 \bmod a = c_0$**.**
2. **Therefore show that** $b_1 = c_1$ **given that** $b_1 a = c_1 a$**.**

Procedure I:29(1.05)

Objective

Choose an integer a and two positive integers b, c. The objective of the following instructions is to show that $ca \bmod cb = c(a \bmod b)$ and that $ca \operatorname{div} cb = a \operatorname{div} b$.

Implementation

1. Show that $bc(a \operatorname{div} b) + c(a \bmod b) = c(b(a \operatorname{div} b) + a \bmod b) = ca = cb(ca \operatorname{div} cb) + ca \bmod cb$.
2. Show that $0 \leq a \bmod b < b$.
3. Show that $0 \leq c(a \bmod b) < cb$.
4. Show that $0 \leq ca \bmod cb < cb$.
5. **Hence show that** $c(a \bmod b) = ca \bmod cb$ **and** $a \operatorname{div} b = ca \operatorname{div} cb$ **using procedure I:28.**

Procedure I:30(1.06)

Objective

Choose two integers a, b and a positive integer c such that $a \bmod c + b \bmod c < c$. The objective of the following instructions is to show that $a \operatorname{div} c + b \operatorname{div} c = (a + b) \operatorname{div} c$ and $a \bmod c + b \bmod c = (a + b) \bmod c$.

Implementation

1. Show that $a = c(a \operatorname{div} c) + a \bmod c$.
2. Show that $b = c(b \operatorname{div} c) + b \bmod c$.
3. Therefore show that $a + b = c(a \operatorname{div} c + b \operatorname{div} c) + (a \bmod c + b \bmod c)$.
4. Show that $0 \leq a \bmod c + b \bmod c < c$.
5. Also show that $a + b = ((a + b) \operatorname{div} c)c + (a + b) \bmod c$.
6. Show that $0 \leq (a + b) \bmod c < c$.
7. **Hence show that** $a \operatorname{div} c + b \operatorname{div} c = (a + b) \operatorname{div} c$ **and** $a \bmod c + b \bmod c = (a + b) \bmod c$ **using procedure I:28.**

Procedure I:31(1.07)

Objective

Choose two integers a, b and a positive integer c such that $a \bmod c + b \bmod c \geq c$. The objective of the following instructions is to show that $1 + a \operatorname{div} c + b \operatorname{div} c = (a+b) \operatorname{div} c$ and $a \bmod c + b \bmod c - c = (a+b) \bmod c$.

Implementation

1. Show that $a = c(a \operatorname{div} c) + a \bmod c$.
2. Show that $b = c(b \operatorname{div} c) + b \bmod c$.
3. Therefore show that $a+b = c(a \operatorname{div} c + b \operatorname{div} c) + a \bmod c + b \bmod c = c(1 + a \operatorname{div} c + b \operatorname{div} c) + (a \bmod c + b \bmod c - c)$.
4. Show that $c \leq a \bmod c + b \bmod c < 2c$.
5. Therefore show that $0 \leq a \bmod c + b \bmod c - c < c$.
6. Also show that $a + b = c((a+b) \operatorname{div} c) + (a+b) \bmod c$.
7. Show that $0 \leq (a+b) \bmod c < c$.
8. **Therefore show that** $1 + a \operatorname{div} c + b \operatorname{div} c = (a+b) \operatorname{div} c$ **and** $a \bmod c + b \bmod c - c = (a+b) \bmod c$ **using procedure I:28.**

Procedure I:32(1.08)

Objective

Choose an integer a and two positive integers b, c. The objective of the following instructions is to show that $a \operatorname{div} bc = (a \operatorname{div} b) \operatorname{div} c$ and $a \bmod bc = ((a \operatorname{div} b) \bmod c)b + a \bmod b$.

Implementation

1. Show that $a = (((a \operatorname{div} b) \operatorname{div} c)c + (a \operatorname{div} b) \bmod c)b + a \bmod b = ((a \operatorname{div} b) \operatorname{div} c)bc + ((a \operatorname{div} b) \bmod c)b + a \bmod b$
   (a) given that $a = (a \operatorname{div} b)b + a \bmod b$
   (b) given that $a \operatorname{div} b = ((a \operatorname{div} b) \operatorname{div} c)c + (a \operatorname{div} b) \bmod c$.
2. Show that $0 \leq ((a \operatorname{div} b) \bmod c)b \leq cb - b$ given that $0 \leq (a \operatorname{div} b) \bmod c \leq c - 1$.
3. Therefore show that $0 \leq ((a \operatorname{div} b) \bmod c)b + a \bmod b < cb$ given that $0 \leq a \bmod b < b$.
4. Now show that $a = (a \operatorname{div} bc)bc + a \bmod bc$ and $0 \leq a \bmod bc < bc$.
5. **Therefore show that** $(a \operatorname{div} b) \operatorname{div} c = a \operatorname{div} bc$ **and** $((a \operatorname{div} b) \bmod c)b + a \bmod b = a \bmod bc$ **using procedure I:28.**

Procedure I:33(1.09)

Objective

Choose an integer a and a non-negative integer b. The objective of the following instructions is to consruct integers c, d, e, f, g such that $a = cd$, $b = ce$, $fa + gb = c$, and if $b = 0$, then $c = |a|$, otherwise $0 < c \leq b$.

Implementation

1. If $b = 0$, then do the following:
   (a) **Show that** $a = \operatorname{sgn}(a)|a|$**.**
   (b) **Show that** $b = 0|a|$**.**
   (c) **Show that** $|a| = \operatorname{sgn}(a)a + 0b$**.**
   (d) **Yield** $\langle |a|, \operatorname{sgn}(a), 0, \operatorname{sgn}(a), 0 \rangle$**.**
2. Otherwise do the following:
   (a) Show that $0 \leq a \bmod b < b$.
   (b) Use procedure I:33 on $\langle b, a \bmod b \rangle$ to construct $\langle c, d, e, f, g \rangle$ and show that:
      i. $b = cd$
      ii. $a \bmod b = ce$
      iii. $c = \|b\|$ if $a \bmod b = 0$, otherwise $0 < c \leq a \bmod b$
      iv. $fb + g(a \mod b) = c$.
   (c) **Hence show that** $a = (a \operatorname{div} b)b + (a \bmod b) = c(d(a \operatorname{div} b) + e)$**.**
   (d) **Also show that** $(f - g(a \operatorname{div} b))b + ga = fb + g(a - (a \operatorname{div} b)b) = fb + g(a \bmod b) = c$**.**
   (e) If $a \bmod b = 0$, then do the following:
      i. **Show that** $0 < b = c \leq b$ **given that** $b \geq 0$**,** $b \neq 0$**, and** $c = \|b\| = b$**.**
   (f) Otherwise do the following:
      i. **Show that** $0 < c \leq a \bmod b < b$ **given** $0 < c \leq a \bmod b$**.**

(g) **Therefore yield** $\langle c, d(a \operatorname{div} b) + e, d, g, f - g(a \operatorname{div} b)\rangle$**.**

Declaration I:15(1.04)

The notation (a, b) will be used to refer to the first part of the quintuple constructed by using procedure I:33 on the pair $\langle a, b\rangle$.

Procedure I:34(1.10)

Objective

Choose an integer a and a positive integer b. Let $1 \leq c \leq b$ be the largest integer such that $a \bmod c = 0$ and $b \bmod c = 0$. The objective of the following instructions is to either show that $0 \neq 0$ or $(a, b) = c$.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle d, e, f, g, h\rangle$ and show that:
   (a) $a = ed$
   (b) $b = fd$
   (c) $ga + hb = d$
   (d) $0 < d \leq b$.
2. If $d > c$, then do the following:
   (a) Show that $a \bmod d \neq 0$ or $b \bmod d \neq 0$ given that $0 < d \leq b$ is larger than the largest integer such that $a \bmod c = 0$ and $b \bmod c = 0$.
   (b) If $a \bmod d \neq 0$, then do the following:
      i. Show that $a \bmod d = 0$ given that $a = ed$.
      ii. **Hence show that** $0 \neq 0$ **given that** $a \bmod d \neq 0$ **and** $a \bmod d = 0$**.**
      iii. **Abort procedure.**
   (c) Otherwise if $b \bmod d \neq 0$, then do the following:
      i. Show that $b \bmod d = 0$ given that $b = fd$.
      ii. **Hence show that** $0 \neq 0$ **given that** $b \bmod d \neq 0$ **and** $b \bmod d = 0$**.**
      iii. **Abort procedure.**
3. Otherwise if $d < c$, then do the following:
   (a) Show that $0 \equiv gc(a \operatorname{div} c) + hc(b \operatorname{div} c) = g(c(a \operatorname{div} c) + a \bmod c) + h(c(b \operatorname{div} c) + b \bmod c) = ga + hb = d \not\equiv 0 \pmod c$ given that:
      i. $ga + hb = d$
      ii. $a \bmod c = 0$
      iii. $b \bmod c = 0$.
   (b) **Hence show that** $0 \neq 0$**.**
   (c) **Abort procedure.**
4. **Otherwise show that** $(a, b) = d = c$**.**

Procedure I:35(1.11)

Objective

Choose integers a, c, d, j and a non-negative integer b. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle e, f, g, h, i\rangle$. The objective of the following instructions is to show that $ca + db = (c + gj)a + (d - fj)b$.

Implementation

1. **Show that** $(c + gj)a + (d - fj)b = ca + db + gja - fjb = ca + db + gjef - fjeg = ca + db$**.**

Procedure I:36(1.12)

Objective

Choose integers a, c, d and a non-negative integer b such that $ca + db = (a, b)$. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle e, f, g, h, i\rangle$. The objective of the following instructions is to construct a j such that $c = h + gj$ and $d = i - fj$.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to show that:
   (a) $a = ef$
   (b) $b = eg$
   (c) $ha + ib = e$.
2. Show that $cf + dg = 1$
   (a) given that $cef + deg = ca + db = (a, b) = e$
   (b) given that $a = ef$ and $b = eg$.
3. Show that $hf + ig = 1$
   (a) given that $hef + ieg = ha + ib = e$
   (b) given that $a = ef$ and $b = eg$.
4. Let $j = ci - hd$.

5. **Show that** $c = h+cig-hdg = h+g(ci-hd) = h+gj$

(a) given that $c - cig = c(1-ig) = chf = h(1-dg) = h - hdg$

(b) given that $cf = 1 - dg$.

6. **Show that** $d = i-icf+dhf = i-f(ic-dh) = i - fj$

(a) given that $d - dhf = d(1-hf) = dig = i(1-cf) = i - icf$

(b) given that $dg = 1 - cf$.

7. **Yield** $\langle j \rangle$**.**

Procedure I:37(1.13)

Objective

Choose an integer a and a positive integer b such that $0 < (a,b) < b$. The objective of the following instructions is to show that $0 \neq 0$ or $a \bmod b \neq 0$.

Implementation

1. If $a \bmod b = 0$, then do the following:

(a) Show that $af \equiv 0f \equiv 0 \pmod{b}$ given that $a \bmod b = 0$.

(b) Use procedure I:33 on $\langle a,b \rangle$ to construct $\langle c, d, e, f, g \rangle$ and show that:

i. $fa + gb = c = (a,b)$

ii. $0 < c = (a,b) \leq b$.

(c) Hence show that $fa \equiv (a,b) \not\equiv 0 \pmod{b}$ given that $0 < (a,b) < b$.

(d) Hence show that $0 \neq 0$ given that $0 \equiv af \not\equiv 0 \pmod{b}$.

(e) **Abort procedure.**

2. **Otherwise show that** $a \bmod b \neq 0$**.**

Procedure I:38(1.14)

Objective

Choose five integers a, d, e, f, g and two non-negative integers b, c such that $a = cd$, $b = ce$, and $fa + gb = c$. The objective of the following instructions is to show that $0 < 0$ or $(a,b) = c$.

Implementation

1. Use procedure I:33 on $\langle a,b \rangle$ to construct $\langle u, v, x, y, z \rangle$ and show that:

(a) $u \geq 0$

(b) $a = uv$

(c) $b = xu$

(d) $u = ya + zb$.

2. Hence show that $c = fa + gb = (fv + gx)u$.

3. If $u = 0$, then do the following:

(a) **Show that** $c = (fv+gx)u = 0 = u = (a,b)$**.**

(b) **Yield.**

4. Show that $u = ya + zb = (yd + ze)c$ given that $u = ya + zb$, $a = cd$, and $b = ce$.

5. If $c = 0$, then do the following:

(a) **Show that** $(a,b) = u = (yd + ze)c = 0 = c$**.**

(b) **Yield.**

6. Show that $fv + gx = yd + ze = \pm 1$

(a) given that $(fv + gx)(yd + ze) = 1$

(b) given that $c = (fv + gx)u = (fv + gx)(yd + ze)c$ and $c > 0$.

7. If $fv + gx = yd + ze = -1$, then do the following:

(a) Show that $u = (yd + ze)c = (-1)c < 0$ given that $u = (yd + ze)c$ and $c > 0$.

(b) **Hence show that** $0 \leq u < 0$ **given that** $u \geq 0$**.**

(c) **Abort procedure.**

8. Otherwise, do the following:

(a) Show that $fv + gx = yd + ze = 1$.

(b) **Hence show that** $c = (fv+gx)u = (1)u = (a,b)$ **given that** $c = (fv + gx)u$**.**

Procedure I:39(1.15)

Objective

Choose an integer a and a non-negative integer b. The objective of the following instructions is to show that $0 < 0$ or $(a,b) = (-a,b)$.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle c, d, e, f, g\rangle$ and show that:

   (a) $a = dc$

   (b) $b = ec$

   (c) $fa + gb = c$.

2. Hence show that $-a = (-d)c$.
3. Also show that $(-f)(-a) + gb = c$.
4. **Use procedure I:38 on $\langle -a, b, c, -d, e, -f, g\rangle$ to show that $(-a, b) = c = (a, b)$.**

Procedure I:40(1.16)

Objective

Choose two non-negative integers a, b. The objective of the following instructions is to show that $0 < 0$ or $(a, b) = (b, a)$.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle c, d, e, f, g\rangle$ and show that:

   (a) $b = ec$

   (b) $a = dc$

   (c) $gb + fa = c$.

2. **Use procedure I:38 on $\langle b, a, c, e, d, g, f\rangle$ to show that $(b, a) = c = (a, b)$.**

Procedure I:41(1.17)

Objective

Choose two integers a, b and a positive integer c such that $a \equiv b \pmod c$. The objective of the following instructions is to show that $0 < 0$ or $(a, c) = (b, c)$.

Implementation

1. Use procedure I:33 on $\langle a, c\rangle$ to construct $\langle d, e, f, g, h\rangle$ and show that:

   (a) $a = ed$

   (b) $c = fd$

   (c) $ga + hc = d$.

2. Let $j = b \operatorname{div} c - a \operatorname{div} c$.
3. Hence show that $b = a + jc = ed + jfd = (e + jf)d$.
4. Also show that $gb + (h - gj)c = g(a + jc) + (h - gj)c = ga + hc = d$ given that $b = a + jc$.
5. **Use procedure I:38 on $\langle b, c, d, e + jf, f, g, h - gj\rangle$ to show that $(b, c) = d = (a, c)$.**

Procedure I:42(1.18)

Objective

Choose an integer a and two non-negative integers b, c. The objective of the following instructions is to show that either $0 < 0$ or $(ca, cb) = c(a, b)$.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle d, e, f, g, h\rangle$ and show that:

   (a) $a = ed$

   (b) $b = df$

   (c) $ga + hb = d$.

2. Hence show that $ca = e(cd)$, $cb = f(cd)$, and $g(ca) + h(cb) = cd$.
3. **Use procedure I:38 on $\langle ca, cb, cd, e, f, g, h\rangle$ to show that $(ca, cb) = cd = c(a, b)$.**

Procedure I:43(1.19)

Objective

Choose an integer a and two non-negative integers b, c. The objective of the following instructions is to show that either $0 < 0$ or $(a, (b, c)) = ((a, b), c)$.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle d_0, e_0, f_0, g_0, h_0\rangle$ and show that:

   (a) $a = d_0 e_0$

   (b) $b = d_0 f_0$

   (c) $g_0 a + h_0 b = d_0$.

2. Use procedure I:33 on $\langle b, c\rangle$ to construct $\langle d_1, e_1, f_1, g_1, h_1\rangle$ and show that:

   (a) $b = d_1 e_1$

   (b) $c = d_1 f_1$

(c) $g_1 b + h_1 c = d_1$.

3. Use procedure I:33 on $\langle (a,b), c\rangle$ to construct $\langle d_2, e_2, f_2, g_2, h_2\rangle$ and show that:

(a) $(a,b) = d_2 e_2$

(b) $c = d_2 f_2$

(c) $g_2(a,b) + h_2 c = d_2$.

4. Show that $a = d_0 e_0 = e_0(a,b) = e_0 d_2 e_2 = e_0 e_2((a,b),c)$.

5. Also show that (b,c)

(a) $= g_1 b + h_1 c$

(b) $= g_1 d_0 f_0 + h_1 d_2 f_2$

(c) $= g_1 f_0(a,b) + h_1 f_2((a,b),c)$

(d) $= g_1 f_0 d_2 e_2 + h_1 f_2((a,b),c)$

(e) $= g_1 f_0 e_2((a,b),c) + h_1 f_2((a,b),c)$

(f) $= (g_1 f_0 e_2 + h_1 f_2)((a,b),c)$.

6. Also show that $((a,b),c)$

(a) $= d_2$

(b) $= g_2(a,b) + h_2 c$

(c) $= g_2 d_0 + h_2 d_1 f_1$

(d) $= g_2(g_0 a + h_0 b) + h_2 f_1(b,c)$

(e) $= g_2 g_0 a + g_2 h_0 d_1 e_1 + h_2 f_1(b,c)$

(f) $= g_2 g_0 a + g_2 h_0 e_1(b,c) + h_2 f_1(b,c)$

(g) $= g_2 g_0 a + (g_2 h_0 e_1 + h_2 f_1)(b,c)$.

7. **Use procedure I:38 on $\langle a, (b,c), ((a,b),c), e_0 e_2, g_1 f_0 e_2 + h_1 f_2, g_2 g_0, g_2 h_0 e_1 + h_2 f_1\rangle$ to show that $((a,b),c) = (a,(b,c))$.**

Declaration I:16(1.05)

The notation $(a_0, a_1, \cdots, a_{n-1})$ will be used to contextually refer to one of the following integers:

1. $((a_0),(a_1, a_2, \cdots, a_{n-1}))$
2. $((a_0, a_1),(a_2, a_3, \cdots, a_{n-1}))$
3. $\vdots$
4. $((a_0, a_1, \cdots, a_{n-2}),(a_{n-1}))$

Procedure I:44(1.20)

Objective

Choose two integers a, b and a non-negative integer c such that $(a,c) = 1$ and $(b,c) = 1$. The objective of the following instructions is to show that either $0 < 0$ or $(ab, c) = 1$.

Implementation

1. Use procedure I:33 on $\langle a, c\rangle$ to construct $\langle d, e, f, g, h\rangle$ and show that $ga + hc = d = (a,c) = 1$.
2. Use procedure I:33 on $\langle b, c\rangle$ to construct $\langle t, u, v, w, x\rangle$ and show that $wb + xc = t = (b,c) = 1$.
3. Hence show that $(gw)(ab) + (gax + wbh + hxc)c = (ga + hc)(wb + xc) = 1$.
4. **Use procedure I:38 on $\langle ab, c, 1, ab, c, gw, gax + wbh + hxc\rangle$ to show that $(ab, c) = 1$.**

Procedure I:45(1.21)

Objective

Choose an integer a and two non-negative integers b, c such that $(a, bc) = 1$. The objective of the following instructions is to show that either $0 < 0$ or $(a,b) = 1$.

Implementation

1. Use procedure I:33 on $\langle a, bc\rangle$ to construct $\langle d, e, f, g, h\rangle$ and show that $ga + (hc)b = ga + h(bc) = d = (a, bc) = 1$.
2. **Now use procedure I:38 on $\langle a, b, 1, a, b, g, hc\rangle$ to show that $(a,b) = 1$.**

Declaration I:17(1.06)

The phrase "prime number" will be used to refer to integers a such that $a > 1$ and $a \bmod k \neq 0$ for $1 < k < a$.

Procedure I:46(1.22)

Objective

Choose an integer a and a prime b such that $a \bmod b \neq 0$. The objective of the following instructions is to show that either $0 \neq 0$ or $(a,b) = 1$.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle c, d, e, f, g\rangle$ and show that:
   (a) $a = cd$
   (b) $b = ce$
   (c) $0 < c \le b$.
2. If $c = b$, then do the following:
   (a) Show that $a \bmod b = 0$ given that $a = cd = bd$.
   (b) **Hence show that $0 \ne 0$ given that $a \bmod b \ne 0$.**
   (c) **Abort procedure.**
3. Otherwise if $1 < c < b$, then do the following:
   (a) Show that $b \bmod c = 0$ given that $b = ce$.
   (b) **Hence show that $0 \ne 0$ given that b is prime.**
   (c) **Abort procedure.**
4. Otherwise, do the following:
   (a) **Show that $(a, b) = c = 1$.**

Procedure I:47(1.23)

Objective

Choose two integers a, b and a prime c such that $a \bmod c \ne 0$ and $b \bmod c \ne 0$. The objective of the following instructions is to show that either $0 \ne 0$ or $ab \bmod c \ne 0$.

Implementation

1. Use procedure I:46 on $\langle a, c\rangle$ to show that $(a, c) = 1$.
2. Use procedure I:46 on $\langle b, c\rangle$ to show that $(b, c) = 1$.
3. Use procedure I:44 on $\langle a, b, c\rangle$ to show that $0 < (ab, c) = 1 < c$.
4. **Use procedure I:37 on $\langle ab, c\rangle$ to show that $ab \bmod c \ne 0$.**

Declaration I:18(1.07)

The notation $|a|$ will be used to refer to the number of items in the list a.

Declaration I:19(1.10)

The notation $a \frown b$ will be used to refer to the list formed by concatenating a and b.

Declaration I:20(1.31)

The notation $f(R)$, where R is a list and $f[r]$ is a function of r, will contextually be used as a shorthand for the list $\langle f(R_0), f(R_1), \cdots, f(R_{|R|-1})\rangle$.

Declaration I:21(1.09)

The notation a_*, where a is a list, will be used as a shorthand for 1 if a is empty, otherwise it will be a shorthand for the product of the entries of a.

Declaration I:22(1.08)

The notation $\prod_r^R f(r)$, where R is a list and $f[r]$ is a function of r, will be used as a shorthand for $f(R)_*$.

Procedure I:48(1.24)

Objective

Choose a positive integer a. The objective of the following instructions is to construct a list of prime numbers b such that $a = b_*$.

Implementation

1. If $a = 1$, then do the following:
   (a) Show that $a = 1 = \langle\rangle_*$.
   (b) Hence yield $\langle\rangle$.
2. Otherwsie, do the following:
   (a) Show that $a > 1$.
   (b) If there is a $c \in [2 : a]$ such that $a \bmod c = 0$, then do the following:
      i. Show that $a = (a \operatorname{div} c)c$.
      ii. Hence show that $1 < a \operatorname{div} c < a$.
      iii. Use procedure I:48 on $\langle a \operatorname{div} c\rangle$ to construct $\langle d\rangle$ and show that:
         A. every element of d is prime.
         B. $a \operatorname{div} c = d_*$.
      iv. Hence show that d is non-empty given that $1 < a \operatorname{div} c = d_*$.

v. Use procedure I:48 on $\langle c \rangle$ to construct $\langle e \rangle$ and show that:

A. every element of e is prime.

B. $c = e_*$.

vi. Hence show that e is non-empty given that $1 < c = e_*$.

vii. **Hence show that $d^\frown e$ is a non-empty list of prime numbers such that $a = (a \operatorname{div} c)c = d_* e_* = (d^\frown e)_*$.**

viii. **Yield $\langle d^\frown e \rangle$.**

(c) Otherwise do the following:

i. **Show that a is prime.**

ii. **Yield $\langle a \rangle$.**

Procedure I:49(1.25)

Objective

Choose a prime a and a list of primes b such that $b_* \equiv 0 \pmod{a}$. The objective of the following instructions is to either show that $0 = 1$ or to construct a k such that $a = b_k$.

Implementation

1. Show that $a > 1$ given that a is prime.
2. If $|b| = 0$, then do the following:
   (a) Show that $1 = b_* \equiv 0 \pmod{a}$.
   (b) **Hence show that $0 = 1$ given that $a > 1$.**
   (c) **Abort procedure.**
3. Otherwise if $0 \notin b \bmod a$, then do the following:
   (a) Show that $b_* \not\equiv 0 \pmod{a}$ using procedure I:47.
   (b) **Hence show that $0 \neq 0$ given that $b_* \equiv 0 \pmod{a}$.**
   (c) **Abort procedure.**
4. Otherwise do the following:
   (a) Let k be such that $b_k \bmod a = 0$.
   (b) Show that $b_k = (b_k \operatorname{div} a)a$.
   (c) Hence show that $b_k \operatorname{div} a \geq 1$.
   (d) If $b_k \operatorname{div} a > 1$, then do the following:

i. Show that $1 < a < b_k$ given that:

A. $a > 1$

B. $b_k \operatorname{div} a > 1$

C. $b_k = (b_k \operatorname{div} a)a$.

ii. Hence show that $b_k \bmod a \neq 0$ given that b_k is prime and $1 < a < b_k$.

iii. **Hence show that $0 \neq b_k \bmod a = 0$ given that $b_k \bmod a = 0$.**

iv. **Abort procedure.**

(e) Otherwise do the following:

i. **Show that $b_k = a$ given that $b_k \operatorname{div} a = 1$.**

ii. **Yield $\langle k \rangle$.**

Declaration I:23(1.11)

The notation $[a : b]$ will be used as a shorthand for the list:

1. $\langle a, a+1, \cdots, b-1 \rangle$, if $b > a$
2. $\langle \rangle$, if $b = a$
3. $\langle a-1, a-2, \cdots, b \rangle$, if $b < a$

Procedure I:50(1.26)

Objective

Choose two lists of primes a, b such that $a_* = b_*$. The objective of the following instructions is to show that either $1 > 1$ or a is included in b.

Implementation

1. If $|a| = 0$, then do the following:
   (a) **Show that a is included in b.**
2. Otherwise, do the following:
   (a) Show that $|a| > 0$.
   (b) Show that $b_* \equiv a_* \equiv 0 \pmod{a_0}$.
   (c) Use procedure I:49 on $\langle a_0, b \rangle$ to construct $\langle k \rangle$ and show that $b_k = a_0$.
   (d) Now show that $(a_{[1:|a|]})_* = (b_{[0:k]^\frown[k+1:|b|]})_*$.
   (e) Now use procedure I:50 on $\langle a_{[1:|a|]}, b_{[0:k]^\frown[k+1:|b|]} \rangle$ to show that $a_{[1:|a|]}$ is included in $b_{[0:k]^\frown[k+1:|b|]}$.

(f) **Hence show that a is included in b.**

Procedure I:51(1.27)

Objective

Choose two lists of primes a, b such that $a_* = b_*$. The objective of the following instructions is to show that either $1 > 1$ or a is a rearrangement of b.

Implementation

1. Use procedure I:50 on $\langle a, b\rangle$ to show that a is included in b.
2. Use procedure I:50 on $\langle b, a\rangle$ to show that b is included in a.
3. **Hence show that a is a rearrangement of b.**

Procedure I:52(1.28)

Objective

Choose a positive integer a. The objective of the following instructions is to either show that $0 = 1$ or to construct a prime b such that $b > a$ and $[a+1 : b]$ does not contain a prime.

Implementation

1. Show that $a! + 1 > 1$.
2. Use procedure I:48 on $\langle a! + 1\rangle$ to construct $\langle d\rangle$ and show that:

(a) $a! + 1 = d_*$

(b) every element of d is prime.

3. Hence show that $|d| > 0$ given that $a! + 1 > 1$.
4. Hence show that $(a! + 1) \bmod d_0 = 0$.
5. If $d_0 \in [2 : a + 1]$, then do the following:

(a) Show that $a! + 1 \equiv 1 \pmod{d_0}$

i. given that $a! \pmod{d_0} \equiv 0$

ii. given that $d_0 \in [2 : a + 1]$.

(b) Show that $0 \equiv a! + 1 \pmod{d_0}$

i. given that $(a! + 1) \bmod d_0 = 0$

ii. given that $a! + 1 = d_*$.

(c) **Hence show that $0 = 1$.**

(d) **Abort procedure.**

6. Otherwise do the following:

(a) **Show that d_0 is prime given that every element of d is prime.**

(b) **Hence show that $d_0 > a$ given that $d_0 > 1$ and $d_0 \notin [2 : a + 1]$.**

(c) **Let b be the least prime in $[a+1 : d_0+1]$.**

(d) **Yield $\langle b\rangle$.**

Procedure I:53(1.29)

Objective

Choose a positive integer a. The objective of the following instructions is to construct a positive integer b such that $[b + 1 : b + a]$ does not contain a prime.

Implementation

1. Let $b = a! + 1$.
2. For $i \in [1 : a]$, do the following:

(a) Show that $b + i = a! + 1 + i = i!(i + 1)(i + 2) \cdots (a) + 1 + i = (1 + i)(i!(i + 2)(i + 3) \cdots (a) + 1)$.

(b) Therefore show that $b + i \equiv 0 \pmod{i + 1}$.

(c) Also show that $b + i = a! + 1 + i > a! \geq a \geq i + 1 > 1$.

(d) **Hence show that $b + i$ is not prime.**

3. **Yield $\langle b\rangle$.**

Procedure I:54(1.30)

Objective

Choose two lists of primes a, b in such a way that their intersection is empty. The objective of the following instructions is to show that $0 = 1$ or $(a_*, b_*) = 1$.

Implementation

1. Use procedure I:33 on $\langle a_*, b_*\rangle$ to construct $\langle c, d, e, f, g\rangle$ and show that:

(a) $0 < c \leq b_*$

(b) $a_* = cd$

(c) $b_* = ce$.

2. If $c > 1$, then do the following:

(a) Use procedure I:48 on $\langle c \rangle$ to construct $\langle h \rangle$ and show that $c = h_*$.

(b) Hence show that $|h| > 0$ given that $h_* = c > 1$.

(c) Now show that $a_* = dc = dh_* = dh_0(h_{[1:|h|]})_* \equiv 0 \pmod{h_0}$.

(d) Use procedure I:49 on $\langle h_0, a \rangle$ to construct $\langle k \rangle$ and show that $h_0 = a_k$.

(e) Now show that $b_* = ec = eh_* = eh_0(h_{[1:|h|]})_* \equiv 0 \pmod{h_0}$.

(f) Use procedure I:49 on $\langle h_0, b \rangle$ to construct $\langle m \rangle$ and show that $h_0 = b_m$.

(g) **Hence show that a and b intersect given that $a_k = h_0 = b_m$.**

(h) **Abort procedure.**

3. Otherwise do the following:

(a) **Show that $(a_*, b_*) = c = 1$ given that $0 < c \leq b_*$ and $c \leq 1$.**

Procedure I:55(1.31)

Objective

Choose two lists of primes a, b. Let c be the common sublist with multiplicity of a and b. The objective of the following instructions is to show that either $0 < 0$ or $(a_*, b_*) = c_*$.

Implementation

1. Let d be the result of removing with multiplicity elements of c from a.

2. Show that $a_* = c_* d_*$.

3. Let e be the result of removing with multiplicity elements of c from b.

4. Show that $b_* = c_* e_*$.

5. Show that d and e share no common elements.

6. **Therefore show that $(a_*, b_*) = (c_* d_*, c_* e_*) = c_*(d_*, e_*) = c_*$ using procedure I:42 and procedure I:54.**

Procedure I:56(1.32)

Objective

Choose an integer a and a positive integer b. The objective of the following instructions is to construct integers c, f, e such that $c = af$, $c = be$, $c(a, b) = ab$, and $|a| \leq |c| \leq |a|b$.

Implementation

1. Use procedure I:33 on $\langle a, b \rangle$ to construct $\langle d, e, f, g, h \rangle$ and show that:

(a) $a = de$

(b) $b = df$

(c) $d > 0$.

2. **Let $c = af$.**

3. **Show that $c = af = def = be$.**

4. **Show that $c(a, b) = cd = afd = ab$.**

5. Show that $1 \leq f \leq b$

(a) given that $0 < b = df$

(b) and $d > 0$.

6. Therefore show that $|a| \leq |a|f \leq |a|b$.

7. **Therefore show that $|a| \leq |c| \leq |a|b$.**

8. **Yield the tuple $\langle c, f, e \rangle$.**

Declaration I:24(1.12)

The notation $[a, b]$ will be used to refer to the first part of the triple yielded by executing procedure I:56 on $\langle a, b \rangle$.

Procedure I:57(1.33)

Objective

Choose two positive integers a, b. The objective of the following instructions is to show that either $0 < 0$ or $[a, b] = [b, a]$.

Implementation

1. Show that $(a, b) > 0$.

2. Show that $[a, b](a, b) = ab = ba = [b, a](b, a) = [b, a](a, b)$ using procedure I:40.

3. **Therefore show that $[a, b] = [b, a]$.**

Procedure I:58(1.34)

Objective

Choose an integer a and two positive integers b, c. The objective of the following instructions is to show that either $0 < 0$ or $[ca, cb] = c[a, b]$.

Implementation

1. Show that $(ca, cb) > 0$.
2. Show that $[ca, cb](ca, cb) = cacb = c^2ab = c^2[a, b](a, b) = c[a, b](ca, cb)$ using procedure I:42.
3. **Therefore show that** $[ca, cb] = c[a, b]$**.**

Procedure I:59(1.35)

Objective

Choose an integer a and two positive integers b, c. The objective of the following instructions is to show that either $0 < 0$ or $[[a, b], c] = [a, [b, c]]$.

Implementation

1. Using procedure I:43, show that $(a, b)(ab, (ac, bc))(b, c)[[a, b], c]$
   (a) $= (ab, (ac, bc))(b, c)[(a, b)[a, b], (a, b)c]$
   (b) $= (ab, (ac, bc))(b, c)[ab, (ac, bc)]$
   (c) $= ab(ac, bc)(b, c)$
   (d) $= abc(a, b)(b, c)$
   (e) $= bc(a, b)(ab, ac)$
   (f) $= (a, b)((ab, ac), bc)[(ab, ac), bc]$
   (g) $= (a, b)(ab, (ac, bc))[(ab, ac), bc]$
   (h) $= (a, b)(ab, (ac, bc))[a(b, c), [b, c](b, c)]$
   (i) $= (a, b)(ab, (ac, bc))(b, c)[a, [b, c]]$.
2. Show that $(a, b)(ab, (ac, bc))(b, c) > 0$.
3. **Therefore show that** $[[a, b], c] = [a, [b, c]]$**.**

Declaration I:25(1.13)

The notation $[a_0, a_1, \cdots, a_{n-1}]$ will be used to contextually refer to one of the following integers:

1. $[[a_0], [a_1, a_2, \cdots, a_{n-1}]]$
2. $[[a_0, a_1], [a_2, a_3, \cdots, a_{n-1}]]$
3. $\vdots$
4. $[[a_0, a_1, \cdots, a_{n-2}], [a_{n-1}]]$

Procedure I:60(1.36)

Objective

Choose three positive integers a, b, c. The objective of the following instructions is to show that either $0 < 0$ or $([a, b], c) = [(a, c), (b, c)]$.

Implementation

1. Using procedure I:56, procedure I:42, procedure I:43, procedure I:40, and procedure I:34, show that $(a, b)((a, c), (b, c))([a, b], c)$
   (a) $= ((a, c), (b, c))((a, b)[a, b], (a, b)c)$
   (b) $= ((a, c), (b, c))(ab, (ac, bc))$
   (c) $= (a^2b, a^2c, c^2a, c^2b, b^2a, bac, b^2c)$
   (d) $= (a, b)(ab, ac, bc, c^2)$
   (e) $= (a, b)(a, c)(b, c)$
   (f) $= (a, b)((a, c), (b, c))[(a, c), (b, c)]$.
2. Show that $(a, b)((a, c), (b, c)) > 0$.
3. **Therefore show that** $([a, b], c) = [(a, c), (b, c)]$**.**

Procedure I:61(1.37)

Objective

Choose three positive integers a, b, c. The objective of the following instructions is to show that either $0 < 0$ or $[(a, b), c] = ([a, c], [b, c])$.

Implementation

1. Using procedure I:56, procedure I:42, procedure I:43, procedure I:40, and procedure I:34, show that $((a, b), c)(a, c)(b, c)[(a, b), c]$
   (a) $= (a, c)(b, c)(a, b)c$
   (b) $= (ab, ac, cb, c^2)(a, b)c$
   (c) $= (a^2b, a^2c, ac^2, ab^2, abc, cb^2, bc^2)c$
   (d) $= (a, b, c)(ab, ac, bc)c$
   (e) $= ((a, b), c)(ac(b, c), bc(a, c))$
   (f) $= ((a, b), c)(a, c)(b, c)([a, c], [b, c])$.

2. Show that $((a, b), c)(a, c)(b, c) > 0$.
3. **Therefore show that** $[(a, b), c] = ([a, c], [b, c])$**.**

Chapter 3

Congruence Equations

Declaration I:26(1.14)

The notation $\chi_{b,d}(a, c)$, where a, c are two integers and b, d are two positive integers such that $a \equiv c \pmod{(b, d)}$, will be used to refer to the result yielded by executing the following instructions:

1. Use procedure I:33 on $\langle b, d\rangle$ to construct $\langle f, g, h, i, j\rangle$.
2. **Yield the tuple** $\langle (a + ((c - a) \operatorname{div}(b, d))ib) \bmod [b, d]\rangle$**.**

Procedure I:62(1.39)

Objective

Choose three integers x, a, c and two positive integers b, d such that $x \equiv a \pmod{b}$ and $x \equiv c \pmod{d}$. The objective of the following instructions is to show that $0 \neq 0$ if $a \not\equiv c \pmod{(b, d)}$, otherwise $x \equiv \chi_{b,d}(a, c) \pmod{[b, d]}$.

Implementation

1. Use procedure I:33 on $\langle b, d\rangle$ to construct $\langle e, f, g, h, i\rangle$ and show that:
   (a) $b = ef$
   (b) $d = eg$
   (c) $hb + id = e$.
2. Let $j = x \operatorname{div} b - a \operatorname{div} b$.
3. Show that $x = a + jb$ given that $x \equiv a \pmod{b}$.
4. Let $k = x \operatorname{div} d - c \operatorname{div} d$.
5. Show that $x = c + kd$ given that $x \equiv c \pmod{d}$.
6. Therefore show that $c - a = jb - kd$.
7. If $a \not\equiv c \pmod{(b, d)}$, then do the following:
   (a) Show that $0 \not\equiv c-a = jb-kd = jef-keg \equiv 0 \pmod{e}$.
   (b) **Therefore show that** $0 \neq 0$**.**
   (c) **Abort procedure.**
8. Otherwise do the following:
   (a) Let $l = (c - a) \operatorname{div}(b, d)$.
   (b) Show that $l(b, d) = le = c - a = jb - kd = jef - keg$ given that $c - a \equiv 0 \pmod{(b, d)}$.
   (c) Hence show that $l \equiv jf \pmod{g}$ given that $l = jf - kg$.
   (d) Hence show that $fh \equiv 1 \pmod{g}$
      i. given that $fh + gi = 1$
      ii. given that $efh + egi = bh + di = e$
      iii. given that $b = ef$, $d = eg$, and $hb+id = e$.
   (e) Hence show that $lh \equiv jfh \equiv j \pmod{g}$
      i. given that $l \equiv jf \pmod{g}$
      ii. and $fh \equiv 1 \pmod{g}$.
   (f) Hence show that $lhb \equiv jb \pmod{bg = [b, d]}$ using procedure I:29.
   (g) **Hence show that** $x = a + jb \equiv a + lhb \equiv \chi_{b,d}(a, c) \pmod{[b, d]}$**.**

Procedure I:63(1.40)

Objective

Choose two integers a, c and two positive integers b, d in such a way that $a \equiv c \pmod{(b,d)}$. The objective of the following instructions is to show that either $0 < 0$ or $\chi_{b,d}(a,c) = \chi_{d,b}(c,a)$.

Implementation

1. Use procedure I:33 on $\langle b, d\rangle$ to construct $\langle f, g, h, i, j\rangle$ and show that $ib + jd = f = (b, d)$.
2. Use procedure I:33 on $\langle d, b\rangle$ to construct $\langle k, l, m, n, p\rangle$ and show that $pb + nd = k = (d, b) = (b, d)$.
3. Use procedure I:36 on $\langle b, p, n, d\rangle$ to construct $\langle q\rangle$ and show that $n = j - qg$.
4. Now using procedure I:57, show that $\chi_{b,d}(a, c)$

   (a) $= (a + ((c - a) \operatorname{div}(b, d))ib) \bmod [b, d]$

   (b) $= (a + ((c - a) \operatorname{div}(b, d))(f - jd)) \bmod [b, d]$

   (c) $= (a + ((c - a) \operatorname{div}(b, d))f + ((a - c) \operatorname{div}(b, d))jd) \bmod [b, d]$

   (d) $= (a+(c-a)+((a-c) \operatorname{div}(b, d))jd) \bmod [b, d]$

   (e) $= (c+((a-c) \operatorname{div}(d, b))(n+qg)d) \bmod [b, d]$

   (f) $= (c + ((a - c) \operatorname{div}(d, b))dn + ((a - c) \operatorname{div}(d, b))q[b, d]) \bmod [b, d]$

   (g) $= (c + ((a - c) \operatorname{div}(d, b))dn) \bmod [b, d]$

   (h) $= (c + ((a - c) \operatorname{div}(d, b))dn) \bmod [d, b]$

   (i) $= \chi_{d,b}(c, a)$.

Procedure I:64(1.41)

Objective

Choose three integers x, a, c and two positive integers b, d such that $a \equiv c \pmod{(b, d)}$ and $x \equiv \chi_{b,d}(a, c) \pmod{[b, d]}$. The objective of the following instructions is to show that $x \equiv a \pmod{b}$.

Implementation

1. Use procedure I:33 on $\langle b, d\rangle$ to construct $\langle e, f, g, h, i\rangle$.
2. Show that $[b, d] = bg$.
3. Hence show that $(x \bmod (bg)) \bmod b = (\chi_{b,d}(a, c) \bmod (bg)) \bmod b$

   (a) given that $x \bmod (bg) = \chi_{b,d}(a, c) \bmod (bg)$

   (b) given that $x \bmod [b, d] = \chi_{b,d}(a, c) \bmod [b, d]$.
4. **Therefore using procedure I:27, show that $x \bmod b = \chi_{b,d}(a, c) \bmod b = (a + ((c - a) \operatorname{div}(b, d))hb) \bmod b = a \bmod b$.**

Procedure I:65(1.42)

Objective

Choose three integers x, a, c and two positive integers b, d such that $a \equiv c \pmod{(b, d)}$ and $x \equiv \chi_{b,d}(a, c) \pmod{[b, d]}$. The objective of the following instructions is to either show that $0 < 0$ or to show that $x \equiv a \pmod{b}$ and $x \equiv c \pmod{d}$.

Implementation

1. **Use procedure I:64 on $\langle x, a, c, b, d\rangle$ to show that $x \equiv a \pmod{b}$.**
2. Show that $x \equiv \chi_{b,d}(a, c) \equiv \chi_{d,b}(c, a) \pmod{[d, b]}$ using procedure I:63.
3. **Use procedure I:64 on $\langle x, c, a, d, b\rangle$ to show that $x \equiv c \pmod{d}$.**

Procedure I:66(1.43)

Objective

Choose two integers a, c and three positive integers b, d, e such that $a \equiv c \pmod{(b, d)}$. The objective of the following instructions is to show that $\chi_{b,d}(ea, ec) = e\chi_{b,d}(a, c)$.

Implementation

1. Use procedure I:65 on $\langle \chi_{b,d}(a, c), a, c, b, d\rangle$ to show that:

   (a) $\chi_{b,d}(a, c) \equiv a \pmod{b}$

   (b) $\chi_{b,d}(a, c) \equiv c \pmod{d}$.
2. Hence show that $e\chi_{b,d}(a, c) \equiv ea \pmod{b}$ using procedure I:29.
3. Also show that $e\chi_{b,d}(a, c) \equiv ec \pmod{d}$ using procedure I:29.
4. Also show that $ea \equiv ec \pmod{(b, d)}$ using using procedure I:26 given that $a \equiv c \pmod{(b, d)}$.

5. **Hence show that** $e\chi_{b,d}(a,c) \equiv \chi_{b,d}(ea,ec) \pmod{[b,d]}$ **using procedure I:62.**

Procedure I:67(1.44)

Objective

Choose two integers a, c and three positive integers b, d, e such that $a \equiv c \pmod{(eb, ed)}$. The objective of the following instructions is to show that $\chi_{eb,ed}(a, c) \bmod [b, d] = \chi_{b,d}(a, c)$.

Implementation

1. Use procedure I:65 on $\langle \chi_{eb,ed}(a, c), a, c, eb, ed\rangle$ to show that:
   (a) $\chi_{eb,ed}(a, c) \equiv a \pmod{eb}$
   (b) $\chi_{eb,ed}(a, c) \equiv c \pmod{ed}$.
2. Show that $\chi_{eb,ed}(a, c) \equiv a \pmod{b}$ using procedure I:27.
3. Show that $\chi_{eb,ed}(a, c) \equiv c \pmod{d}$ using procedure I:27.
4. Show that $a \equiv c \pmod{(b, d)}$ using procedure I:27 given that $a \equiv c \pmod{e(b, d)}$.
5. Hence show that $\chi_{eb,ed}(a, c) \equiv \chi_{b,d}(a, c) \pmod{[b, d]}$ using procedure I:62.
6. **Hence show that** $\chi_{eb,ed}(a, c) \bmod [b, d] = \chi_{b,d}(a, c)$**.**

Procedure I:68(1.46)

Objective

Choose three integers a, c, e and three positive integers b, d, f such that $a \equiv c \pmod{(b, d)}$ and $\chi_{b,d}(a, c) \equiv e \pmod{([b, d], f)}$. The objective of the following instructions is to show that $0 \neq 0$ if $c \not\equiv e \pmod{(d, f)}$ or $a \not\equiv \chi_{d,f}(c, e) \pmod{(b, [d, f])}$, otherwise $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) = \chi_{b,[d,f]}(a, \chi_{d,f}(c, e))$.

Implementation

1. Show that $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) \equiv e \pmod{f}$ using procedure I:65.
2. Show that $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) \equiv \chi_{b,d}(a, c) \pmod{[b, d] = gb = hd}$ using procedure I:65.
3. Show that $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) \equiv \chi_{b,d}(a, c) \equiv a \pmod{b}$ using procedure I:27 and procedure I:65.
4. Show that $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) \equiv \chi_{b,d}(a, c) \equiv c \pmod{d}$ using procedure I:27 and procedure I:65.
5. Use procedure I:62 on $\langle\chi_{[b,d],f}(\chi_{b,d}(a, c), e), c, e, d, f\rangle$ to show that $0 \neq 0$ if $c \not\equiv e \pmod{(d, f)}$, otherwise $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) \equiv \chi_{d,f}(c, e) \pmod{[d, f]}$.
6. Use procedure I:62 on $\langle\chi_{[b,d],f}(\chi_{b,d}(a, c), e), a, \chi_{d,f}(c, e), b, [d, f]\rangle$ to show that $0 \neq 0$ if $a \not\equiv \chi_{d,f}(c, e) \pmod{(b, [d, f])}$, otherwise $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) \equiv \chi_{b,[d,f]}(a, \chi_{d,f}(c, e)) \pmod{[b, [d, f]] = [[b, d], f]}$.
7. **Hence show that** $\chi_{[b,d],f}(\chi_{b,d}(a, c), e) = \chi_{b,[d,f]}(a, \chi_{d,f}(c, e))$**.**

Declaration I:27(1.15)

The notation $\chi_{b_0,b_1,\cdots,b_{n-1}}(a_0, a_1, \cdots, a_{n-1})$ will be used to contextually refer to one of the following integers:

1. $\chi_{b_0,[b_1,b_2,\cdots,b_{n-1}]}(a_0, \chi_{b_1,b_2,\cdots,b_{n-1}}(a_1, a_2, \cdots, a_{n-1}))$
2. $\chi_{[b_0,b_1],[b_2,b_3,\cdots,b_{n-1}]}(\chi_{b_0,b_1}(a_0, a_1), \chi_{b_2,b_3,\cdots,b_{n-1}}(a_2, a_3, \cdots, a_{n-1})$
3. $\vdots$
4. $\chi_{[b_0,b_1,\cdots,b_{n-2}],b_{n-1}}(\chi_{b_0,b_1,\cdots,b_{n-2}}(a_0, a_1, \cdots, a_{n-2}), a_{n-1})$

Declaration I:28(1.16)

The notation $\phi(n)$ will be used as a shorthand for the sublist of $[0 : n]$ where each entry x is such that $(x, n) = 1$.

Procedure I:69(1.47)

Objective

Choose an integer a and a positive integer b such that $(a, b) = 1$. The objective of the following instructions is to either show that $0 < 0$ or to show that each element of $a\phi(b) \bmod b$ is in $\phi(b)$.

Implementation

1. Show that $(a, b) = 1$.
2. For i in $[0 : |\phi(b)|]$, do the following:

(a) Show that $(\phi(b)_i, b) = 1$ using declaration I:28.

(b) Use procedure I:44 on $\langle a, \phi(b)_i, b\rangle$ to show that $(a\phi(b)_i, b) = 1$.

(c) Use procedure I:41 on $\langle a\phi(b)_i \bmod b, a\phi(b)_i, b\rangle$ to show that $(a\phi(b)_i \bmod b, b) = (a\phi(b)_i, b) = 1$.

(d) Hence show that $a\phi(b)_i \bmod b$ is contained in the list $\phi(b)$ given that $0 \leq a\phi(b)_i \bmod b < b$.

3. **Hence show that each element of** $a\phi(b) \bmod b$ **is in** $\phi(b)$**.**

Procedure I:70(1.48)

Objective

Choose an integer a and a positive integer b such that $(a, b) = 1$. The objective of the following instructions is to either show that $0 \neq 0$ or to show that each element of $a\phi(b) \bmod b$ is distinct.

Implementation

1. Use procedure I:33 on $\langle a, b\rangle$ to construct $\langle r, t, u, v, w\rangle$ and show that $va + wb = r = (a, b) = 1$.
2. Hence show that $va \equiv 1 \pmod b$.
3. Now for i in $[0 : |\phi(b)|]$, do the following:

(a) For j in $[i + 1 : |\phi(b)|]$, do the following:

i. If $a\phi(b)_i \equiv a\phi(b)_j \pmod b$, then do the following:

A. Show that $\phi(b)_i \equiv va\phi(b)_i \equiv va\phi(b)_j \equiv \phi(b)_j \pmod b$.

B. Hence show that $\phi(b)_i = \phi(b)_j$.

C. Show that $\phi(b)_i \neq \phi(b)_j$ using declaration I:28 given that $i \neq j$.

D. **Hence show that** $\phi(b)_i \neq \phi(b)_i$ **given that** $\phi(b)_i = \phi(b)_j$ **and** $\phi(b)_i \neq \phi(b)_j$**.**

E. **Abort procedure.**

ii. Otherwise, do the following:

A. Show that $a\phi(b)_i \not\equiv a\phi(b)_j \pmod b$.

4. **Therefore show that** $a\phi(b) \bmod b$ **is composed of distinct elements.**

Procedure I:71(1.49)

Objective

Choose an integer a and a positive integer b such that $(a, b) = 1$. The objective of the following instructions is to either show that $0 < 0$ or to show that $a\phi(b) \bmod b$ is a rearrangement of $\phi(b)$.

Implementation

1. Use procedure I:69 on $\langle a, b\rangle$ to show that each element of $a\phi(b) \bmod b$ is in $\phi(b)$.
2. Show that $|a\phi(b) \bmod b| = |\phi(b)|$.
3. Use procedure I:70 on $\langle a, b\rangle$ to show that $a\phi(b) \bmod b$ is composed of distinct elements.
4. **Hence show that** $a\phi(b) \bmod b$ **is a rearrangement of** $\phi(b)$**.**

Procedure I:72(1.50)

Objective

Choose an integer a and a positive integer b such that $(a, b) = 1$. The objective of the following instructions is to show that either $0 < 0$ or $a^{|\phi(b)|} \equiv 1 \pmod b$.

Implementation

1. For i in $[0 : |\phi(b)|]$, do the following:

(a) Use procedure I:33 on $\langle \phi(b)_i, b\rangle$ to construct $\langle r_i, t_i, u_i, v_i, w_i\rangle$ and show that $v_i\phi(b)_i + w_ib = r_i = (\phi(b)_i, b)$.

(b) Show that $v_i\phi(b)_i + w_ib = (\phi(b)_i, b) = 1$ using declaration I:28.

(c) Hence show that $v_i\phi(b)_i \equiv 1 \pmod b$.

2. Hence using procedure I:71, show that $\prod_i^{[0:|\phi(b)|]} \phi(b)_i$

(a) $\equiv \prod_i^{[0:|\phi(b)|]} a\phi(b)_i$

(b) $\equiv a^{|\phi(b)|} \prod_i^{[0:|\phi(b)|]} \phi(b)_i \pmod b$.

3. **Hence show that** 1

(a) $\equiv \prod_i^{[0:|\phi(b)|]}(v_i\phi(b)_i)$

(b) $= \prod_i^{[0:|\phi(b)|]} v_i \prod_i^{[0:|\phi(b)|]} \phi(b)_i$

(c) $\equiv a^{|\phi(b)|} \prod_i^{[0:|\phi(b)|]} \phi(b)_i \prod_i^{[0:|\phi(b)|]} v_i$

(d) $\equiv a^{|\phi(b)|} \pmod b$.

Declaration I:29(1.17)

The notation $a \times b$ as a shorthand for the $|a| \times |b|$ matrix such that for i in $[0 : |a|]$, for j in $[0 : |b|]$, $(a \times b)_{i,j} = \langle a_i, b_j \rangle$.

Procedure I:73(1.52)

Objective

Choose two positive integers a, b such that $(a, b) = 1$. The objective of the following instructions is to show that each entry of $\chi_{a,b}([0 : a] \times [0 : b])$ is in $[0 : ab]$.

Implementation

1. Let $h = \chi_{a,b}([0 : a] \times [0 : b])$.
2. Show that $0 \leq h_{i,j} < [a, b] = [a, b](a, b) = ab$ for i in $[0 : a]$, for j in $[0 : b]$.
3. **Hence show that each entry of h is in $[0 : ab]$.**

Procedure I:74(1.53)

Objective

Choose two positive integers a, b such that $(a, b) = 1$. The objective of the following instructions is to either show that $0 < 0$ or to show that each entry of $\chi_{a,b}([0 : a] \times [0 : b])$ is distinct.

Implementation

1. Let $h = \chi_{a,b}([0 : a] \times [0 : b])$.
2. For each distinct unordered pair of index pairs $\langle i, j \rangle$ and $\langle k, l \rangle$ of h, do the following:

(a) If $h_{i,j} = h_{k,l}$, then do the following:

i. Show that $\chi_{a,b}(i, j) = \chi_{a,b}([0 : a]_i, [0 : b]_j) = h_{i,j} = h_{k,l} = \chi_{a,b}([0 : a]_k, [0 : b]_l) = \chi_{a,b}(k, l)$.

ii. Show that $i \equiv \chi_{a,b}(i, j) = \chi_{a,b}(k, l) \equiv k \pmod{a}$ using procedure I:65 given that $\chi_{a,b}(i, j) = \chi_{a,b}(k, l)$.

iii. Hence show that $i = k$.

iv. Show that $j \equiv \chi_{a,b}(i, j) = \chi_{a,b}(k, l) \equiv l \pmod{b}$ using procedure I:65 given that $\chi_{a,b}(i, j) = \chi_{a,b}(k, l)$.

v. Hence show that $j = l$.

vi. Hence show that $\langle i, j \rangle = \langle k, l \rangle$.

vii. **Hence show that $\langle i, j \rangle \neq \langle i, j \rangle$ given that $\langle i, j \rangle$ and $\langle k, l \rangle$ are distinct.**

viii. **Abort procedure.**

(b) Otherwise do the following:

i. Show that $h_{i,j} \neq h_{k,l}$.

3. **Hence show that each entry of h is distinct.**

Procedure I:75(1.54)

Objective

Choose two positive integers a, b such that $(a, b) = 1$. The objective of the following instructions is to show that either $0 < 0$ or $\chi_{a,b}([0 : a] \times [0 : b])$ is a rearrangement $[0 : ab]$.

Implementation

1. Let $h = \chi_{a,b}([0 : a] \times [0 : b])$.
2. Use procedure I:73 on $\langle a, b \rangle$ to show that each element of h is in $[0 : ab]$.
3. Also show that h has the same number of entries as $[0 : ab]$.
4. Use procedure I:74 on $\langle a, b \rangle$ to show that h is composed of distinct elements.
5. **Hence show that h is a rearrangement of $[0 : ab]$.**

Procedure I:76(1.55)

Objective

Choose two positive integers a, b such that $(a, b) = 1$. The objective of the following instructions is to either show that $0 < 0$ or to show that each entry of $\chi_{a,b}(\phi(a) \times \phi(b))$ is in $\phi(ab)$.

Implementation

1. Let $h = \chi_{a,b}(\phi(a) \times \phi(b))$.
2. Now, for each index pair $\langle i, j \rangle$ of h, do the following:

(a) Show that $0 \leq h_{i,j} < [a, b] = [a, b](a, b) = ab$.

(b) Show that $h_{i,j} = \chi_{a,b}(\phi(a)_i, \phi(b)_j) \equiv \phi(a)_i \pmod{a}$.

(c) Hence use procedure I:41 on $\langle h_{i,j}, \phi(a)_i, a\rangle$ to show that $(a, h_{i,j}) = (h_{i,j}, a) = (\phi(a)_i, a) = 1$.

(d) Also show that $h_{i,j} = \chi_{a,b}(\phi(a)_i, \phi(b)_j) \equiv \phi(b)_j \pmod b$.

(e) Hence use procedure I:41 on $\langle h_{i,j}, \phi(b)_j, b\rangle$ to show that $(b, h_{i,j}) = (h_{i,j}, b) = (\phi(b)_j, b) = 1$.

(f) Hence show that $(h_{i,j}, ab) = (ab, h_{i,j}) = 1$.

(g) Hence show that $h_{i,j}$ is in $\phi(ab)$.

3. **Hence show that each entry of $\chi_{a,b}(\phi(a)\times\phi(b))$ is in $\phi(ab)$.**

Procedure I:77(1.56)

Objective

Choose two positive integers a, b such that $(a, b) = 1$. The objective of the following instructions is to either show that $0 < 0$ or to show that each entry of $\phi(ab)$ is in $\chi_{a,b}(\phi(a) \times \phi(b))$.

Implementation

1. For i in $[0 : |\phi(ab)|]$, do the following:

(a) Show that $(\phi(ab)_i, ab) = 1$.

(b) Show that $\phi(ab)_i \equiv \phi(ab)_i \bmod a \pmod a$.

(c) Hence show that $(\phi(ab)_i \bmod a, a) = (\phi(ab)_i, a) = 1$ using procedure I:41.

(d) Hence show that $\phi(ab)_i \bmod a$ is amongst $\phi(a)$ given that $0 \le \phi(ab)_i \bmod a < a$.

(e) Show that $\phi(ab)_i \equiv \phi(ab)_i \bmod b \pmod b$.

(f) Hence show that $(\phi(ab)_i \bmod b, b) = (\phi(ab)_i, b) = 1$ using procedure I:41.

(g) Hence show that $\phi(ab)_i \bmod b$ is amongst $\phi(b)$ given that $0 \le \phi(ab)_i \bmod b < b$.

(h) Hence show that $\langle\phi(ab)_i \bmod a, \phi(ab)_i \bmod b\rangle$ is amongst $\phi(a) \times \phi(b)$.

(i) Show that $\phi(ab)_i \equiv \chi_{a,b}(\phi(ab)_i \bmod a, \phi(ab)_i \bmod b) \pmod{[a, b] = [a, b](a, b) = ab}$ using procedure I:62 given that $\phi(ab)_i \equiv \phi(ab)_i \bmod a \pmod a$ and $\phi(ab)_i \equiv \phi(ab)_i \bmod b \pmod b$.

(j) Hence show that $\phi(ab)_i = \chi_{a,b}(\phi(ab)_i \bmod a, \phi(ab)_i \bmod b)$.

(k) Hence show that $\phi(ab)_i$ is amongst $\chi_{a,b}(\phi(a) \times \phi(b))$ given that $\langle\phi(ab)_i \bmod a, \phi(ab)_i \bmod b\rangle$ is amongst $\phi(a) \times \phi(b)$ and $\phi(ab)_i = \chi_{a,b}(\phi(ab)_i \bmod a, \phi(ab)_i \bmod b)$.

2. **Hence show that each entry of $\phi(ab)$ is in $\chi_{a,b}(\phi(a) \times \phi(b))$.**

Procedure I:78(1.57)

Objective

Choose two positive integers a, b such that $(a, b) = 1$. The objective of the following instructions is to either show that $0 < 0$ or to show that $\phi(ab)$ is a rearrangement of $\chi_{a,b}(\phi(a) \times \phi(b))$ and that $|\phi(ab)| = |\phi(a)||\phi(b)|$.

Implementation

1. Use procedure I:75 on $\langle a, b\rangle$ to show that $\chi_{a,b}([0 : a] \times [0 : b])$ is a rearrangement of $[0 : ab]$.
2. Show that $\chi_{a,b}(\phi(a) \times \phi(b))$ is a submatrix of $\chi_{a,b}([0 : a] \times [0 : b])$.
3. Hence show that the entries of $\chi_{a,b}(\phi(a)\times\phi(b))$ are distinct.
4. Use procedure I:76 on $\langle a, b\rangle$ to show that the entries of $\chi_{a,b}(\phi(a) \times \phi(b))$ are in $\phi(ab)$.
5. Show that the entries of $\phi(ab)$ are distinct.
6. Use procedure I:77 on $\langle a, b\rangle$ to show that the entries of $\phi(ab)$ are in $\chi_{a,b}(\phi(a) \times \phi(b))$.
7. **Hence show that $\phi(ab)$ is a rearrangement of $\chi_{a,b}(\phi(a) \times \phi(b))$.**
8. **Hence show that $|\phi(ab)| = |\chi_{a,b}(\phi(a) \times \phi(b))| = |\phi(a) \times \phi(b)| = |\phi(a)||\phi(b)|$.**

Declaration I:30(1.18)

The notation $[P]$, where P is a condition, will be used as a shorthand for 1 if P, otherwise it will stand for 0.

Declaration I:31(1.32)

The notation a_+, where a is a list, will be used as a shorthand for 0 if a is empty, otherwise it will be a shorthand for the sum of the entries of a.

Declaration I:32(1.19)

The notation $\sum_r^R f(r)$, where R is a list and $f[r]$ is a function of r, will be used as a shorthand for $f(R)_+$.

Procedure I:79(1.58)

Objective

Choose a positive integer a and a prime b. The objective of the following instructions is to show that either $0 < 0$ or $|\phi(b^a)| = b^a - b^{a-1}$.

Implementation

1. Show that $\sum_r^{[0:b^a]}[(r, b^a) = 1] \leq \sum_r^{[0:b^a]}[(r, b) = 1]$ using procedure I:45.
2. Show that $\sum_r^{[0:b^a]}[(r, b) = 1] \leq \sum_r^{[0:b^a]}[(r, b^a) = 1]$ using procedure I:44.
3. Hence show that $\sum_r^{[0:b^a]}[(r, b^a) = 1] = \sum_r^{[0:b^a]}[(r, b) = 1]$.
4. Show that $\sum_r^{[0:b^a]}[(r, b) = 1] \leq \sum_r^{[0:b^a]}[r \bmod b \neq 0]$ using procedure I:37.
5. Show that $\sum_r^{[0:b^a]}[r \bmod b \neq 0] \leq \sum_r^{[0:b^a]}[(r, b) = 1]$ using procedure I:46.
6. Hence show that $\sum_r^{[0:b^a]}[(r, b) = 1] = \sum_r^{[0:b^a]}[r \bmod b \neq 0]$.
7. **Hence show that** $|\phi(b^a)| = \sum_r^{[0:b^a]}[(r, b^a) = 1] = \sum_r^{[0:b^a]}[(r, b) = 1] = \sum_r^{[0:b^a]}[r \bmod b \neq 0] = \sum_r^{[0:b^a]}(1 - [r \bmod b = 0]) = b^a - b^{a-1}$**.**

Procedure I:80(1.59)

Objective

Choose a list of primes a. Let b be the list of distinct primes in a. Let c be a list such that c_i is the multiplicity of b_i in a for $i = 1$ to $i = |b|$. The objective of the following instructions is to show that either $0 < 0$ or $|\phi(a_*)| = \prod_i^{[0:|b|]}(b_i{}^{c_i} - b_i{}^{c_i - 1})$.

Implementation

1. If $a = \langle\rangle$, then do the following:
   (a) Show that $|b| = |a| = 0$.
   (b) **Hence show that** $\phi(a_*) = \phi(1) = 1 = \prod_i^{[0:|b|]}(b_i{}^{c_i} - b_i{}^{c_i - 1})$**.**
2. Otherwise, do the following:
   (a) Show that $a_* = \prod_i^{[0:|b|]} b_i{}^{c_i}$.
   (b) Show that $|a| > 0$.
   (c) Hence show that $|c| = |b| > 0$.
   (d) Hence show that $(b_0{}^{c_0}, \prod_i^{[1:|b|]} b_i{}^{c_i}) = 1$ using procedure I:54.
   (e) Let d be the list a with all instances of a_0 removed.
   (f) Verify that $|d| < |a|$.
   (g) Now use procedure I:80 on $\langle d\rangle$ to show that $\phi(d_*) = \phi(\prod_i^{[1:|b|]} b_i{}^{c_i}) = \prod_i^{[1:|b|]}(b_i{}^{c_i} - b_i{}^{c_i - 1})$.
   (h) **Hence show that** $|\phi(a_*)| = |\phi(\prod_i^{[0:|b|]} b_i{}^{c_i})| = |\phi(b_0{}^{c_0} \prod_i^{[1:|b|]} b_i{}^{c_i})| = |\phi(b_0{}^{c_0})||\phi(\prod_i^{[1:|b|]} b_i{}^{c_i})| = (b_0{}^{c_0} - b_0{}^{c_0 - 1})|\phi(\prod_i^{[1:|b|]} b_i{}^{c_i})| = (b_0{}^{c_0} - b_0{}^{c_0 - 1}) \prod_i^{[1:|b|]}(b_i{}^{c_i} - b_i{}^{c_i - 1}) = \prod_i^{[0:|b|]}(b_i{}^{c_i} - b_i{}^{c_i - 1})$ **using procedure I:78 and procedure I:79 given that** $(b_0{}^{c_0}, \prod_i^{[1:|b|]} b_i{}^{c_i}) = 1$ **and** $\phi(\prod_i^{[1:|b|]} b_i{}^{c_i}) = \prod_i^{[1:|b|]}(b_i{}^{c_i} - b_i{}^{c_i - 1})$**.**

Chapter 4

Permutations and Combinations

Declaration I:33(1.20)

The notation $a^{\underline{b}}$ will be used as a shorthand for $\prod_i^{[0:b]}(a-i)$.

Declaration I:34(1.33)

The notation $a^{\overline{b}}$ will be used as a shorthand for $\prod_i^{[0:b]}(a+i)$.

Procedure I:81(1.60)

Objective

Choose a list of distinct elements a and a non-negative integer b such that $b \leq |a|$. Let c be a list of length-b permutations of a. The objective of the following instructions is to show that $|c| = |a|^{\underline{b}}$.

Implementation

1. If $|b| > 0$, then do the following:

(a) For each entry d in a, do the following:

i. Let e be the list formed by removing d from a.

ii. Show that the entries of e are distinct given that the entries of a are distinct.

iii. Show that $|e| = |a| - 1$.

iv. Now use procedure I:81 on $\langle e, b-1\rangle$ to show that the number of length-$b-1$ permutations of e is $|e|^{\underline{b-1}}$.

v. Hence show that the number of length-b permutations of a beginning with d is $|e|^{\underline{b-1}} = (|a|-1)^{\underline{b-1}}$.

(b) Hence show that the number of length-b permutations of a beginning with any entry of a is $|a|(|a|-1)^{\underline{b-1}} = |a|^{\underline{b}}$.

(c) Hence show that the number of length-b permutations of a are $|a|^{\underline{b}}$.

(d) **Hence show that** $|c| = |a|^{\underline{b}}$**.**

2. Otherwise do the following:

(a) Show that $b = 0$.

(b) Show that the number of length-0 permutations of a is 1.

(c) **Therefore show that** $|c| = 1 = |a|^{\underline{0}} = |a|^{\underline{b}}$**.**

Declaration I:35(1.21)

The notation $\binom{n}{r}$ will be used as a shorthand for $n^{\underline{r}} \operatorname{div}(r!)$.

Procedure I:82(1.61)

Objective

Choose a list of distinct elements n and a non-negative integer r such that $r \leq |n|$. Let b be the largest list of length-r sublists of n such that no two of them are permutations of each other. The objective of the following instructions is to either show that b contains at least two permutations of the same list, construct a list larger than b that is also a list of length-r sublists of n such that no two of them are permutations of each other, or to show that $|b| = \binom{|n|}{r}$ and that $|n|^{\underline{r}} \bmod r! = 0$.

Implementation

1. Let a and f be a list of all the permutations of n.
2. Show that $|a| = |n|^{\underline{|n|}}$ using procedure I:81.
3. For each list c in b, do the following:
   (a) Show that the number of permutations of c is $r!$ using procedure I:81.
   (b) Let d be the list obtained by removing the elements of c from n.
   (c) Show that the number of permutations of d is $(n-r)!$ using procedure I:81.
   (d) Let e be the list of permutations of n beginning with a permutation of c.
   (e) Show that $|e| = r!(|n|-r)!$ given that there are $r!$ possible choices for the first part of e and $(|n|-r)!$ possible choices for the second part of e.
   (f) If e is not a sublist of a, then do the following:
      i. Let g be a list in e that is not in a.
      ii. Show that e is a sublist of f.
      iii. Therefore show that g was in a but then was removed.
      iv. Therefore show that the variable c was formerly equal to a permutation of the current c.
      v. **Therefore show that b contains at least two permutations of c.**
      vi. **Abort procedure.**
   (g) Otherwise, do the following:
      i. Show that e is a sublist of a.
      ii. Remove the lists in e from a.
4. If $a \neq \langle\rangle$, then do the following:
   (a) Let g be a list in a.
   (b) Let h be the sublist of g corresponding to its first r elements.
   (c) Therefore show that the permutations of n beginning with a permutation of h were never removed from a.
   (d) Therefore show that the variable c was never equal to a permutation of h.
   (e) Therefore show that no permutation of h is in b.
   (f) **Therefore show that $b \frown \langle h \rangle$ is larger than b and is also a list of length-r sublists of n such that no two of them are permutations of each other.**
   (g) **Abort procedure.**
5. Otherwise do the following:
   (a) Show that $|n|! \bmod (r!(|n|-r)!) = 0$.
   (b) **Therefore show that $n^{\underline{r}} \bmod r!$**
      i. $= (|n|! \operatorname{div} (|n|-r)!) \bmod r!$
      ii. $= ((|n|! \bmod (r!(|n| - r)!)r!(|n| - r)!) \operatorname{div} (|n|-r)!) \bmod r!$
      iii. $= ((|n|! \operatorname{div} (r!(|n|-r)!))r!) \bmod r!$
      iv. $= 0$.
   (c) Also show that (3) iterated $|n|! \operatorname{div} (r!(|n|-r)!)$ times.
   (d) **Therefore using procedure I:32, show that $|b|$**
      i. $= |n|! \operatorname{div} (r!(|n|-r)!)$
      ii. $= (|n|! \operatorname{div} (|n|-r)!) \operatorname{div} (r!)$
      iii. $= n^{\underline{r}} \operatorname{div} (r!)$
      iv. $= \binom{n}{r}$.

Procedure I:83(1.62)

Objective

Choose two positive integers a, b. The objective of the following instructions is to show that $\binom{a}{b} = \binom{a-1}{b-1} + \binom{a-1}{b}$.

Implementation

1. Using procedure I:29 and procedure I:30, show that $\binom{a-1}{b-1} + \binom{a-1}{b}$
   (a) $= (a-1)^{\underline{b-1}} \operatorname{div} (b-1)! + (a-1)^{\underline{b}} \operatorname{div} b!$
   (b) $= ((a-1)^{\underline{b-1}} b) \operatorname{div} b! + (a-1)^{\underline{b}} \operatorname{div} b!$
   (c) $= ((a-1)^{\underline{b-1}} b + (a-1)^{\underline{b}}) \operatorname{div} b!$
   (d) $= ((a-1)^{\underline{b-1}} b + (a-1)^{\underline{b-1}}(a-b)) \operatorname{div} b!$

(e) $= ((a-1)^{\underline{b-1}}a) \operatorname{div} b!$

(f) $= a^{\underline{b}} \operatorname{div} b!$

(g) $= \binom{a}{b}$.

Procedure I:84(1.63)

Objective

Choose an integer x and a non-negative integer a. The objective of the following instructions is to show that the $(1+x)^a = \sum_r^{[0:a+1]} \binom{a}{r} x^r$.

Implementation

1. If $a = 0$, then do the following:

   (a) **Show that** $(1+x)^a = (1+x)^0 = 1 = \sum_r^{[0:1]} \binom{0}{r} x^r = \sum_r^{[0:a+1]} \binom{a}{r} x^r$**.**

2. Otherwise, do the following:

   (a) Show that $a > 0$.

   (b) Therefore show that $a - 1 \geq 0$.

   (c) Use procedure I:84 on $\langle x, a-1 \rangle$ to show that $(1+x)^{a-1} = \sum_r^{[0:a]} \binom{a-1}{r} x^r$.

   (d) Therefore using procedure I:83, show that $(1+x)^a$

      i. $= (1+x)(1+x)^{a-1}$

      ii. $= (1+x) \sum_r^{[0:a]} \binom{a-1}{r} x^r$

      iii. $= \sum_r^{[0:a]} \binom{a-1}{r} x^r + \sum_r^{[0:a]} \binom{a-1}{r} x^{r+1}$

      iv. $= \sum_r^{[0:a+1]} \binom{a-1}{r} x^r + \sum_r^{[1:a+1]} \binom{a-1}{r-1} x^r$

      v. $= 1 + \sum_r^{[1:a+1]} (\binom{a-1}{r} + \binom{a-1}{r-1}) x^r$

      vi. $= 1 + \sum_r^{[1:a+1]} \binom{a}{r} x^r$

      vii. $= \sum_r^{[0:a+1]} \binom{a}{r} x^r$.

Part II

Rational Arithmetic

Chapter 5

Rational Arithmetic

Declaration II:0(2.12)

The phrase "rational number" will be used as a shorthand for an ordered pair comprising an integer followed by a non-zero natural number.

Declaration II:1(2.13)

The phrase "the numerator of a" and the notation $\mathrm{nu}(a)$, where a is a rational number, will be used as a shorthand for the first entry of a.

Declaration II:2(2.14)

The phrase "the denominator of a" and the notation $\mathrm{de}(a)$, where a is a rational number, will be used as a shorthand for the second entry of a.

Declaration II:3(2.15)

The phrase "$a = b$", where a, b are rational numbers, will be used as a shorthand for "$\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b)$".

Procedure II:0(2.27)

Objective

Choose a rational number a. The objective of the following instructions is to show that $a = a$.

Implementation

1. **Show that $a = a$ using declaration II:3 given that $\mathrm{nu}(a)\,\mathrm{de}(a) = \mathrm{de}(a)\,\mathrm{nu}(a)$.**

Procedure II:1(2.28)

Objective

Choose two rational numbers a, b such that $a = b$. The objective of the following instructions is to show that $b = a$.

Implementation

1. Show that $\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b)$ using declaration II:3 given that $a = b$.
2. **Hence show that $b = a$ using declaration II:3 given that $\mathrm{nu}(b)\,\mathrm{de}(a) = \mathrm{de}(b)\,\mathrm{nu}(a)$.**

Procedure II:2(2.29)

Objective

Choose three rational numbers a, b, c such that $a = b$ and $b = c$. The objective of the following instructions is to show that $a = c$.

Implementation

1. Show that $\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b)$ using declaration II:3 given that $a = b$.
2. Show that $\mathrm{nu}(b)\,\mathrm{de}(c) = \mathrm{de}(b)\,\mathrm{nu}(c)$ using declaration II:3 given that $b = c$.
3. If $\mathrm{nu}(b) \neq 0$, then do the following:
   (a) Show that $\mathrm{nu}(a)\,\mathrm{de}(b)\,\mathrm{nu}(b)\,\mathrm{de}(c) = \mathrm{de}(a)\,\mathrm{nu}(b)\,\mathrm{de}(b)\,\mathrm{nu}(c)$.
   (b) Hence show that $\mathrm{nu}(a)\,\mathrm{de}(c) = \mathrm{de}(a)\,\mathrm{nu}(c)$.
4. Otherwise do the following:

(a) Show that $\mathrm{nu}(b) = 0$.

(b) Show that $\mathrm{de}(b) \neq 0$ using declaration II:0.

(c) Show that $\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b) = 0\,\mathrm{de}(a) = 0$ given that $a = b$.

(d) Hence show that $\mathrm{nu}(a) = 0$.

(e) Show that $0 = 0\,\mathrm{de}(c) = \mathrm{nu}(b)\,\mathrm{de}(c) = \mathrm{de}(b)\,\mathrm{nu}(c)$.

(f) Hence show that $\mathrm{nu}(c) = 0$.

(g) Hence show that $\mathrm{nu}(a)\,\mathrm{de}(c) = 0\,\mathrm{de}(c) = \mathrm{de}(a)0 = \mathrm{de}(a)\,\mathrm{nu}(c)$.

5. **Hence show that $a = c$.**

Declaration II:4(2.16)

The notation $a + b$, where a, b are rational numbers, will be used as a shorthand for the pair $\langle \mathrm{nu}(a)\,\mathrm{de}(b) + \mathrm{de}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$.

Procedure II:3(2.30)

Objective

Choose two rational numbers a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $a + b = c + d$.

Implementation

1. Show that $\mathrm{nu}(a)\,\mathrm{de}(c) = \mathrm{de}(a)\,\mathrm{nu}(c)$ using declaration II:3 given that $a = c$.

2. Show that $\mathrm{nu}(b)\,\mathrm{de}(d) = \mathrm{de}(b)\,\mathrm{nu}(d)$ using declaration II:3 given that $b = d$.

3. Hence using declaration II:4, show that $a + b$

(a) $= \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle + \langle \mathrm{nu}(b), \mathrm{de}(b)\rangle$

(b) $= \langle \mathrm{nu}(a)\,\mathrm{de}(b) + \mathrm{de}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(c) $= \langle \mathrm{de}(c)\,\mathrm{de}(d)(\mathrm{nu}(a)\,\mathrm{de}(b) + \mathrm{de}(a)\,\mathrm{nu}(b)), \mathrm{de}(c)\,\mathrm{de}(d)(\mathrm{de}(a)\,\mathrm{de}(b))\rangle$

(d) $= \langle \mathrm{nu}(a)\,\mathrm{de}(c)\,\mathrm{de}(b)\,\mathrm{de}(d) + \mathrm{de}(a)\,\mathrm{de}(c)\,\mathrm{nu}(b)\,\mathrm{de}(d), \mathrm{de}(c)\,\mathrm{de}(d)\,\mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(e) $= \langle \mathrm{de}(a)\,\mathrm{nu}(c)\,\mathrm{de}(b)\,\mathrm{de}(d) + \mathrm{de}(a)\,\mathrm{de}(c)\,\mathrm{de}(b)\,\mathrm{nu}(d), \mathrm{de}(c)\,\mathrm{de}(d)\,\mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(f) $= \langle \mathrm{de}(a)\,\mathrm{de}(b)(\mathrm{nu}(c)\,\mathrm{de}(d) + \mathrm{de}(c)\,\mathrm{nu}(d)), \mathrm{de}(a)\,\mathrm{de}(b)(\mathrm{de}(c)\,\mathrm{de}(d))\rangle$

(g) $= \langle \mathrm{nu}(c)\,\mathrm{de}(d) + \mathrm{de}(c)\,\mathrm{nu}(d), \mathrm{de}(c)\,\mathrm{de}(d)\rangle$

(h) $= \langle \mathrm{nu}(c), \mathrm{de}(c)\rangle + \langle \mathrm{nu}(d), \mathrm{de}(d)\rangle$

(i) $= c + d$.

Procedure II:4(2.31)

Objective

Choose three rational numbers a, b, c. The objective of the following instructions is to show that $(a + b) + c = a + (b + c)$.

Implementation

1. Using declaration II:4, show that $(a + b) + c$

(a) $= \langle \mathrm{nu}(a)\,\mathrm{de}(b) + \mathrm{de}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle + \langle \mathrm{nu}(c), \mathrm{de}(c)\rangle$

(b) $= \langle (\mathrm{nu}(a)\,\mathrm{de}(b) + \mathrm{de}(a)\,\mathrm{nu}(b))\,\mathrm{de}(c) + (\mathrm{de}(a)\,\mathrm{de}(b))\,\mathrm{nu}(c), (\mathrm{de}(a)\,\mathrm{de}(b))\,\mathrm{de}(c)\rangle$

(c) $= \langle \mathrm{nu}(a)(\mathrm{de}(b)\,\mathrm{de}(c)) + \mathrm{de}(a)(\mathrm{nu}(b)\,\mathrm{de}(c) + \mathrm{de}(b)\,\mathrm{nu}(c)), \mathrm{de}(a)(\mathrm{de}(b)\,\mathrm{de}(c))\rangle$

(d) $= \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle + \langle \mathrm{nu}(b)\,\mathrm{de}(c) + \mathrm{de}(b)\,\mathrm{nu}(c), \mathrm{de}(b)\,\mathrm{de}(c)\rangle$

(e) $= a + (b + c)$.

Procedure II:5(2.32)

Objective

Choose two rational numbers a, b. The objective of the following instructions is to show that $a + b = b + a$.

Implementation

1. Using declaration II:4, show that $a + b$

(a) $= \langle \mathrm{nu}(a)\,\mathrm{de}(b) + \mathrm{de}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(b) $= \langle \mathrm{nu}(b)\,\mathrm{de}(a) + \mathrm{de}(b)\,\mathrm{nu}(a), \mathrm{de}(b)\,\mathrm{nu}(a)\rangle$

(c) $= b + a$.

Declaration II:5(2.17)

The notation a, where a is an integer, will contextually be used as a shorthand for the pair $\langle a, 1\rangle$.

Procedure II:6(2.33)

Objective

Choose a rational number a. The objective of the following instructions is to show that $0 + a = a$.

Implementation

1. Using declaration II:4 and declaration II:5, show that $0 + a$

(a) $= \langle 0, 1\rangle + \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle$

(b) $= \langle 0 \,\mathrm{de}(a) + 1 \,\mathrm{nu}(a), 1 \,\mathrm{de}(a)\rangle$

(c) $= \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle$

(d) $= a$.

Declaration II:6(2.18)

The notation $-a$, where a is a rational number, will be used as a shorthand for the pair $\langle -\mathrm{nu}(a), \mathrm{de}(a)\rangle$.

Procedure II:7(2.34)

Objective

Choose two rational numbers a, b such that $a = b$. The objective of the following instructions is to show that $-a = -b$.

Implementation

1. Show that $\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b)$ using declaration II:3 given that $a = b$.
2. Hence using declaration II:6, show that $-a$

(a) $= \langle -\mathrm{nu}(a), \mathrm{de}(a)\rangle$

(b) $= \langle -\mathrm{nu}(a)\,\mathrm{de}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(c) $= \langle -\mathrm{de}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(d) $= \langle -\mathrm{nu}(b), \mathrm{de}(b)\rangle$

(e) $= -b$.

Procedure II:8(2.35)

Objective

Choose a rational number a. The objective of the following instructions is to show that $-a + a = 0$.

Implementation

1. Using declaration II:4 and declaration II:6, show that $-a + a$

(a) $= (-a) + a$

(b) $= \langle -\mathrm{nu}(a), \mathrm{de}(a)\rangle + \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle$

(c) $= \langle -\mathrm{nu}(a)\,\mathrm{de}(a) + \mathrm{de}(a)\,\mathrm{nu}(a), \mathrm{de}(a)^2\rangle$

(d) $= \langle 0, \mathrm{de}(a)^2\rangle$

(e) $= \langle 0, 1\rangle$

(f) $= 0$.

Declaration II:7(2.19)

The notation ab, where a, b are rational numbers, will be used as a shorthand for the pair $\langle \mathrm{nu}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$.

Procedure II:9(2.36)

Objective

Choose two rational numbers a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $ab = cd$.

Implementation

1. Show that $\mathrm{nu}(a)\,\mathrm{de}(c) = \mathrm{de}(a)\,\mathrm{nu}(c)$ using declaration II:3 given that $a = c$.
2. Show that $\mathrm{nu}(b)\,\mathrm{de}(d) = \mathrm{de}(b)\,\mathrm{nu}(d)$ using declaration II:3 given that $b = d$.
3. Hence using declaration II:7, show that ab

(a) $= \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle\langle \mathrm{nu}(b), \mathrm{de}(b)\rangle$

(b) $= \langle \mathrm{nu}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(c) $= \langle (\mathrm{de}(c)\,\mathrm{de}(d))\,\mathrm{nu}(a)\,\mathrm{nu}(b), (\mathrm{de}(c)\,\mathrm{de}(d))\,\mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(d) $= \langle (\mathrm{nu}(a)\,\mathrm{de}(c))(\mathrm{nu}(b)\,\mathrm{de}(d)), \mathrm{de}(c)\,\mathrm{de}(d)\,\mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(e) $= \langle (\mathrm{de}(a)\,\mathrm{nu}(c))(\mathrm{de}(b)\,\mathrm{nu}(d)), \mathrm{de}(c)\,\mathrm{de}(d)\,\mathrm{de}(a)\,\mathrm{de}(b)\rangle$

(f) $= \langle (\mathrm{de}(a)\,\mathrm{de}(b))\,\mathrm{nu}(c)\,\mathrm{nu}(d), (\mathrm{de}(a)\,\mathrm{de}(b))\,\mathrm{de}(c)\,\mathrm{de}(d)\rangle$

(g) $= \langle \mathrm{nu}(c)\,\mathrm{nu}(d), \mathrm{de}(c)\,\mathrm{de}(d)\rangle$

(h) $= \langle \mathrm{nu}(c), \mathrm{de}(c)\rangle\langle \mathrm{nu}(d), \mathrm{de}(d)\rangle$

(i) $= cd$.

Procedure II:10(2.37)

Objective

Choose three rational numbers a, b, c. The objective of the following instructions is to show that $(ab)c = a(bc)$.

Implementation

1. Using declaration II:7, show that $(ab)c$

   (a) $= \langle \mathrm{nu}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle\langle \mathrm{nu}(c), \mathrm{de}(c)\rangle$

   (b) $= \langle \mathrm{nu}(a)\,\mathrm{nu}(b)\,\mathrm{nu}(c), \mathrm{de}(a)\,\mathrm{de}(b)\,\mathrm{de}(c)\rangle$

   (c) $= \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle\langle \mathrm{nu}(b)\,\mathrm{nu}(c), \mathrm{de}(b)\,\mathrm{de}(c)\rangle$

   (d) $= a(bc)$.

Procedure II:11(2.38)

Objective

Choose two rational numbers a, b. The objective of the following instructions is to show that $ab = ba$.

Implementation

1. Using declaration II:7, show that ab

   (a) $= \langle \mathrm{nu}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle$

   (b) $= \langle \mathrm{nu}(b)\,\mathrm{nu}(a), \mathrm{de}(b)\,\mathrm{de}(a)\rangle$

   (c) $= ba$.

Procedure II:12(2.39)

Objective

Choose a rational number a. The objective of the following instructions is to show that $1a = a$.

Implementation

1. Using declaration II:7, show that $1a$

   (a) $= \langle 1, 1\rangle\langle \mathrm{nu}(a), \mathrm{de}(a)\rangle$

   (b) $= \langle 1\,\mathrm{nu}(a), 1\,\mathrm{de}(a)\rangle$

   (c) $= \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle$

   (d) $= a$.

Declaration II:8(2.20)

The notation $\frac{1}{a}$, where a is a rational number, will be used as a shorthand for the pair $\langle \mathrm{de}(a), \mathrm{nu}(a)\rangle$ if $\mathrm{nu}(a) > 0$ and $\langle -\mathrm{de}(a), -\mathrm{nu}(a)\rangle$ if $\mathrm{nu}(a) < 0$.

Procedure II:13(2.40)

Objective

Choose two rational numbers a, b such that $a = b$ and $a \neq 0$. The objective of the following instructions is to show that $\frac{1}{a} = \frac{1}{b}$.

Implementation

1. Show that $\mathrm{nu}(a) = \mathrm{nu}(a)\,\mathrm{de}(0) \neq \mathrm{de}(a)\,\mathrm{nu}(0) = 0$ using declaration II:3 and declaration II:5 given that $a \neq 0$.
2. Show that $\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b)$ using declaration II:3 given that $a = b$.
3. Hence show that $\mathrm{de}(a)\,\mathrm{nu}(b) = \mathrm{nu}(a)\,\mathrm{de}(b) \neq 0$ using declaration II:0 given that $\mathrm{nu}(a) \neq 0$.
4. Hence show that $\mathrm{nu}(b) \neq 0$.
5. If $\mathrm{nu}(a)\,\mathrm{nu}(b) > 0$, then do the following:

   (a) Using declaration II:8, show that $\frac{1}{a}$

      i. $= \langle \mathrm{de}(a)\,\mathrm{nu}(b), \mathrm{nu}(a)\,\mathrm{nu}(b)\rangle$

      ii. $= \langle \mathrm{nu}(a)\,\mathrm{de}(b), \mathrm{nu}(a)\,\mathrm{nu}(b)\rangle$

      iii. $= \frac{1}{b}$.

6. Otherwise do the following:

   (a) Show that $\mathrm{nu}(a)\,\mathrm{nu}(b) < 0$.

   (b) Hence using declaration II:8, show that $\frac{1}{a}$

      i. $= \langle -\mathrm{de}(a)\,\mathrm{nu}(b), -\mathrm{nu}(a)\,\mathrm{nu}(b)\rangle$

      ii. $= \langle -\mathrm{nu}(a)\,\mathrm{de}(b), -\mathrm{nu}(a)\,\mathrm{nu}(b)\rangle$

      iii. $= \frac{1}{b}$.

Procedure II:14(2.41)

Objective

Choose a rational number a such that $a \neq 0$. The objective of the following instructions is to show that $\frac{1}{a}a = 1$.

Implementation

1. Show that $\mathrm{nu}(a) = \mathrm{nu}(a)\,\mathrm{de}(0) \neq \mathrm{de}(a)\,\mathrm{nu}(0) = 0$ using declaration II:3 and declaration II:5, given that $a \neq 0$.
2. If $\mathrm{nu}(a) > 0$, then do the following:

   (a) Using declaration II:8, show that $\frac{1}{a}a$

i. $= \langle \mathrm{de}(a), \mathrm{nu}(a)\rangle \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle$

ii. $= \langle \mathrm{de}(a)\,\mathrm{nu}(a), \mathrm{nu}(a)\,\mathrm{de}(a)\rangle$

iii. $= \langle 1, 1\rangle$

iv. $= 1$.

3. Otherwise do the following:

(a) Show that $\mathrm{nu}(a) < 0$.

(b) Hence using declaration II:8, show that $\frac{1}{a}a$

i. $= \langle -\mathrm{de}(a), -\mathrm{nu}(a)\rangle \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle$

ii. $= \langle -\mathrm{de}(a)\,\mathrm{nu}(a), -\mathrm{nu}(a)\,\mathrm{de}(a)\rangle$

iii. $= \langle 1, 1\rangle$

iv. $= 1$.

Procedure II:15(2.42)

Objective

Choose three rational numbers a, b, c. The objective of the following instructions is to show that $a(b + c) = ab + ac$.

Implementation

1. Using declaration II:4 and declaration II:7, show that $a(b + c)$

(a) $= \langle \mathrm{nu}(a), \mathrm{de}(a)\rangle \langle \mathrm{nu}(b)\,\mathrm{de}(c) + \mathrm{de}(b)\,\mathrm{nu}(c), \mathrm{de}(b)\,\mathrm{de}(c)\rangle$

(b) $= \langle \mathrm{nu}(a)(\mathrm{nu}(b)\,\mathrm{de}(c) + \mathrm{de}(b)\,\mathrm{nu}(c)), \mathrm{de}(a)(\mathrm{de}(b)\,\mathrm{de}(c))\rangle$

(c) $= \langle \mathrm{nu}(a)\,\mathrm{nu}(b)\,\mathrm{de}(c) + \mathrm{nu}(a)\,\mathrm{de}(b)\,\mathrm{nu}(c), \mathrm{de}(a)\,\mathrm{de}(b)\,\mathrm{de}(c)\rangle$

(d) $= \langle \mathrm{de}(a)(\mathrm{nu}(a)\,\mathrm{nu}(b)\,\mathrm{de}(c)+\mathrm{nu}(a)\,\mathrm{de}(b)\,\mathrm{nu}(c)), \mathrm{de}(a)(\mathrm{de}(a)\,\mathrm{de}(b)\,\mathrm{de}(c))\rangle$

(e) $= \langle (\mathrm{nu}(a)\,\mathrm{nu}(b))(\mathrm{de}(a)\,\mathrm{de}(c))+(\mathrm{de}(a)\,\mathrm{de}(b))(\mathrm{nu}(a)\,\mathrm{nu}(c)), (\mathrm{de}(a)\,\mathrm{de}(b))(\mathrm{de}(a)\,\mathrm{de}(c))\rangle$

(f) $= \langle \mathrm{nu}(a)\,\mathrm{nu}(b), \mathrm{de}(a)\,\mathrm{de}(b)\rangle + \langle \mathrm{nu}(a)\,\mathrm{nu}(c), \mathrm{de}(a)\,\mathrm{de}(c)\rangle$

(g) $= ab + ac$.

Procedure II:16(2.09)

Objective

Choose an integer a. The objective of the following instructions is to show that $(-1)^{2a} = 1$ and $(-1)^{2a+1} = -1$.

Implementation

Implementation is analogous to that of procedure I:14.

Declaration II:9(2.22)

The phrases "$a < b$" and "$b > a$", where a, b are rational numbers, will be used as a shorthand for "$\mathrm{nu}(a)\,\mathrm{de}(b) < \mathrm{de}(a)\,\mathrm{nu}(b)$".

Procedure II:17(2.43)

Objective

Choose four rational numbers a, b, c, d such that $a < b$, $a = c$ and $b = d$. The objective of the following instructions is to show that $c < d$.

Implementation

1. Show that $\mathrm{nu}(a)\,\mathrm{de}(c) = \mathrm{de}(a)\,\mathrm{nu}(c)$ using declaration II:3 given that $a = c$.

2. Show that $\mathrm{nu}(b)\,\mathrm{de}(d) = \mathrm{de}(b)\,\mathrm{nu}(d)$ using declaration II:3 given that $b = d$.

3. Show that $\mathrm{nu}(a)\,\mathrm{de}(b) < \mathrm{de}(a)\,\mathrm{nu}(b)$ using declaration II:9 given that $a < b$.

4. Hence show that $\mathrm{nu}(c)\,\mathrm{de}(d)\,\mathrm{de}(a)\,\mathrm{de}(b)$

(a) $= \mathrm{nu}(a)\,\mathrm{de}(c)\,\mathrm{de}(d)\,\mathrm{de}(b)$

(b) $< \mathrm{de}(a)\,\mathrm{nu}(b)\,\mathrm{de}(c)\,\mathrm{de}(d)$

(c) $= \mathrm{de}(b)\,\mathrm{nu}(d)\,\mathrm{de}(a)\,\mathrm{de}(c)$.

5. Hence show that $\mathrm{nu}(c)\,\mathrm{de}(d) < \mathrm{de}(c)\,\mathrm{nu}(d)$.

6. **Hence show that $c < d$ using declaration II:9.**

Procedure II:18(2.44)

Objective

Choose three rational numbers a, b, c such that $a < b$. The objective of the following instructions is to show that $a + c < b + c$.

Implementation

1. Show that $\mathrm{nu}(a)\,\mathrm{de}(b) < \mathrm{de}(a)\,\mathrm{nu}(b)$ using declaration II:9 given that $a < b$.
2. Show that $0 < \mathrm{de}(c)$ using declaration II:0.
3. Hence show that $\mathrm{nu}(a + c)\,\mathrm{de}(b + c)$
   (a) $= (\mathrm{nu}(a)\,\mathrm{de}(c) + \mathrm{de}(a)\,\mathrm{nu}(c))\,\mathrm{de}(b)\,\mathrm{de}(c)$
   (b) $= \mathrm{nu}(a)\,\mathrm{de}(c)\,\mathrm{de}(b)\,\mathrm{de}(c) + \mathrm{de}(a)\,\mathrm{nu}(c)\,\mathrm{de}(b)\,\mathrm{de}(c)$
   (c) $< \mathrm{de}(a)\,\mathrm{de}(c)\,\mathrm{nu}(b)\,\mathrm{de}(c) + \mathrm{de}(a)\,\mathrm{nu}(c)\,\mathrm{de}(b)\,\mathrm{de}(c)$
   (d) $= (\mathrm{nu}(b)\,\mathrm{de}(c) + \mathrm{nu}(c)\,\mathrm{de}(b))\,\mathrm{de}(a)\,\mathrm{de}(c)$
   (e) $= \mathrm{nu}(b + c)\,\mathrm{de}(a + c)$.
4. **Hence show that $a + c < b + c$.**

Procedure II:19(2.45)

Objective

Choose two rational numbers a, b. The objective of the following instructions is to show that either $a < b$, $a = b$ and $b < a$.

Implementation

1. Using procedure I:17, show that either
   (a) $\mathrm{nu}(a)\,\mathrm{de}(b) < \mathrm{de}(a)\,\mathrm{nu}(b)$
   (b) $\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b)$
   (c) $\mathrm{nu}(a)\,\mathrm{de}(b) > \mathrm{de}(a)\,\mathrm{nu}(b)$
2. Hence show that either
   (a) $a < b$ using declaration II:9 given that $\mathrm{nu}(a)\,\mathrm{de}(b) < \mathrm{de}(a)\,\mathrm{nu}(b)$.
   (b) $a = b$ using declaration II:3 given that $\mathrm{nu}(a)\,\mathrm{de}(b) = \mathrm{de}(a)\,\mathrm{nu}(b)$.
   (c) $b > a$ using declaration II:9 given that $\mathrm{nu}(b)\,\mathrm{de}(a) > \mathrm{de}(b)\,\mathrm{nu}(a)$.

Procedure II:20(2.49)

Objective

Choose two rational numbers a, b such that $0 < a$ and $0 < b$. The objective of the following instructions is to show that $0 < a + b$.

Implementation

1. Show that $0 = \mathrm{nu}(0)\,\mathrm{de}(a) < \mathrm{de}(0)\,\mathrm{nu}(a) = \mathrm{nu}(a)$ using declaration II:9 given that $0 < a$.
2. Show that $0 < \mathrm{de}(a)$ using declaration II:0.
3. Show that $0 = \mathrm{nu}(0)\,\mathrm{de}(b) < \mathrm{de}(0)\,\mathrm{nu}(b) = \mathrm{nu}(b)$ using declaration II:9 given that $0 < b$.
4. Show that $0 < \mathrm{de}(b)$ using declaration II:0.
5. Hence show that $\mathrm{nu}(0)\,\mathrm{de}(a + b) = 0 < \mathrm{nu}(a)\,\mathrm{de}(b) + \mathrm{de}(a)\,\mathrm{nu}(b) = \mathrm{de}(0)\,\mathrm{nu}(a + b)$.
6. **Hence show that $0 < a + b$ using declaration II:9 given that $\mathrm{nu}(0)\,\mathrm{de}(a + b) < \mathrm{de}(0)\,\mathrm{nu}(a + b)$.**

Procedure II:21(2.50)

Objective

Choose two rational numbers a, b such that $0 < a$ and $0 < b$. The objective of the following instructions is to show that $0 < ab$.

Implementation

1. Show that $0 = \mathrm{nu}(0)\,\mathrm{de}(a) < \mathrm{de}(0)\,\mathrm{nu}(a) = \mathrm{nu}(a)$ using declaration II:9 given that $0 < a$.
2. Show that $0 = \mathrm{nu}(0)\,\mathrm{de}(b) < \mathrm{de}(0)\,\mathrm{nu}(b) = \mathrm{nu}(b)$ using declaration II:9 given that $0 < b$.
3. Hence show that $\mathrm{nu}(0)\,\mathrm{de}(ab) = 0 < \mathrm{nu}(a)\,\mathrm{nu}(b) = \mathrm{de}(0)\,\mathrm{nu}(ab)$.
4. **Hence show that $0 < ab$ using declaration II:9 given that $\mathrm{nu}(0)\,\mathrm{de}(ab) < \mathrm{de}(0)\,\mathrm{nu}(ab)$.**

Procedure II:22(2.81)

Objective

Choose two rational numbers a, b. The objective of the following instructions is to show that $\|ab\| = \|a\|\|b\|$.

Implementation

Implementation is analogous to that of procedure I:20.

Procedure II:23(2.82)

Objective

Choose two rational numbers a, b. The objective of the following instructions is to show that $\|a+b\| \leq \|a\| + \|b\|$.

Implementation

Implementation is analogous to that of procedure I:21.

Procedure II:24(2.83)

Objective

Choose two rational numbers a, b. The objective of the following instructions is to show that $\|a\| - \|b\| \leq \|a-b\|$.

Implementation

Implementation is analogous to that of procedure I:22.

Procedure II:25(2.84)

Objective

Choose a rational number a. The objective of the following instructions is to show that $a = \operatorname{sgn}(a)\|a\|$.

Implementation

Implementation is analogous to that of procedure I:23.

Procedure II:26(thu3001201131)

Objective

Choose two rational numbers x, y such that $xy \leq 0$. The objective of the following instructions is to show that $\|x\| \leq \|y-x\|$ and $\|y\| \leq \|y-x\|$.

Implementation

1. Show that $-\frac{1}{2}(y-x)^2 + \frac{1}{2}y^2 + \frac{1}{2}x^2 = xy \leq 0$.
2. Hence show that $\frac{1}{2}(y^2 + x^2) \leq \frac{1}{2}(y-x)^2$.
3. **Hence show that $\|y\| \leq \|y-x\|$ given that $y^2 \leq y^2 + x^2 \leq (y-x)^2$.**
4. **Also show that $\|x\| \leq \|y-x\|$ given that $x^2 \leq y^2 + x^2 \leq (y-x)^2$.**

Declaration II:10(2.02)

The notation $\lfloor a \rfloor$, where a is a rational number, will be used as a shorthand for $\operatorname{nu}(a) \operatorname{div} \operatorname{de}(a)$.

Declaration II:11(2.03)

The notation $\lceil a \rceil$, where a is a rational number, will be used as a shorthand for $(\operatorname{nu}(a) \operatorname{div} \operatorname{de}(a)) + 1$.

Procedure II:27(2.04)

Objective

Choose a rational number $r \neq 1$ and an integer $n \geq 0$. The objective of the following instructions is to show that $\sum_t^{[0:n]} r^t = \frac{1-r^n}{1-r}$.

Implementation

1. Show that $r\sum_t^{[0:n]} r^t = \sum_t^{[0:n]} r^{t+1} = \sum_t^{[1:n+1]} r^t$.
2. Therefore show that $(1-r)\sum_t^{[0:n]} r^t = \sum_t^{[0:n]} r^t - \sum_t^{[1:n+1]} r^t = 1 - r^n$.
3. **Therefore show that $\sum_t^{[0:n]} r^t = \frac{1-r^n}{1-r}$.**

Procedure II:28(2.05)

Objective

Choose a rational $0 < r < 1$ and an integer $n \geq 0$. The objective of the following instructions is to show that $\sum_t^{[0:n]} r^t < \frac{1}{1-r}$.

Implementation

1. **Show that $\sum_t^{[0:n]} r^t = \frac{1-r^n}{1-r} < \frac{1}{1-r}$ using procedure II:27.**

Procedure II:29(2.06)

Objective

Choose a non-negative integer a and a rational number x. The objective of the following instructions is to show that $(1+x)^a = \sum_r^{[0:a+1]} \binom{a}{r} x^r$.

Implementation

Instructions are analogous to those of procedure I:84.

Procedure II:30(2.07)

Objective

Choose an integer $r \geq 0$ and a rational number $x \geq -1$. The objective of the following instructions is to show that $(1+x)^r \geq 1 + rx$.

Implementation

1. If $-1 \leq x < 0$, then do the following:
   (a) Using procedure II:27, show that $(1+x)^r$
      i. $= 1 + (1+x)^r - 1$
      ii. $= 1 + x\frac{(1+x)^r - 1}{(1+x)-1}$
      iii. $= 1 + x\sum_k^{[0:r]}(1+x)^k$
      iv. $\geq 1 + x\sum_k^{[0:r]} 1$
      v. $= 1 + rx$.
2. Otherwise, do the following:
   (a) Show that $x \geq 0$.
   (b) Now using procedure II:29, show that $(1+x)^r$
      i. $= \sum_k^{[0:r+1]} \binom{r}{k} x^k$
      ii. $\geq \binom{r}{0}x^0 + \binom{r}{1}x^1$
      iii. $= 1 + rx$

Procedure II:31(wed2407191348)

Objective

Choose a non-negative integer r and a rational number $x > -1$ such that $(r-1)x < 1$. The objective of the following instructions is to show that $(1+x)^r \leq \frac{1+x}{1-(r-1)x}$.

Implementation

1. Show that $1 - \frac{x}{1+x} = \frac{1}{1+x} > 0$.
2. Hence show that $(1 - \frac{x}{1+x})^r \geq 1 - \frac{rx}{1+x}$ using procedure II:30.
3. Hence show that $(1 - \frac{x}{1+x})^r \geq 1 - \frac{rx}{1+x} > 0$
   (a) given that $0 < \frac{1+x-rx}{1+x} = 1 - \frac{rx}{1+x}$
   (b) given that $0 < 1 + x - rx$
   (c) given that $(r-1)x < 1$.
4. Hence show that $(1+x)^r$
   (a) $= (\frac{1}{1+x})^{-r}$
   (b) $= (1 - \frac{x}{1+x})^{-r}$
   (c) $\leq (1 - \frac{rx}{1+x})^{-1}$
   (d) $= \frac{1+x}{1-(r-1)x}$.

Chapter 6

Perplex Arithmetic

Declaration II:12(wed0502201651)

The phrase "perplex number" will be used as a shorthand for a pair of rational numbers.

Declaration II:13(sun0902201114)

The phrase "the real part of a" and the notation $\mathrm{re}(a)$, where a is a perplex number, will be used as a shorthand for the first entry of a.

Declaration II:14(sun0902201115)

The phrase "the imaginary part of a" and the notation $\mathrm{im}(a)$, where a is a perplex number, will be used as a shorthand for the second entry of a.

Declaration II:15(sat0802201051)

The phrase "$a = b$", where a, b are perplex numbers, will be used as a shorthand for "$\mathrm{re}(a) = \mathrm{re}(b)$ and $\mathrm{im}(a) = \mathrm{im}(b)$".

Procedure II:32(sun0902201116)

Objective

Choose a perplex number a. The objective of the following instructions is to show that $a = a$.

Implementation

1. Show that $\mathrm{re}(a) = \mathrm{re}(a)$.
2. Show that $\mathrm{im}(a) = \mathrm{im}(a)$.
3. **Hence show that $a = a$.**

Procedure II:33(sun0902201117)

Objective

Choose two perplex numbers a, b such that $a = b$. The objective of the following instructions is to show that $b = a$.

Implementation

1. Show that $\mathrm{re}(b) = \mathrm{re}(a)$ given that $\mathrm{re}(a) = \mathrm{re}(b)$.
2. Show that $\mathrm{im}(b) = \mathrm{im}(a)$ given that $\mathrm{im}(a) = \mathrm{im}(b)$.
3. **Hence show that $b = a$.**

Procedure II:34(sun0902201118)

Objective

Choose three perplex numbers a, b, c such that $a = b$ and $b = c$. The objective of the following instructions is to show that $a = c$.

Implementation

1. Show that $\mathrm{re}(a) = \mathrm{re}(c)$
   (a) given that $\mathrm{re}(a) = \mathrm{re}(b)$
   (b) and $\mathrm{re}(b) = \mathrm{re}(c)$.
2. Show that $\mathrm{im}(a) = \mathrm{im}(c)$
   (a) given that $\mathrm{im}(a) = \mathrm{im}(b)$
   (b) and $\mathrm{im}(b) = \mathrm{im}(c)$.
3. **Hence verify that $a = c$.**

Declaration II:16(sun0902201119)

The notation $a + b$, where a, b are perplex numbers, will be used as a shorthand for the perplex number $\langle \mathrm{re}(a) + \mathrm{re}(b), \mathrm{im}(a) + \mathrm{im}(b) \rangle$.

Procedure II:35(sun0902201120)

Objective

Choose two perplex numbers a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $a + b = c + d$.

Implementation

1. Using declaration II:15, show that
   (a) $\mathrm{re}(a) = \mathrm{re}(c)$
   (b) $\mathrm{im}(a) = \mathrm{im}(c)$
   (c) $\mathrm{re}(b) = \mathrm{re}(d)$
   (d) $\mathrm{im}(b) = \mathrm{im}(d)$.
2. Hence show that $a + b$
   (a) $= \langle \mathrm{re}(a), \mathrm{im}(a) \rangle + \langle \mathrm{re}(b), \mathrm{im}(b) \rangle$
   (b) $= \langle \mathrm{re}(a) + \mathrm{re}(b), \mathrm{im}(a) + \mathrm{im}(b) \rangle$
   (c) $= \langle \mathrm{re}(c) + \mathrm{re}(d), \mathrm{im}(c) + \mathrm{im}(d) \rangle$
   (d) $= \langle \mathrm{re}(c), \mathrm{im}(c) \rangle + \langle \mathrm{re}(d), \mathrm{im}(d) \rangle$
   (e) $= c + d$.

Procedure II:36(sun0902201121)

Objective

Choose three perplex numbers a, b, c. The objective of the following instructions is to show that $(a + b) + c = a + (b + c)$.

Implementation

1. Show that $(a + b) + c$
   (a) $= \langle \mathrm{re}(a) + \mathrm{re}(b), \mathrm{im}(a) + \mathrm{im}(b) \rangle + \langle \mathrm{re}(c), \mathrm{im}(c) \rangle$
   (b) $= \langle (\mathrm{re}(a) + \mathrm{re}(b)) + \mathrm{re}(c), (\mathrm{im}(a) + \mathrm{im}(b)) + \mathrm{im}(c) \rangle$
   (c) $= \langle \mathrm{re}(a) + (\mathrm{re}(b) + \mathrm{re}(c)), \mathrm{im}(a) + (\mathrm{im}(b) + \mathrm{im}(c)) \rangle$
   (d) $= \langle \mathrm{re}(a), \mathrm{im}(a) \rangle + \langle \mathrm{re}(b) + \mathrm{re}(c), \mathrm{im}(b) + \mathrm{im}(c) \rangle$
   (e) $= a + (b + c)$.

Procedure II:37(sun0902201122)

Objective

Choose two perplex numbers a, b. The objective of the following instructions is to show that $a + b = b + a$.

Implementation

1. Show that $a + b$
   (a) $= \langle \mathrm{re}(a) + \mathrm{re}(b), \mathrm{im}(a) + \mathrm{im}(b) \rangle$
   (b) $= \langle \mathrm{re}(b) + \mathrm{re}(a), \mathrm{im}(b) + \mathrm{im}(a) \rangle$
   (c) $= b + a$.

Declaration II:17(sun0902201123)

The notation a, where a is a rational number, will contextually be used as a shorthand for the perplex number $\langle a, 0 \rangle$.

Procedure II:38(sun0902201124)

Objective

Choose a perplex number a. The objective of the following instructions is to show that $0 + a = a$.

Implementation

1. Show that $0 + a$
   (a) $= \langle 0, 0 \rangle + \langle \mathrm{re}(a), \mathrm{im}(a) \rangle$
   (b) $= \langle 0 + \mathrm{re}(a), 0 + \mathrm{im}(a) \rangle$
   (c) $= \langle \mathrm{re}(a), \mathrm{im}(a) \rangle$
   (d) $= a$.

Declaration II:18(sun0902201125)

The notation $-a$, where a is a perplex number, will be used as a shorthand for the pair $\langle -\mathrm{re}(a), -\mathrm{im}(a) \rangle$.

Procedure II:39(sun0902201126)

Objective

Choose a perplex number a. The objective of the following instructions is to show that $-a + a = 0$.

Implementation

1. Show that $-a + a$
   (a) $= (-a) + a$
   (b) $= \langle -\operatorname{re}(a), -\operatorname{im}(a)\rangle + \langle \operatorname{re}(a), \operatorname{im}(a)\rangle$
   (c) $= \langle -\operatorname{re}(a) + \operatorname{re}(a), -\operatorname{im}(a) + \operatorname{im}(a)\rangle$
   (d) $= \langle 0, 0\rangle$
   (e) $= 0.$

Declaration II:19(sun0902201127)

The notation ab, where a, b are perplex numbers, will be used as a shorthand for the perplex number $\langle \operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b)\rangle$.

Procedure II:40(sun0902201128)

Objective

Choose four perplex numbers a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $ab = cd$.

Implementation

1. Using declaration II:15, show that
   (a) $\operatorname{re}(a) = \operatorname{re}(c)$
   (b) $\operatorname{im}(a) = \operatorname{im}(c)$
   (c) $\operatorname{re}(b) = \operatorname{re}(d)$
   (d) $\operatorname{im}(b) = \operatorname{im}(d)$.
2. Hence show that ab
   (a) $= \langle \operatorname{re}(a), \operatorname{im}(a)\rangle\langle \operatorname{re}(b), \operatorname{im}(b)\rangle$
   (b) $= \langle \operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b)\rangle$
   (c) $= \langle \operatorname{re}(c)\operatorname{re}(d) + \operatorname{im}(c)\operatorname{im}(d), \operatorname{re}(c)\operatorname{im}(d) + \operatorname{im}(c)\operatorname{re}(d)\rangle$
   (d) $= \langle \operatorname{re}(c), \operatorname{im}(c)\rangle\langle \operatorname{re}(d), \operatorname{im}(d)\rangle$
   (e) $= cd$.

Procedure II:41(sun0902201129)

Objective

Choose three perplex numbers a, b, c. The objective of the following instructions is to show that $(ab)c = a(bc)$.

Implementation

1. Show that $(ab)c$
   (a) $= \langle \operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b)\rangle\langle \operatorname{re}(c), \operatorname{im}(c)\rangle$
   (b) $= \langle(\operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b))\operatorname{re}(c) + (\operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b))\operatorname{im}(c), (\operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b))\operatorname{im}(c) + (\operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b))\operatorname{re}(c)\rangle$
   (c) $= \langle \operatorname{re}(a)(\operatorname{re}(b)\operatorname{re}(c) + \operatorname{im}(b)\operatorname{im}(c)) + \operatorname{im}(a)(\operatorname{re}(b)\operatorname{im}(c) + \operatorname{im}(b)\operatorname{re}(c)), \operatorname{re}(a)(\operatorname{re}(b)\operatorname{im}(c) + \operatorname{im}(b)\operatorname{re}(c)) + \operatorname{im}(a)(\operatorname{re}(b)\operatorname{re}(c) + \operatorname{im}(b)\operatorname{im}(c))\rangle$
   (d) $= \langle \operatorname{re}(a), \operatorname{im}(a)\rangle\langle \operatorname{re}(b)\operatorname{re}(c) + \operatorname{im}(b)\operatorname{im}(c), \operatorname{re}(b)\operatorname{im}(c) + \operatorname{im}(b)\operatorname{re}(c)\rangle$
   (e) $= a(bc)$.

Procedure II:42(sun0902201130)

Objective

Choose two perplex numbers a, b. The objective of the following instructions is to show that $ab = ba$.

Implementation

1. Show that ab
   (a) $= \langle \operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b)\rangle$
   (b) $= \langle \operatorname{re}(b)\operatorname{re}(a) + \operatorname{im}(b)\operatorname{im}(a), \operatorname{re}(b)\operatorname{im}(a) + \operatorname{im}(b)\operatorname{re}(a)\rangle$
   (c) $= ba$.

Procedure II:43(sun0902201131)

Objective

Choose a perplex number a. The objective of the following instructions is to show that $1a = a$.

Implementation

1. Show that $1a$
   (a) $= \langle 1, 0\rangle\langle \operatorname{re}(a), \operatorname{im}(a)\rangle$
   (b) $= \langle 1\operatorname{re}(a) + 0\operatorname{im}(a), 1\operatorname{im}(a) + 0\operatorname{re}(a)\rangle$
   (c) $= \langle \operatorname{re}(a), \operatorname{im}(a)\rangle$
   (d) $= a$.

Procedure II:44(sat0802201553)

Objective

Choose three perplex numbers a, b, c. The objective of the following instructions is to show that $a(b+c) = ab + ac$.

Implementation

1. $a(b+c)$
   (a) $= \langle \operatorname{re}(a), \operatorname{im}(a)\rangle \langle \operatorname{re}(b) + \operatorname{re}(c), \operatorname{im}(b) + \operatorname{im}(c)\rangle$
   (b) $= \langle \operatorname{re}(a)(\operatorname{re}(b)+\operatorname{re}(c)) + \operatorname{im}(a)(\operatorname{im}(b)+\operatorname{im}(c)), \operatorname{re}(a)(\operatorname{im}(b) + \operatorname{im}(c)) + \operatorname{im}(a)(\operatorname{re}(b) + \operatorname{re}(c))\rangle$
   (c) $= \langle (\operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b)) + (\operatorname{re}(a)\operatorname{re}(c) + \operatorname{im}(a)\operatorname{im}(c)), (\operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b)) + (\operatorname{re}(a)\operatorname{im}(c) + \operatorname{im}(a)\operatorname{re}(c))\rangle$
   (d) $= \langle \operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b) + \operatorname{im}(a)\operatorname{re}(b)\rangle + \langle \operatorname{re}(a)\operatorname{re}(c) + \operatorname{im}(a)\operatorname{im}(c), \operatorname{re}(a)\operatorname{im}(c) + \operatorname{im}(a)\operatorname{re}(c)\rangle$
   (e) $= ab + ac$.

Declaration II:20(sun0902201132)

The notation $(a)^-$, where a is a perplex number, will be used as a shorthand for the perplex number $\langle \operatorname{re}(a), -\operatorname{im}(a)\rangle$.

Procedure II:45(sun0902201133)

Objective

Choose two perplex numbers a, b. The objective of the following instructions is to show that $(a+b)^- = (a)^- + (b)^-$.

Implementation

1. Show that $(a+b)^-$
   (a) $= \langle \operatorname{re}(a+b), -\operatorname{im}(a+b)\rangle$
   (b) $= \langle \operatorname{re}(a) + \operatorname{re}(b), -\operatorname{im}(a) - \operatorname{im}(b)\rangle$
   (c) $= (a)^- + (b)^-$.

Procedure II:46(sun0902201134)

Objective

Choose two perplex numbers a, b. The objective of the following instructions is to show that $(ab)^- = (a)^-(b)^-$.

Implementation

1. Show that $(ab)^-$
   (a) $= \langle \operatorname{re}(ab), -\operatorname{im}(ab)\rangle$
   (b) $= \langle \operatorname{re}(a)\operatorname{re}(b) + \operatorname{im}(a)\operatorname{im}(b)), -\operatorname{re}(a)\operatorname{im}(b) - \operatorname{im}(a)\operatorname{re}(b)\rangle$
   (c) $= \langle \operatorname{re}(a), -\operatorname{im}(a)\rangle\langle \operatorname{re}(b), -\operatorname{im}(b)\rangle$
   (d) $= (a)^-(b)^-$.

Declaration II:21(sun0902201140)

The notation $\|a\|^2$, where a is a perplex number, will be used as a shorthand for $\operatorname{re}(a)^2 - \operatorname{im}(a)^2$.

Procedure II:47(sun0902201141)

Objective

Choose a perplex number a. The objective of the following instructions is to show that $a(a)^- = \|a\|^2$.

Implementation

1. **Show that** $a(a)^- = \|a\|^2$**.**

Declaration II:22(wed0502201719)

The notation $a < b$, where a, b are perplex numbers, will be used as a shorthand for $0 < \operatorname{re}(b-a)$ and $\|b-a\|^2 \geq 0$.

Procedure II:48(sat0802200648)

Objective

Choose four perplex numbers a, b, c, d such that $a < b$, $a = c$ and $b = d$. The objective of the following instructions is to show that $c < d$.

Implementation

1. Show that $\operatorname{re}(a) = \operatorname{re}(c)$ and $\operatorname{im}(a) = \operatorname{im}(c)$ using declaration II:15 given that $a = c$.
2. Show that $\operatorname{re}(b) = \operatorname{re}(d)$ and $\operatorname{im}(b) = \operatorname{im}(d)$ using declaration II:15 given that $b = d$.
3. Show that $0 < \operatorname{re}(b-a)$ and $\|b-a\|^2 \geq 0$ using declaration II:22 given that $a < b$.
4. Hence show that $\operatorname{re}(d-c) = \operatorname{re}(b-a) > 0$.
5. Also show that $\|d-c\|^2 = \|b-a\|^2 \geq 0$.

6. **Hence show that $c < d$ using declaration II:22.**

Procedure II:49(sun0902201135)

Objective

Choose three perplex numbers a, b, c such that $a < b$. The objective of the following instructions is to show that $a + c < b + c$.

Implementation

1. Show that $0 < \mathrm{re}(b-a)$ and $\|b-a\|^2 \geq 0$ using declaration II:22 given that $a < b$.
2. Hence show that $\mathrm{re}((b+c)-(a+c)) = \mathrm{re}(b-a) > 0$.
3. Also show that $\|(b+c)-(a+c)\|^2 = \|b-a\|^2 \geq 0$.
4. **Hence show that $a + c < b + c$ using declaration II:22.**

Procedure II:50(sun0902201138)

Objective

Choose two perplex numbers a, b such that $0 < a$ and $0 < b$. The objective of the following instructions is to show that $0 < a + b$.

Implementation

1. Show that $0 < \mathrm{re}(a)$ and $\|a\|^2 \geq 0$ using declaration II:22 given that $0 < a$.
2. Show that $0 < \mathrm{re}(b)$ and $\|b\|^2 \geq 0$ using declaration II:22 given that $0 < b$.
3. Hence show that $\mathrm{re}(a + b) = \mathrm{re}(a) + \mathrm{re}(b) > 0$ given that $0 < \mathrm{re}(a)$ and $0 < \mathrm{re}(b)$.
4. Also show that $\|a + b\|^2 = \mathrm{re}(a + b)^2 - \mathrm{im}(a + b)^2 = \mathrm{re}(a)^2 - \mathrm{im}(a)^2 + \mathrm{re}(b)^2 - \mathrm{im}(b)^2 + 2(\mathrm{re}(a)\,\mathrm{re}(b) - \mathrm{im}(a)\,\mathrm{im}(b)) = \|a\|^2 + \|b\|^2 + (\mathrm{re}(a) - \mathrm{im}(a))(\mathrm{re}(b) + \mathrm{im}(b)) + (\mathrm{re}(a) + \mathrm{im}(a))(\mathrm{re}(b) - \mathrm{im}(b)) \geq 0$.
5. **Hence show that $0 < a + b$ using declaration II:22 given that $\mathrm{re}(a + b) > 0$ and $\|a + b\|^2 \geq 0$.**

Procedure II:51(sun0902201139)

Objective

Choose two perplex numbers a, b such that $0 < a$ and $0 < b$. The objective of the following instructions is to show that $0 \leq ab$.

Implementation

1. Show that $0 < \mathrm{re}(a)$ and $\|a\|^2 \geq 0$ using declaration II:22 given that $0 < a$.
2. Show that $0 < \mathrm{re}(b)$ and $\|b\|^2 \geq 0$ using declaration II:22 given that $0 < b$.
3. Hence show that $\mathrm{re}(ab) = \mathrm{re}(a)\,\mathrm{re}(b) + \mathrm{im}(a)\,\mathrm{im}(b) \geq \mathrm{re}(a)\,\mathrm{re}(b) - \mathrm{re}(a)\,\mathrm{re}(b) = 0$.
4. Also show that $\|ab\|^2 = \|a\|^2\|b\|^2 \geq 0$.
5. If $\mathrm{re}(ab) = 0$, then do the following:
   (a) **Show that $ab = 0$ using declaration II:15 given that $\mathrm{im}(ab) = 0$ given that $\mathrm{im}(ab)^2 \leq \mathrm{re}(ab)^2 = 0$ given that $\|ab\|^2 \geq 0$.**
6. Otherwise do the following:
   (a) **Show that $ab > 0$ using declaration II:22 given that $\mathrm{re}(ab) > 0$ and $\|ab\|^2 \geq 0$.**

Declaration II:23(wed0502201655)

The notations $a \subset b$ and $b \supset a$, where a, b are perplex numbers, will be used as shorthands for $\|b - a\|^2 \leq 0$ and $\mathrm{im}(b - a) > 0$.

Procedure II:52(sun1602201324)

Objective

Choose four perplex numbers a, b, c, d such that $a \subset b$, $a = c$ and $b = d$. The objective of the following instructions is to show that $c \subset d$.

Implementation

1. Show that $\mathrm{re}(a) = \mathrm{re}(c)$ and $\mathrm{im}(a) = \mathrm{im}(c)$ using declaration II:15 given that $a = c$.
2. Show that $\mathrm{re}(b) = \mathrm{re}(d)$ and $\mathrm{im}(b) = \mathrm{im}(d)$ using declaration II:15 given that $b = d$.
3. Show that $0 < \mathrm{im}(b - a)$ and $\|b - a\|^2 \leq 0$ using declaration II:23 given that $a \subset b$.

4. Hence show that $\mathrm{im}(d-c)=\mathrm{im}(b-a)>0$.

5. Also show that $\|d-c\|^2=\|b-a\|^2\leq 0$.

6. **Hence show that $c\subset d$ using declaration II:23.**

Procedure II:53(sun1602201330)

Objective

Choose three perplex numbers a,b,c such that $a\subset b$. The objective of the following instructions is to show that $a+c\subset b+c$.

Implementation

1. Show that $0<\mathrm{im}(b-a)$ and $\|b-a\|^2\leq 0$ using declaration II:23 given that $a\subset b$.

2. Hence show that $\mathrm{im}((b+c)-(a+c))=\mathrm{im}(b-a)>0$.

3. Also show that $\|(b+c)-(a+c)\|^2=\|b-a\|^2\leq 0$.

4. **Hence show that $a+c\subset b+c$ using declaration II:23.**

Procedure II:54(sun1602201336)

Objective

Choose two perplex numbers a,b such that $0\subset a$ and $0\subset b$. The objective of the following instructions is to show that $0\subset a+b$.

Implementation

1. Show that $0<\mathrm{im}(a)$ and $\|a\|^2\leq 0$ using declaration II:23 given that $0\subset a$.

2. Show that $0<\mathrm{im}(b)$ and $\|b\|^2\leq 0$ using declaration II:23 given that $0\subset b$.

3. Hence show that $\mathrm{im}(a+b)=\mathrm{im}(a)+\mathrm{im}(b)>0$ given that $0<\mathrm{im}(a)$ and $0<\mathrm{im}(b)$.

4. Also show that $\|a+b\|^2=\mathrm{re}(a+b)^2-\mathrm{im}(a+b)^2=\mathrm{re}(a)^2-\mathrm{im}(a)^2+\mathrm{re}(b)^2-\mathrm{im}(b)^2+2(\mathrm{re}(a)\,\mathrm{re}(b)-\mathrm{im}(a)\,\mathrm{im}(b))=\|a\|^2+\|b\|^2+(\mathrm{re}(a)-\mathrm{im}(a))(\mathrm{re}(b)+\mathrm{im}(b))+(\mathrm{re}(a)+\mathrm{im}(a))(\mathrm{re}(b)-\mathrm{im}(b))\leq 0$.

5. **Hence show that $0\subset a+b$ using declaration II:23 given that $\mathrm{im}(a+b)>0$ and $\|a+b\|^2\leq 0$.**

Procedure II:55(sun1602201526)

Objective

Choose two perplex numbers a,b such that $0\subset a$ and $0\subset b$. The objective of the following instructions is to show that $0\leq ab$.

Implementation

1. Show that $0<\mathrm{im}(a)$ and $\|a\|^2\leq 0$ using declaration II:23 given that $0\subset a$.

2. Show that $0<\mathrm{im}(b)$ and $\|b\|^2\leq 0$ using declaration II:23 given that $0\subset b$.

3. Hence show that $\mathrm{re}(ab)=\mathrm{re}(a)\,\mathrm{re}(b)+\mathrm{im}(a)\,\mathrm{im}(b)\geq -\mathrm{im}(a)\,\mathrm{im}(b)+\mathrm{im}(a)\,\mathrm{im}(b)=0$.

4. Also show that $\|ab\|^2=\|a\|^2\|b\|^2\geq 0$.

5. If $\mathrm{re}(ab)=0$, then do the following:

   (a) **Show that $ab=0$ using declaration II:15 given that $\mathrm{im}(ab)=0$ given that $\mathrm{im}(ab)^2\leq\mathrm{re}(ab)^2=0$ given that $\|ab\|^2\geq 0$.**

6. Otherwise do the following:

   (a) **Show that $ab>0$ using declaration II:22 given that $\mathrm{re}(ab)>0$ and $\|ab\|^2\geq 0$.**

Procedure II:56(sun1602201531)

Objective

Choose two perplex numbers a,b such that $0\subset a$ and $0<b$. The objective of the following instructions is to show that $0\subseteq ab$.

Implementation

1. Show that $0<\mathrm{im}(a)$ and $\|a\|^2\leq 0$ using declaration II:23 given that $0\subset a$.

2. Show that $0<\mathrm{re}(b)$ and $\|b\|^2\geq 0$ using declaration II:22 given that $0<b$.

3. Hence show that $\mathrm{im}(ab)=\mathrm{re}(a)\,\mathrm{im}(b)+\mathrm{im}(a)\,\mathrm{re}(b)\geq -\mathrm{im}(a)\,\mathrm{re}(b)+\mathrm{im}(a)\,\mathrm{im}(b)=0$.

4. Also show that $\|ab\|^2=\|a\|^2\|b\|^2\leq 0$.

5. If $\mathrm{im}(ab)=0$, then do the following:

   (a) **Show that $ab=0$ using declaration II:15 given that $\mathrm{re}(ab)=0$ given that**

$\mathrm{re}(ab)^2 \leq \mathrm{im}(ab)^2 = 0$ **given that** $\|ab\|^2 \leq 0$**.**

6. Otherwise do the following:

   (a) **Show that** $ab \supset 0$ **using declaration II:23 given that** $\mathrm{im}(ab) > 0$ **and** $\|ab\|^2 \leq 0$**.**

Procedure II:57(sun0902201136)

Objective

Choose two perplex numbers a, b such that $\|b - a\|^2 \neq 0$. The objective of the following instructions is to show that either $a < b$, $a > b$, $a \subset b$, or $a \supset b$.

Implementation

1. Given that $\|b - a\|^2 \neq 0$, show that either

   (a) $\|b - a\|^2 > 0$ and $\mathrm{re}(b - a) > 0$

   (b) $\|b - a\|^2 > 0$ and $\mathrm{re}(b - a) < 0$

   (c) $\|b - a\|^2 < 0$ and $\mathrm{im}(b - a) > 0$

   (d) $\|b - a\|^2 < 0$ and $\mathrm{im}(b - a) < 0$.

2. Hence show that either:

   (a) $a < b$ using declaration II:22 given that $\|b - a\|^2 > 0$ and $\mathrm{re}(b - a) > 0$

   (b) $a > b$ using declaration II:22 given that $\|b - a\|^2 > 0$ and $\mathrm{re}(b - a) < 0$

   (c) $a \subset b$ using declaration II:23 given that $\|b - a\|^2 < 0$ and $\mathrm{im}(b - a) > 0$

   (d) $a \supset b$ using declaration II:23 given that $\|b - a\|^2 < 0$ and $\mathrm{im}(b - a) < 0$.

Declaration II:24(tue2502201203)

The phrases "proper perplex number" and "improper perplex number" will be used as shorthands for perplex numbers, a, such that $\mathrm{im}(a) \geq 0$ and $\mathrm{im}(a) \leq 0$ respectively.

Declaration II:25(sun1602200918)

The phrases "a and b intersect", "a and b are disjoint", and "a and b adjoin", where a and b are perplex numbers, will be used to paraphrase $\|b-(a)^-\|^2 \leq 0$, $\|b-(a)^-\|^2 \geq 0$, and $\|b-(a)^-\|^2 = 0$ respectively.

Procedure II:58(sat0802201500)

Objective

Choose a list of positive perplex numbers a. The objective of the following instructions is to show that $\|\sum_r^{[0:|a|]} a_r\|^2 \geq \sum_r^{[0:|a|]} \|a_r\|^2$.

Implementation

1. Show that $\mathrm{re}(\sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} a_r(a_k)^-) > 0$ given that $\sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} a_r(a_k)^- > 0$.

2. Hence show that $\|\sum_r^{[0:|a|]} a_r\|^2$

   (a) $= \sum_r^{[0:|a|]} \sum_k^{[0:|a|]} a_r(a_k)^-$

   (b) $= \sum_r^{[0:|a|]} \|a_r\|^2 + \sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} (a_r(a_k)^- + (a_r(a_k)^-)^-)$

   (c) $= \sum_r^{[0:|a|]} \|a_r\|^2 + 2\sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} \mathrm{re}(a_r(a_k)^-)$

   (d) $= \sum_r^{[0:|a|]} \|a_r\|^2 + 2\,\mathrm{re}(\sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} a_r(a_k)^-)$

   (e) $\geq \sum_r^{[0:|a|]} \|a_r\|^2$.

Procedure II:59(sat0802201518)

Objective

Choose a non-empty list of positive perplex numbers a such that $a_0 > \sum_r^{[1:|a|]} a_r$. The objective of the following instructions is to show that $\|a_0\|^2 - \sum_r^{[1:|a|]} \|a_r\|^2 \geq \|a_0 - \sum_r^{[1:|a|]} a_r\|^2$.

Implementation

1. Using procedure II:58, show that $\|a_0\|^2$

   (a) $= \|\sum_r^{[1:|a|]} a_r + (a_0 - \sum_r^{[1:|a|]} a_r)\|^2$

   (b) $\geq \sum_r^{[1:|a|]} \|a_r\|^2 + \|a_0 - \sum_r^{[1:|a|]} a_r\|^2$

2. **Therefore show that** $\|a_0\|^2 - \sum_r^{[1:|a|]} \|a_r\|^2 \geq \|a_0 - \sum_r^{[1:|a|]} a_r\|^2$**.**

Procedure II:60(sat0802201359)

Objective

Choose a list of positive perplex numbers a and a list of rational numbers b such that $|a| = |b|$ and $\|a_i\|^2 \geq {b_i}^2$ for each $i \in [0 : |a|]$. The objective of the following instructions is to show that $\|\sum_r^{[0:|a|]} a_r\|^2 \geq (\sum_r^{[0:|b|]} b_r)^2$.

Implementation

1. If $|a| = 0$, then do the following:
   (a) **Show that** $\|\sum_i^{[0:|a|]} a_i\|^2 = \|0\|^2 = (\sum_i^{[0:|b|]} b_i)^2$**.**
2. Otherwise do the following:
   (a) Show that $|a| > 0$.
   (b) Show that $\|\sum_i^{[1:|a|]} a_i\|^2 \geq (\sum_i^{[1:|b|]} b_i)^2$ using procedure II:60 on $a_{[1:|a|]}$ and $b_{[1:|b|]}$.
   (c) Show that $\mathrm{re}((a_0)^- \sum_i^{[1:|a|]} a_i) > 0$
      i. given that $(a_0)^- \sum_i^{[1:|a|]} a_i > 0$
      ii. given that $\sum_i^{[1:|a|]} a_i > 0$
      iii. and $(a_0)^- > 0$.
   (d) Show that $\mathrm{re}((a_0)^- \sum_i^{[1:|a|]} a_i)^2$
      i. $\geq \|(a_0)^- \sum_i^{[1:|a|]} a_i\|^2$
      ii. $= \|(a_0)^-\|^2 \|\sum_i^{[1:|a|]} a_i\|^2$
      iii. $\geq {b_0}^2 (\sum_i^{[1:|a|]} b_i)^2$.
   (e) Hence show that $\|\sum_i^{[0:|a|]} a_i\|^2$
      i. $= (a_0 + \sum_i^{[1:|a|]} a_i)((a_0 + \sum_i^{[1:|a|]} a_i)^-)$
      ii. $= \|a_0\|^2 + a_0(\sum_i^{[1:|a|]} a_i)^- + (a_0)^- \sum_i^{[1:|a|]} a_i + \|\sum_i^{[1:|a|]} a_i\|^2$
      iii. $\geq {b_0}^2 + ((a_0)^- \sum_i^{[1:|a|]} a_i)^- + (a_0)^- \sum_i^{[1:|a|]} a_i + (\sum_i^{[1:|a|]} b_i)^2$
      iv. $= {b_0}^2 + 2\,\mathrm{re}((a_0)^- \sum_i^{[1:|a|]} a_i) + (\sum_i^{[1:|a|]} b_i)^2$
      v. $\geq {b_0}^2 + 2b_0 \sum_i^{[1:|a|]} b_i + (\sum_i^{[1:|a|]} b_i)^2$
      vi. $= (b_0 + \sum_i^{[1:|a|]} b_i)^2$
      vii. $= (\sum_i^{[0:|a|]} b_i)^2$.

Declaration II:26(sun0902201142)

The notation $\frac{1}{a}$, where a is a perplex number, will be used as a shorthand for the pair $\frac{1}{\|a\|^2}(a)^-$.

Procedure II:61(sun0902201143)

Objective

Choose a perplex number a such that $\|a\|^2 \neq 0$. The objective of the following instructions is to show that $\frac{1}{a}a = 1$.

Implementation

1. Show that $\frac{1}{a}a$
   (a) $= (\frac{1}{\|a\|^2}(a)^-)a$
   (b) $= \frac{1}{\|a\|^2}((a)^- a)$
   (c) $= \frac{1}{\|a\|^2}\|a\|^2$
   (d) $= 1$.

Declaration II:27(sat0802201702)

The notations j and k will be used as a shorthand for the perplex numbers $\langle 0, 1\rangle$ and $\langle \frac{1}{2}, \frac{1}{2}\rangle$ respectively.

Procedure II:62(thu0602201510)

Objective

The objective of the following instructions is to show that $j^2 = 1$, $k^2 = k$, $(k)^{-2} = (k)^-$, $k(k)^- = 0$, $k + (k)^- = 1$, and $k - (k)^- = j$.

Implementation

1. **Show that** $j^2 = 1$**.**
2. **Show that** $k^2 = k$**.**
3. **Show that** $(k)^{-2} = (k)^-$**.**
4. **Show that** $k(k)^- = 0$**.**
5. **Show that** $k + (k)^- = 1$**.**
6. **Show that** $k - (k)^- = j$**.**

Procedure II:63(fri1402201203)

Objective

Choose a perplex number a. The objective of the following instructions is to show that $a = \mathrm{re}(a) + \mathrm{im}(a)j$.

Implementation

1. Show that a
   (a) $= \langle \mathrm{re}(a), \mathrm{im}(a)\rangle$
   (b) $= \langle \mathrm{re}(a), 0\rangle + \langle 0, \mathrm{im}(a)\rangle$
   (c) $= \mathrm{re}(a) + \mathrm{im}(a)j$.

Procedure II:64(fri1402201147)

Objective

Choose a perplex number a. The objective of the following instructions is to show that $a = (\mathrm{re}(a) + \mathrm{im}(a))k + (\mathrm{re}(a) - \mathrm{im}(a))(k)^-$.

Implementation

1. Using procedure II:62, show that a
   (a) $= \mathrm{re}(a) + \mathrm{im}(a)j$
   (b) $= \mathrm{re}(a)(k + (k)^-) + \mathrm{im}(a)(k - (k)^-)$
   (c) $= (\mathrm{re}(a) + \mathrm{im}(a))k + (\mathrm{re}(a) - \mathrm{im}(a))(k)^-$.

Procedure II:65(sat0802201559)

Objective

Choose rational numbers a, b, c, d. The objective of the following instructions is to show that $(ak + b(k)^-) + (ck + d(k)^-) = (a + c)k + (b + d)(k)^-$.

Implementation

1. Show that $(ak + b(k)^-) + (ck + d(k)^-) = (a + c)k + (b + d)(k)^-$.

Procedure II:66(sun0902201144)

Objective

Choose rational numbers a, b, c, d. The objective of the following instructions is to show that $(ak + b(k)^-)(ck + d(k)^-) = ack + bd(k)^-$.

Implementation

1. Show that $(ak + b(k)^-)(ck + d(k)^-)$
   (a) $= ak(ck + d(k)^-) + b(k)^-(ck + d(k)^-)$
   (b) $= akck + akd(k)^- + b(k)^-ck + b(k)^-d(k)^-$
   (c) $= ack + 0ad + 0bc + bd(k)^-$
   (d) $= ack + bd(k)^-$.

Chapter 7

Polynomial Arithmetic

Declaration II:28(2.08)

The notation $\min(c)$, where c is a list, will be used as a shorthand for ∞ if c is empty, otherwise it will stand for the minimum entry of c. The related notation $\min_r^R c(r)$, where R is a list and $c[r]$ is a function of r, will be used as a shorthand for $\min(c(R))$.

Declaration II:29(2.11)

The notation $\max(c)$, where c is a list, will be used as a shorthand for $-\infty$ if c is empty, otherwise it will stand for the maximum entry of c. The related notation $\max_r^R c(r)$, where R is a list and $c[r]$ is a function of r, will be used as a shorthand for $\max(c(R))$.

Declaration II:30(2.25)

The phrase "polynomial" will be used as a shorthand for a list of rational numbers.

Declaration II:31(2.26)

The notation a_i, where a is a polynomial and i is a natural number such that $i \geq |a|$, will be used as a shorthand for 0.

Declaration II:32(2.27)

The phrase "$a = b$", where a, b are polynomials, will be used as a shorthand for "$a_i = b_i$ for each $i \in [0 : \max(|a|, |b|)]$".

Declaration II:33(2.28)

The notation $\Lambda(a, b)$ will be used as a shorthand for $\sum_r^{[0:|a|]} a_r b^r$.

Procedure II:67(2.51)

Objective

Choose two polynomials a, b and a rational number c such that $a = b$. The objective of the following instructions is to show that $\Lambda(a, c) = \Lambda(b, c)$.

Implementation

1. Using declaration II:32 and declaration II:33, show that $\Lambda(a, c)$
   (a) $= \sum_r^{[0:|a|]} a_r c^r$
   (b) $= \sum_r^{[0:\max(|a|,|b|)]} a_r c^r$
   (c) $= \sum_r^{[0:\max(|a|,|b|)]} b_r c^r$
   (d) $= \sum_r^{[0:|b|]} b_r c^r$
   (e) $= \Lambda(b, c)$.

Procedure II:68(2.52)

Objective

Choose a natural number c and two polynomials a, b such that $a = b$. The objective of the following instructions is to show that $a_c = b_c$.

Implementation

1. If $c < \max(|a|, |b|)$, then do the following:
   (a) **Show that $a_c = b_c$.**
2. Otherwise do the following:
   (a) **Show that $a_c = 0 = b_c$ given that $c \geq \max(|a|, |b|)$.**

Procedure II:69(2.53)

Objective

Choose a polynomial a. The objective of the following instructions is to show that $a = a$.

Implementation

1. Show that $a_i = a_i$ for each $i \in [0 : \max(|a|, |a|)]$.
2. **Hence show that $a = a$ using declaration II:32.**

Procedure II:70(2.54)

Objective

Choose two polynomials a, b such that $a = b$. The objective of the following instructions is to show that $b = a$.

Implementation

1. Show that $a_i = b_i$ for each $i \in [0 : \max(|a|, |b|)]$ using declaration II:32.
2. Hence show that $b_i = a_i$ for each $i \in [0 : \max(|b|, |a|)]$.
3. **Hence show that $b = a$ using declaration II:32.**

Procedure II:71(2.55)

Objective

Choose three polynomials a, b, c such that $a = b$ and $b = c$. The objective of the following instructions is to show that $a = c$.

Implementation

1. Show that $a_i = b_i$ for each $i \in [0 : \max(|a|, |b|, |c|)]$ using declaration II:32.
2. Show that $b_i = c_i$ for each $i \in [0 : \max(|a|, |b|, |c|)]$ using declaration II:32.
3. Hence show that $a_i = c_i$ for each $i \in [0 : \max(|a|, |b|, |c|)]$.
4. **Hence verify that $a = c$ using declaration II:32.**

Declaration II:34(2.37)

The notation $\langle f(j) \text{ for } j \in R\rangle$, where $f[j]$ is a function of j and R is a list, will be used as a shorthand for $\langle f(R)\rangle$.

Declaration II:35(2.29)

The notation $a + b$, where a, b are polynomials, will be used as a shorthand for the list $\langle a_i + b_i \text{ for } i \in [0 : \max(|a|, |b|)]\rangle$.

Procedure II:72(2.56)

Objective

Choose two polynomials a, b and a rational number c. The objective of the following instructions is to show that $\Lambda(a + b, c) = \Lambda(a, c) + \Lambda(b, c)$.

Implementation

1. Using declaration II:33 and declaration II:35, show that $\Lambda(a + b, c)$
   (a) $= \Lambda(\langle a_r + b_r \text{ for } r \in [0 : \max(|a|, |b|)]\rangle, c)$
   (b) $= \sum_r^{[0:\max(|a|,|b|)]} (a_r + b_r)c^r$
   (c) $= \sum_r^{[0:\max(|a|,|b|)]} a_r c^r + \sum_r^{[0:\max(|a|,|b|)]} b_r c^r$
   (d) $= \sum_r^{[0:|a|]} a_r c^r + \sum_r^{[0:|b|]} b_r c^r$
   (e) $= \Lambda(a, c) + \Lambda(b, c)$.

Procedure II:73(2.57)

Objective

Choose a natural number c and two polynomials a, b. The objective of the following instructions is to show that $(a + b)_c = a_c + b_c$.

Implementation

1. If $c < \max(|a|, |b|)$, then do the following:
   (a) **Show that $(a+b)_c = a_c + b_c$ using declaration II:35.**
2. Otherwise do the following:
   (a) Show that $c \geq \max(|a|, |b|)$.
   (b) Hence show that $a_c = 0$, $b_c = 0$, and $(a + b)_c = 0$ using declaration II:31.
   (c) **Hence show that $(a + b)_c = a_c + b_c$.**

Procedure II:74(2.58)

Objective

Choose four polynomials a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $a + b = c + d$.

Implementation

1. Show that $a_i = c_i$ for each $i \in [0 : \max(|a|, |b|, |c|, |d|)]$ using declaration II:32 given that $a = c$.
2. Verify that $b_i = d_i$ for each $i \in [0 : \max(|a|, |b|, |c|, |d|)]$ using declaration II:32 given that $b = d$.
3. Hence using declaration II:35, show that $a + b$

(a) $= \langle a_i + b_i \text{ for } i \in [0 : \max(|a|, |b|, |c|, |d|)]\rangle$

(b) $= \langle c_i + d_i \text{ for } i \in [0 : \max(|a|, |b|, |c|, |d|)]\rangle$

(c) $= c + d$.

Procedure II:75(2.59)

Objective

Choose three polynomials a, b, c. The objective of the following instructions is to show that $(a+b)+c = a + (b + c)$.

Implementation

1. Using declaration II:35, show that $(a + b) + c$

(a) $\langle (a + b)_i + c_i \text{ for } i \in [0 : \max(|a + b|, |c|)]\rangle$

(b) $\langle (a_i + b_i) + c_i \text{ for } i \in [0 : \max(|a|, |b|, |c|)]\rangle$

(c) $\langle a_i + (b_i + c_i) \text{ for } i \in [0 : \max(|a|, |b + c|)]\rangle$

(d) $\langle a_i + (b + c)_i \text{ for } i \in [0 : \max(|a|, |b + c|)]\rangle$

(e) $= a + (b + c)$.

Procedure II:76(2.60)

Objective

Choose two polynomials a, b. The objective of the following instructions is to show that $a + b = b + a$.

Implementation

1. Using declaration II:35, show that $a + b$

(a) $= \langle a_i + b_i \text{ for } i \in [0 : \max(|a|, |b|)]\rangle$

(b) $= \langle b_i + a_i \text{ for } i \in [0 : \max(|b|, |a|)]\rangle$

(c) $= b + a$.

Declaration II:36(2.30)

The notation a, where a is a rational number, will contextually be used as a shorthand for the list $\langle a\rangle$.

Procedure II:77(2.61)

Objective

Choose a polynomial a. The objective of the following instructions is to show that $0 + a = a$.

Implementation

1. Using declaration II:35 and declaration II:36, show that $0 + a$

(a) $= \langle 0_i + a_i \text{ for } i \in [0 : |a|]\rangle$

(b) $= \langle 0 + a_i \text{ for } i \in [0 : |a|]\rangle$

(c) $= a$.

Declaration II:37(2.31)

The notation $-a$, where a is a polynomial, will be used as a shorthand for the list $\langle -a_i \text{ for } i \in [0 : |a|]\rangle$.

Procedure II:78(2.00)

Objective

Choose a polynomial a and a rational number b. The objective of the following instructions is to show that $\Lambda(-a, b) = -\Lambda(a, b)$.

Implementation

1. Using declaration II:33 and declaration II:37, show that $\Lambda(-a, b)$

(a) $= \Lambda(\langle -a_i \text{ for } i \in [0 : |a|]\rangle, b)$

(b) $= \sum_j^{[0:|a|]} (-a_j) b^j$

(c) $= -\sum_j^{[0:|a|]} a_j b^j$

(d) $= -\Lambda(a, b)$.

Procedure II:79(2.62)

Objective

Choose two polynomials a, b such that $a = b$. The objective of the following instructions is to show that $-a = -b$.

Implementation

1. Show that $a_i = b_i$ for $i \in [0 : \max(|a|, |b|)]$ using declaration II:32 given that $a = b$.
2. Hence using declaration II:37, show that $-a$
   (a) $= \langle -a_i \text{ for } i \in [0 : \max(|a|, |b|)]\rangle$
   (b) $= \langle -b_i \text{ for } i \in [0 : \max(|a|, |b|)]\rangle$
   (c) $= -b$.

Procedure II:80(2.63)

Objective

Choose a polynomial a. The objective of the following instructions is to show that $-a + a = 0$.

Implementation

1. Using declaration II:35 and declaration II:37, show that $-a + a$
   (a) $= (-a) + a$
   (b) $= \langle -a_i \text{ for } i \in [0 : |a|]\rangle + \langle a_i \text{ for } i \in [0 : |a|]\rangle$
   (c) $= \langle -a_i + a_i \text{ for } i \in [0 : |a|]\rangle$
   (d) $= \langle 0 \text{ for } i \in [0 : |a|]\rangle$
   (e) $= 0$.

Declaration II:38(2.32)

The notation *ab*, where a, b are integers, will be used as a shorthand for the list $\langle \sum_r^{[0:i+1]} a_r b_{i-r} \text{ for } i \in [0 : |a| + |b| - 1]\rangle$.

Procedure II:81(2.64)

Objective

Choose two polynomials a, b and a rational number c. The objective of the following instructions is to show that $\Lambda(ab, c) = \Lambda(a, c)\Lambda(b, c)$.

Implementation

1. Using declaration II:33 and declaration II:38, show that $\Lambda(ab, c)$
   (a) $= \Lambda(\langle \sum_r^{[0:j+1]} a_r b_{j-r} \text{ for } j \in [0 : |a| + |b| - 1]\rangle, c)$
   (b) $= \sum_j^{[0:|a|+|b|-1]} (\sum_r^{[0:j+1]} a_r b_{j-r}) c^j$
   (c) $= \sum_j^{[0:|a|+|b|-1]} \sum_r^{[0:j+1]} a_r c^r b_{j-r} c^{j-r}$
   (d) $= \sum_r^{[0:|a|+|b|-1]} \sum_j^{[r:|a|+|b|-1]} a_r c^r b_{j-r} c^{j-r}$
   (e) $= \sum_r^{[0:|a|+|b|-1]} a_r c^r \sum_j^{[r:|a|+|b|-1]} b_{j-r} c^{j-r}$
   (f) $= \sum_r^{[0:|a|+|b|-1]} a_r c^r \sum_j^{[0:|a|+|b|-1-r]} b_j c^j$
   (g) $= \sum_r^{[0:|a|]} a_r c^r \sum_j^{[0:|a|+|b|-1-r]} b_j c^j$
   (h) $= \sum_r^{[0:|a|]} a_r c^r \sum_j^{[0:|b|]} b_j c^j$
   (i) $= (\sum_j^{[0:|a|]} a_j c^j)(\sum_j^{[0:|b|]} b_j c^j)$
   (j) $= \Lambda(a, c)\Lambda(b, c)$.

Procedure II:82(2.65)

Objective

Choose a natural number c and two polynomials a, b. The objective of the following instructions is to show that $(ab)_c = \sum_r^{[0:c+1]} a_r b_{c-r}$.

Implementation

1. If $c < |a| + |b| - 1$, then do the following:
   (a) **Show that $(ab)_c = \sum_r^{[0:c+1]} a_r b_{c-r}$ using declaration II:38.**
2. Otherwise do the following:
   (a) Show that $c \geq |a| + |b| - 1$.
   (b) Hence using declaration II:31, show that $(ab)_c$
      i. $= 0$
      ii. $= \sum_r^{[0:|a|]} 0a_r + \sum_r^{[|a|:c+1]} 0b_{c-r}$
      iii. $= \sum_r^{[0:|a|]} a_r b_{c-r} + \sum_r^{[|a|:c+1]} a_r b_{c-r}$
      iv. $= \sum_r^{[0:c+1]} a_r b_{c-r}$.

Procedure II:83(2.66)

Objective

Choose four polynomials a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $ab = cd$.

Implementation

1. Show that $a_i = c_i$ for $i \in [0 : \max(|a|, |c|) + \max(|b|, |d|) - 1]$ using procedure II:68 given that $a = c$.
2. Show that $b_i = d_i$ for $i \in [0 : \max(|a|, |c|) + \max(|b|, |d|) - 1]$ using procedure II:68 given that $b = d$.
3. Hence using declaration II:38, show that ab

(a) $= \langle \sum_r^{[0:i+1]} a_r b_{i-r}$ for $i \in [0 : \max(|a|, |c|) + \max(|b|, |d|) - 1]\rangle$

(b) $= \langle \sum_r^{[0:i+1]} c_r d_{i-r}$ for $i \in [0 : \max(|a|, |c|) + \max(|b|, |d|) - 1]\rangle$

(c) $= cd$.

Procedure II:84(2.67)

Objective

Choose three polynomials a, b, c. The objective of the following instructions is to show that $(ab)c = a(bc)$.

Implementation

1. Using declaration II:38, show that $(ab)c$

(a) $= \langle \sum_t^{[0:j+1]} (ab)_t c_{j-t}$ for $j \in [0 : |ab| + |c| - 1]\rangle$

(b) $= \langle \sum_t^{[0:j+1]} \langle \sum_r^{[0:i+1]} a_r b_{i-r}$ for $i \in [0 : |a| + |b| - 1]\rangle_t c_{j-t}$ for $j \in [0 : |a| + |b| + |c| - 2]\rangle$

(c) $= \langle \sum_t^{[0:j+1]} \sum_r^{[0:t+1]} a_r b_{t-r} c_{j-t}$ for $j \in [0 : |a| + |b| + |c| - 2]\rangle$

(d) $= \langle \sum_r^{[0:j+1]} \sum_t^{[r:j+1]} a_r b_{t-r} c_{j-t}$ for $j \in [0 : |a| + |b| + |c| - 2]\rangle$

(e) $= \langle \sum_r^{[0:j+1]} a_r \sum_t^{[r:j+1]} b_{t-r} c_{j-t}$ for $j \in [0 : |a| + |b| + |c| - 2]\rangle$

(f) $= \langle \sum_r^{[0:j+1]} a_r \sum_t^{[0:j-r+1]} b_t c_{j-r-t}$ for $j \in [0 : |a| + |b| + |c| - 2]\rangle$

(g) $= \langle \sum_r^{[0:j+1]} a_r \langle \sum_t^{[0:i+1]} b_t c_{i-t}$ for $i \in [0 : |b| + |c| - 1]\rangle_{j-r}$ for $j \in [0 : |a| + |b| + |c| - 2]\rangle$

(h) $= \langle \sum_r^{[0:j+1]} a_r (bc)_{j-r}$ for $j \in [0 : |a| + |bc| - 1]\rangle$

(i) $= a(bc)$.

Procedure II:85(2.68)

Objective

Choose two polynomials a, b. The objective of the following instructions is to show that $ab = ba$.

Implementation

1. Using declaration II:38, show that ab

(a) $= \langle \sum_r^{[0:i+1]} a_r b_{i-r}$ for $i \in [0 : |a| + |b| - 1]\rangle$

(b) $= \langle \sum_r^{[0:i+1]} b_r a_{i-r}$ for $i \in [0 : |a| + |b| - 1]\rangle$

(c) $= ba$.

Procedure II:86(2.69)

Objective

Choose a polynomial a. The objective of the following instructions is to show that $1a = a$.

Implementation

1. Using declaration II:36 and declaration II:38, show that $1a$

(a) $= \langle \sum_r^{[0:i+1]} 1_r a_{i-r}$ for $i \in [0 : |1| + |a| - 1]\rangle$

(b) $= \langle 1_0 a_{i-0}$ for $i \in [0 : |a|]\rangle$

(c) $= \langle a_i$ for $i \in [0 : |a|]\rangle$

(d) $= a$.

Procedure II:87(2.70)

Objective

Choose three polynomials a, b, c. The objective of the following instructions is to show that $a(b + c) = ab + ac$.

Implementation

1. Using declaration II:35 and declaration II:38, show $a(b+c)$

   (a) $= \langle \sum_r^{[0:i+1]} a_r(b+c)_{i-r}$ for $i \in [0 : |a| + |b+c| - 1]\rangle$

   (b) $= \langle \sum_r^{[0:i+1]} a_r(b_{i-r} + c_{i-r})$ for $i \in [0 : |a| + |b+c| - 1]\rangle$

   (c) $= \langle \sum_r^{[0:i+1]} (a_r b_{i-r} + a_r c_{i-r})$ for $i \in [0 : |a| + |b+c| - 1]\rangle$

   (d) $= \langle \sum_r^{[0:i+1]} a_r b_{i-r} + \sum_r^{[0:i+1]} a_r c_{i-r}$ for $i \in [0 : |a| + |b+c| - 1]\rangle$

   (e) $= \langle \sum_r^{[0:i+1]} a_r b_{i-r}$ for $i \in [0 : |a| + |b| - 1]\rangle + \langle \sum_r^{[0:i+1]} a_r c_{i-r}$ for $i \in [0 : |a| + |c| - 1]\rangle$

   (f) $= ab + ac$.

Declaration II:39(2.33)

The notation λ will be used as a shorthand for the list $\langle 0, 1\rangle$.

Procedure II:88(2.71)

Objective

Choose a polynomial a. The objective of the following instructions is to show that $\lambda a = \langle 0\rangle ^\frown a$.

Implementation

1. Show that $|\lambda a| = |\lambda| + |a| - 1 = |a| + 1$ using declaration II:38.

2. For $j \in [1 : |a| + 1]$, do the following:

   (a) Using declaration II:38, show that $(\lambda a)_j$

      i. $= \sum_r^{[0:j+1]} \lambda_r a_{j-r}$

      ii. $= \sum_r^{[0:j+1]} [r = 1] a_{j-r}$

      iii. $= a_{j-1}$

3. Hence using declaration II:38, show that $(\lambda a)_0 = \sum_r^{[0:1]} \lambda_r a_{0-r} = \lambda_0 a_0 = 0$.

4. **Hence show that $\lambda a = \langle 0\rangle ^\frown a$.**

Procedure II:89(2.72)

Objective

Choose a natural number n. The objective of the following instructions is to show that $\lambda^n = \langle [j = n]$ for $j \in [0 : n+1]\rangle$.

Implementation

1. If $n = 0$, then do the following:

   (a) Show that λ^n

      i. $= \lambda^0$

      ii. $= \langle 1\rangle$

      iii. $= \langle [j = 0]$ for $j \in [0 : 1]\rangle$

      iv. $= \langle [j = n]$ for $j \in [0 : n+1]\rangle$.

2. Otherwise do the following:

   (a) Use procedure II:96 on $\langle n-1\rangle$ to show that $\lambda^{n-1} = \langle [j = n-1]$ for $j \in [0 : n]\rangle$.

   (b) Hence using procedure II:88, show that λ^n

      i. $= \lambda\lambda^{n-1}$

      ii. $= \lambda\langle [j = n-1]$ for $j \in [0 : n]\rangle$

      iii. $= \langle 0\rangle ^\frown \langle [j = n-1]$ for $j \in [0 : n]\rangle$

      iv. $= \langle [j = n]$ for $j \in [0 : n+1]\rangle$.

Declaration II:40(2.34)

The notation $\deg(a)$, where a is a polynomial such that $a \neq 0$, will be used as a shorthand for the largest natural number $j < |a|$ such that $a_j \neq 0$.

Procedure II:90(2.73)

Objective

Choose two polynomials a, b such that $a = b$ and $a \neq 0$. The objective of the following instructions is to show that $\deg(a) = \deg(b)$.

Implementation

1. For $j \in [\max(|a|, |b|) : 0]$, do the following:

   (a) If $a_j = 0$, then do the following:

      i. Show that $0 = a_j = b_j$ using declaration II:32 given that $a = b$.

   (b) Otherwise do the following:

i. Show that $0 \neq a_j = b_j$ using declaration II:32 given that $a = b$.

ii. Show that $j < \min(|a|, |b|)$.

iii. **Hence show that** $\deg(a) = j = \deg(b)$**.**

iv. **Yield.**

Procedure II:91(2.74)

Objective

Let $\deg(0) = -1$. Choose two polynomials a, b such that $\deg(a) < \deg(b)$. The objective of the following instructions is to show that $\deg(a + b) = \deg(b)$.

Implementation

1. For $j \in [\max(|a|, |b|) : \deg(b) + 1]$, do the following:
   (a) Show that $j > \deg(b) > \deg(a)$.
   (b) Hence show that $a_j = b_j = 0$ using declaration II:40.
   (c) Hence show that $(a + b)_j = a_j + b_j = 0$.
2. Show that $(a + b)_{\deg(b)} = a_{\deg(b)} + b_{\deg(b)} = 0 + b_{\deg(b)} = b_{\deg(b)} \neq 0$ using declaration II:40 given that $\deg(b) > \deg(a)$.
3. **Hence show that** $\deg(a + b) = \deg(b)$**.**

Procedure II:92(2.75)

Objective

Let $\deg(0) = -1$. Choose two polynomials a, b. The objective of the following instructions is to show that $\deg(a + b) \leq \max(\deg(a), \deg(b))$.

Implementation

1. For $j \in [\max(|a|, |b|) : \max(\deg(a), \deg(b)) + 1]$, do the following:
   (a) Show that $a_j = b_j = 0$ using declaration II:40 given that $j > \deg(a)$ and $j > \deg(b)$.
   (b) Hence show that $(a + b)_j = a_j + b_j = 0$ using declaration II:35.
2. **Hence show that** $\deg(a + b) \leq \max(\deg(a), \deg(b))$ **using declaration II:40.**

Procedure II:93(2.76)

Objective

Let $\deg(0) = -1$. Choose a polynomial a. The objective of the following instructions is to show that $\deg(-a) = \deg(a)$.

Implementation

1. For $j \in [|a| : \deg(a) + 1]$, do the following:
   (a) Show that $a_j = 0$ using declaration II:40 given that $j > \deg(a)$.
   (b) Hence show that $(-a)_j = -(a_j) = -0 = 0$ using declaration II:37.
2. Show that $(-a)_{\deg(a)} = -(a_{\deg(a)}) \neq 0$ given that $a_{\deg(a)} \neq 0$.
3. **Hence show that** $\deg(-a) = \deg(a)$ **using declaration II:40.**

Procedure II:94(2.77)

Objective

Choose two polynomials a, b such that $a \neq 0$ and $b \neq 0$. The objective of the following instructions is to show that $(ab)_{\deg(a)+\deg(b)} = a_{\deg(a)} b_{\deg(b)} \neq 0$.

Implementation

1. Show that $a_{\deg(a)} \neq 0$ given that $a \neq 0$.
2. Show that $b_{\deg(b)} \neq 0$ given that $b \neq 0$.
3. Hence using declaration II:38, show that $(ab)_{\deg(a)+\deg(b)}$
   (a) $= \sum_r^{[0:\deg(a)+\deg(b)+1]} a_r b_{\deg(a)+\deg(b)-r}$
   (b) $= \sum_r^{[0:\deg(a)]} a_r b_{\deg(a)+\deg(b)-r} + a_{\deg(a)} b_{\deg(a)+\deg(b)-\deg(a)} + \sum_r^{[\deg(a)+1:\deg(a)+\deg(b)+1]} a_r b_{\deg(}$
   (c) $= \sum_r^{[0:\deg(a)]} 0 a_r + a_{\deg(a)} b_{\deg(b)} + \sum_r^{[\deg(a)+1:\deg(a)+\deg(b)+1]} 0 b_{\deg(a)+\deg(b)-r}$
   (d) $= a_{\deg(a)} b_{\deg(b)}$
   (e) $\neq 0$.

Procedure II:95(2.78)

Objective

Choose two polynomials a, b such that $a \neq 0$ and $b \neq 0$. The objective of the following instructions is to show that $\deg(ab) = \deg(a) + \deg(b)$.

Implementation

1. For $j \in [\deg(a) + \deg(b) + 1 : |a| + |b| - 1]$, do the following:

   (a) Using declaration II:38, show that $(ab)_j$

   i. $= \sum_r^{[0:j+1]} a_r b_{j-r}$

   ii. $= \sum_r^{[0:\deg(a)+1]} a_r b_{j-r} + \sum_r^{[\deg(a)+1:j+1]} a_r b_{j-r}$

   iii. $= \sum_r^{[0:\deg(a)+1]} 0 a_r + \sum_r^{[\deg(a)+1:j+1]} 0 b_{j-r}$

   iv. $= 0$.

2. Now show that $(ab)_{\deg(a)+\deg(b)} = a_{\deg(a)} b_{\deg(b)} \neq 0$ using procedure II:94.

3. **Hence show that $\deg(ab) = \deg(a) + \deg(b)$ using declaration II:40.**

Declaration II:41(2.00)

The phrase "monic polynomial" will be used to refer to polynomials p such that $p \neq 0$ and $p_{\deg(p)} = 1$.

Declaration II:42(2.01)

The notation $\mathrm{mon}(p)$, where p is a polynomial such that $p \neq 0$, will be used as a shorthand for $\frac{p}{p_{\deg(p)}}$.

Procedure II:96(2.25)

Objective

Choose two polynomials, a, b such that $b \neq 0$. The objective of the following instructions is to construct two polynomials u, w such that $a = ub + w$ and $\deg(w) < \deg(b)$.

Implementation

1. If $\deg(a) \geq \deg(b)$, then do the following:

   (a) Let $y = \frac{a_{\deg(a)}}{b_{\deg(b)}} \lambda^{\deg(a)-\deg(b)}$

   (b) Let $e = a - yb$.

   (c) Show that $\deg(e) < \deg(a)$.

   (d) Use procedure II:96 on $\langle e, b\rangle$ to construct $\langle c, d\rangle$ and show that:

   i. $cb + d = e$.

   ii. $\deg(d) < \deg(b)$.

   (e) Hence show that $cb + d = a - yb$ given that $cb + d = e$ and $e = a - yb$.

   (f) **Hence show that $(y + c)b + d = a$.**

   (g) **Now yield the tuple $\langle y + c, d\rangle$.**

2. Otherwise do the following:

   (a) **Show that $0b + a = a$ and $\deg(a) < \deg(b)$.**

   (b) **Yield the tuple $\langle 0, a\rangle$.**

Declaration II:43(2.35)

The notation $a \operatorname{div} b$, where a, b are polynomials, will be used to refer to the first part of the pair yielded by executing procedure II:96 on $\langle a, b\rangle$.

Declaration II:44(2.36)

The notation $a \bmod b$, where a, b are polynomials, will be used to refer to the second part of the pair yielded by executing procedure II:96 on $\langle a, b\rangle$.

Procedure II:97(2.79)

Objective

Choose a polynomial a and a rational number b. The objective of the following instructions is to show that $a \bmod (\lambda - b) = \Lambda(a, b)$.

Implementation

1. Let $d = \lambda - b$.

2. Show that $d \neq 0$.

3. Let $c = a \operatorname{div} d$.

4. Using procedure II:96, show that:

   (a) $a = cd + (a \bmod d)$

   (b) $\deg(a \bmod d) < \deg(d) = 1$.

5. Hence show that $\deg(a \bmod d) = 0$.

6. Now using procedure II:72 and procedure II:81, show that $\Lambda(a, b)$

   (a) $= \Lambda(cd + (a \bmod d), b)$

   (b) $= \Lambda(cd, b) + \Lambda(a \bmod d, b)$

   (c) $= \Lambda(c, b)\Lambda(d, b) + \Lambda(a \bmod d, b)$

   (d) $= \Lambda(c, b)(-b + b) + \Lambda(a \bmod d, b)$

   (e) $= 0\Lambda(c, b) + \Lambda(a \bmod d, b)$

(f) $= \Lambda(a \bmod d, b)$

(g) $= a \bmod d$

(h) $= a \bmod (\lambda - b)$.

Procedure II:98(fri1402201125)

Objective

Choose a polynomial a and a perplex number b. The objective of the following instructions is to show that $\mathrm{re}(\Lambda(a,b)) = \frac{1}{2}(\Lambda(a, \mathrm{re}(b)+\mathrm{im}(b)) + \Lambda(a, \mathrm{re}(b) - \mathrm{im}(b)))$.

Implementation

1. Show that $\mathrm{re}(\Lambda(a,b))$

(a) $= \mathrm{re}(\sum_r^{[0:|a|]} a_r b^r)$

(b) $= \mathrm{re}(\sum_r^{[0:|a|]} a_r((\mathrm{re}(b) + \mathrm{im}(b))k + (\mathrm{re}(b) - \mathrm{im}(b))(k)^-)^r)$

(c) $= \sum_r^{[0:|a|]} a_r \,\mathrm{re}((\mathrm{re}(b) + \mathrm{im}(b))^r k + (\mathrm{re}(b) - \mathrm{im}(b))^r (k)^-)$

(d) $= \frac{1}{2} \sum_r^{[0:|a|]} a_r((\mathrm{re}(b) + \mathrm{im}(b))^r + (\mathrm{re}(b) - \mathrm{im}(b))^r)$

(e) $= \frac{1}{2}(\sum_r^{[0:|a|]} a_r(\mathrm{re}(b) + \mathrm{im}(b))^r + \sum_r^{[0:|a|]} a_r(\mathrm{re}(b) - \mathrm{im}(b))^r)$

(f) $= \frac{1}{2}(\Lambda(a, \mathrm{re}(b)+\mathrm{im}(b))+\Lambda(a, \mathrm{re}(b)-\mathrm{im}(b)))$.

Procedure II:99(fri1402201210)

Objective

Choose a polynomial a and a perplex number b. The objective of the following instructions is to show that $\mathrm{im}(\Lambda(a,b)) = \frac{1}{2}(\Lambda(a, \mathrm{re}(b)+\mathrm{im}(b)) - \Lambda(a, \mathrm{re}(b) - \mathrm{im}(b)))$.

Implementation

The implementation is analogous to that of procedure II:98.

Procedure II:100(fri1402201213)

Objective

Choose a polynomial a and a perplex number b. The objective of the following instructions is to show that $\|\Lambda(a,b)\|^2 = \Lambda(a, \mathrm{re}(b) - \mathrm{im}(b))\Lambda(a, \mathrm{re}(b) + \mathrm{im}(b))$.

Implementation

1. Using declaration II:21, procedure II:98, and procedure II:99, show that $\|\Lambda(a,b)\|^2$

(a) $= \mathrm{re}(\Lambda(a,b))^2 - \mathrm{im}(\Lambda(a,b))^2$

(b) $= (\frac{1}{2}(\Lambda(a, \mathrm{re}(b) + \mathrm{im}(b)) + \Lambda(a, \mathrm{re}(b) - \mathrm{im}(b))))^2 - (\frac{1}{2}(\Lambda(a, \mathrm{re}(b) + \mathrm{im}(b)) - \Lambda(a, \mathrm{re}(b) - \mathrm{im}(b))))^2$

(c) $= \Lambda(a, \mathrm{re}(b) - \mathrm{im}(b))\Lambda(a, \mathrm{re}(b) + \mathrm{im}(b))$.

Procedure II:101(mon1702200807)

Objective

Choose a polynomial a and a perplex number b. The objective of the following instructions is to show that $(\Lambda(a,b))^- = \Lambda(a, (b)^-)$.

Implementation

1. Show that $(\Lambda(a,b))^-$

(a) $= (\sum_r^{[0:|a|]} a_r b^r)^-$

(b) $= \sum_r^{[0:|a|]} (a_r b^r)^-$

(c) $= \sum_r^{[0:|a|]} a_r (b)^{-r}$

(d) $= \Lambda(a, (b)^-)$.

Procedure II:102(mon1702200743)

Objective

Choose a polynomial a and two adjoint perplex numbers b, c. The objective of the following instructions is to show that $\Lambda(a,b)$ and $\Lambda(a,c)$ are adjoint.

Implementation

1. Show that $\|c - (b)^-\|^2 = 0$ given that b and c are adjoint.

2. Using procedure II:101, show that $\|\Lambda(a,c) - (\Lambda(a,b))^-\|^2$

(a) $= \|\Lambda(a,c) - \Lambda(a,(b)^-)\|^2$

(b) $= \|\sum_r^{[0:|a|]} a_r c^r - \sum_r^{[0:|a|]} a_r (b)^{-r}\|^2$

(c) $= \|\sum_r^{[0:|a|]} a_r (c^r - (b)^{-r})\|^2$

(d) $= \|\sum_r^{[0:|a|]} a_r (c - (b)^-) \sum_t^{[0:r]} c^t (b)^{-r-1-t}\|^2$

(e) $= \|c - (b)^-\|^2 \|\sum_r^{[0:|a|]} a_r \sum_t^{[0:r]} c^t (b)^{-r-1-t}\|^2$

(f) $= 0\|\sum_r^{[0:|a|]} a_r \sum_t^{[0:r]} c^t (b)^{-r-1-t}\|^2$

(g) $= 0.$

3. **Hence show that $\Lambda(a, b)$ and $\Lambda(a, c)$ are adjoint.**

Chapter 8

Polynomial Sign Changes

Procedure II:103(2.80)

Objective

Choose a polynomial $p \neq 0$ and rational numbers $a_0 < a_1 < \cdots < a_{\deg(p)-2} < a_{\deg(p)-1}$ in such a way that $\Lambda(p, a_i) = 0$ for $i \in [0 : \deg(p)]$. The objective of the following instructions is to show that $p = p_{\deg(p)} \prod_j^{[0:\deg(p)]}(\lambda - a_j)$.

Implementation

1. Let $n = \deg(p)$.
2. If $n = 0$, then do the following:
   (a) **Show that** $p = p_0 = p_{\deg(p)} \prod_j^{[0:n]}(\lambda - a_j)$**.**
3. Otherwise do the following:
   (a) Show that $p \bmod (\lambda - a_{n-1}) = \Lambda(p, a_{n-1}) = 0$ using procedure II:97 given that $\Lambda(p, a_{n-1}) = 0$.
   (b) Let $q = p \operatorname{div}(\lambda - a_{n-1})$.
   (c) Hence show that $p = (\lambda - a_{n-1})q + p \bmod (\lambda - a_{n-1}) = (\lambda - a_{n-1})q$.
   (d) For $i \in [0 : n - 1]$, do the following:
      i. Show that 0
         A. $= \Lambda(p, a_i)$
         B. $= \Lambda((\lambda - a_{n-1})q, a_i)$
         C. $= \Lambda(\lambda - a_{n-1}, a_i)\Lambda(q, a_i)$
         D. $= (a_i - a_{n-1})\Lambda(q, a_i)$.
      ii. Hence show that $\Lambda(q, a_i) = 0$ given that $a_i - a_{n-1} \neq 0$.
   (e) Hence use procedure II:103 on $\langle q, a_{[0:n-1]}\rangle$ to show that $q = q_{\deg(q)} \prod_j^{[0:n-1]}(\lambda - a_j)$.
   (f) Now show that $p_{\deg(p)} = (\lambda - a_{n-1})_{\deg(\lambda - a_{n-1})} q_{\deg q} = 1 q_{\deg q} = q_{\deg q}$ using procedure II:94 given that $p = (\lambda - a_{n-1})q$.
   (g) **Hence show that** $p = (\lambda - a_{n-1})q = q_{\deg q}(\lambda - a_{n-1}) \prod_j^{[0:n-1]}(\lambda - a_j) = p_{\deg p} \prod_j^{[0:n]}(\lambda - a_j)$**.**

Procedure II:104(2.16)

Objective

Choose a polynomial $p \neq 0$ and rational numbers $a_0 < a_1 < \cdots < a_{\deg(p)-1} < a_{\deg(p)}$ in such a way that $\Lambda(p, a_i) = 0$ for $i \in [0 : \deg(p) + 1]$. The objective of the following instructions is to show that $0 \neq 0$.

Implementation

1. Let $n = \deg(p)$.
2. Use procedure II:103 on $\langle p, a_{[0:n]}\rangle$ to show that $p = p_n \prod_j^{[0:n]}(\lambda - a_j)$.
3. Hence show that $\Lambda(p, a_n) = \Lambda(q_0 \prod_j^{[0:n]}(\lambda - a_j), a_n) = \Lambda(q_0, a_n) \prod_j^{[0:n]} \Lambda(\lambda - a_j, a_n) = q_0 \prod_j^{[0:n]}(a_n - a_j) \neq 0$.
4. Hence show that $0 = \Lambda(p, a_n) \neq 0$ given that $\Lambda(p, a_n) = 0$.
5. **Abort procedure.**

Procedure II:105(thu2001191149)

Objective

Choose a polynomial p and a rational number X. The objective of the following instructions is to construct a rational number a and a procedure $q(y)$ to show that $\|\Lambda(p,y)\| \leq a$ when a rational number y such that $\|y\| \leq X$ is chosen.

Implementation

1. Let $a = \sum_r^{[0:|p|]} \|p_r\| X^r$.
2. Let $q(y)$ be the following procedure:
   (a) Given that $\|y\| \leq X$, show that $\|\Lambda(p,y)\|$
      i. $= \|\sum_r^{[0:|p|]} p_r y^r\|$
      ii. $\leq \sum_r^{[0:|p|]} \|p_r y^r\|$
      iii. $= \sum_r^{[0:|p|]} \|p_r\| \|y\|^r$
      iv. $\leq \sum_r^{[0:|p|]} \|p_r\| X^r$
      v. $= a$.
3. **Yield the tuple $\langle a, q\rangle$.**

Procedure II:106(2.15)

Objective

Choose a polynomial p and a rational number X. The objective of the following instructions is to construct a rational number a and a procedure $q(z)$ to show that $\|\mathrm{im}(\Lambda(p,z))\| \leq a\|\mathrm{im}(z)\|$ when a proper perplex number z such that $z \subseteq Xj$ are chosen.

Implementation

1. Let $a = \sum_r^{[1:|p|]} r\|p_r\| X^{r-1}$.
2. Let $q(y,z)$ be the following procedure:
   (a) Show that $\|\mathrm{im}(\Lambda(p,z))\|$
      i. $= \|\mathrm{im}(\sum_r^{[0:|p|]} p_r z^r)\|$
      ii. $= \|\mathrm{im}(\sum_r^{[0:|p|]} p_r((\mathrm{re}(z) - \mathrm{im}(z))(k)^- + (\mathrm{re}(z) + \mathrm{im}(z))k)^r)\|$
      iii. $= \|\sum_r^{[0:|p|]} p_r \,\mathrm{im}((\mathrm{re}(z) - \mathrm{im}(z))^r(k)^- + (\mathrm{re}(z) + \mathrm{im}(z))^r k)\|$
      iv. $= \|\frac{1}{2} \sum_r^{[0:|p|]} p_r((\mathrm{re}(z) + \mathrm{im}(z))^r - (\mathrm{re}(z) - \mathrm{im}(z))^r)\|$
      v. $= \|\sum_r^{[1:|p|]} p_r \,\mathrm{im}(z) \sum_t^{[0:r]} (\mathrm{re}(z) + \mathrm{im}(z))^t (\mathrm{re}(z) - \mathrm{im}(z))^{r-1-t}\|$
      vi. $\leq \sum_r^{[1:|p|]} \|p_r\| \|\mathrm{im}(z)\| \|\sum_t^{[0:r]} (\mathrm{re}(z) + \mathrm{im}(z))^t (\mathrm{re}(z) - \mathrm{im}(z))^{r-1-t}\|$
      vii. $\leq \sum_r^{[1:|p|]} \|p_r\| \|\mathrm{im}(z)\| \sum_t^{[0:r]} \|(\mathrm{re}(z) + \mathrm{im}(z))^t\| \|(\mathrm{re}(z) - \mathrm{im}(z))^{r-1-t}\|$
      viii. $\leq \sum_r^{[1:|p|]} \|p_r\| \|\mathrm{im}(z)\| \sum_t^{[0:r]} X^t X^{r-1-t}$
      ix. $= \|\mathrm{im}(z)\| \sum_r^{[1:|p|]} \|p_r\| \sum_t^{[0:r]} X^{r-1}$
      x. $= \|\mathrm{im}(z)\| \sum_r^{[1:|p|]} r\|p_r\| X^{r-1}$
      xi. $= a\|\mathrm{im}(z)\|$
3. **Yield the tuple $\langle a, q\rangle$.**

Procedure II:107(thu3001201111)

Objective

Choose a polynomial p and a rational number X. The objective of the following instructions is to construct a rational number $a > 0$ and a procedure $q(z)$ to show that $\|\Lambda(p, \mathrm{re}(z) \pm \mathrm{im}(z))\| \leq a\|\mathrm{im}(z)\|$ when a proper perplex number z such that $z \subseteq Xj$, and $\|\Lambda(p,z)\|^2 \leq 0$ are chosen.

Implementation

1. Use procedure II:106 on $\langle p, X\rangle$ to construct $\langle a_1, q_1\rangle$.
2. Let $a = 2a_1$.
3. Let $q(y,z)$ be the following procedure:
   (a) Show that $\|\mathrm{im}(\Lambda(p,z))\| \leq a_1\|\mathrm{im}(z)\|$ using procedure q_1.
   (b) Show that $\Lambda(p, \mathrm{re}(z) + \mathrm{im}(z))\Lambda(p, \mathrm{re}(z) - \mathrm{im}(z)) = \|\Lambda(p,z)\|^2 \leq 0$ using procedure II:100.
   (c) Hence using procedure II:26 show that $\|\Lambda(p, \mathrm{re}(z) \pm \mathrm{im}(z))\|$
      i. $\leq \|\Lambda(p, \mathrm{re}(z) + \mathrm{im}(z))\| + \|\Lambda(p, \mathrm{re}(z) - \mathrm{im}(z))\|$
      ii. $= \|\Lambda(p, \mathrm{re}(z) + \mathrm{im}(z)) - \Lambda(p, \mathrm{re}(z) - \mathrm{im}(z))\|$
      iii. $= 2\|\mathrm{im}(\Lambda(p,z))\|$
      iv. $\leq 2a_1\|\mathrm{im}(z)\|$
      v. $\leq a\|\mathrm{im}(z)\|$.

4. **Yield the tuple $\langle a, q\rangle$.**

Procedure II:108(sat0102201050)

Objective

Choose a polynomial f, a proper perplex number c, and a rational number B such that $\|\Lambda(f, c)\|^2 \leq 0$ and $B > 0$. The objective of the following instructions is to construct a proper perplex number e such that $e \subseteq c$, $\mathrm{im}(e) < B$ and $\|\Lambda(f, e)\|^2 \leq 0$.

Implementation

1. If $\|\mathrm{im}(c)\| < B$, then do the following:
   (a) **Yield the tuple $\langle c\rangle$.**
2. Otherwise do the following:
   (a) Let $g = (\mathrm{re}(c) - \mathrm{im}(c))(k)^{-} + \mathrm{re}(c)k$ and show that $g \subseteq c$ and $\|\mathrm{im}(g)\| = \frac{1}{2}\|\mathrm{im}(c)\|$.
   (b) Let $m = \mathrm{re}(c)(k)^{-} + (\mathrm{re}(c) + \mathrm{im}(c))k$ and show that $m \subseteq c$ and $\|\mathrm{im}(m)\| = \frac{1}{2}\|\mathrm{im}(c)\|$.
   (c) Show that $\mathrm{re}(c) - \mathrm{im}(c) = \mathrm{re}(g) - \mathrm{im}(g)$, $\mathrm{re}(g) + \mathrm{im}(g) = \mathrm{re}(m) - \mathrm{im}(m)$, and $\mathrm{re}(m) + \mathrm{im}(m) = \mathrm{re}(c) + \mathrm{im}(c)$.
   (d) If $\|\Lambda(f, g)\|^2 \leq 0$, then do the following:
      i. Use procedure II:108 on $\langle f, g, B\rangle$ to construct $\langle e, h\rangle$ and show that:
         A. $e \subseteq g \subseteq c$
         B. $\|\mathrm{im}(e)\| < B$
         C. $\|\Lambda(f, e)\|^2 \leq 0$.
   (e) Otherwise do the following:
      i. Given that $\|\Lambda(f, c)\|^2 \leq 0$ and $\|\Lambda(f, g)\|^2 > 0$, show that $\|\Lambda(f, m)\|^2$
         A. $= \Lambda(f, \mathrm{re}(m) - \mathrm{im}(m))\Lambda(f, \mathrm{re}(m) + \mathrm{im}(m))$
         B. $= \frac{\Lambda(f, \mathrm{re}(m) - \mathrm{im}(m))}{\Lambda(f, \mathrm{re}(g) - \mathrm{im}(g))}\Lambda(f, \mathrm{re}(g) - \mathrm{im}(g))\Lambda(f, \mathrm{re}(m) + \mathrm{im}(m))$
         C. $= \frac{\Lambda(f, \mathrm{re}(g) + \mathrm{im}(g))}{\Lambda(f, \mathrm{re}(g) - \mathrm{im}(g))}\|\Lambda(f, c)\|^2$
         D. ≤ 0.
      ii. Hence use procedure II:108 on $\langle f, m, B\rangle$ to construct $\langle e\rangle$ and show that:
         A. $e \subseteq m \subseteq c$
         B. $\|\mathrm{im}(e)\| < B$
         C. $\|\Lambda(f, e)\|^2 \leq 0$.
   (f) **Yield the tuple $\langle e\rangle$.**

Procedure II:109(2.17)

Objective

Choose a polynomial f, a proper perplex number a, and a rational number B such that $\|\Lambda(f, a)\|^2 \leq 0$ and $B > 0$. The objective of the following instructions is to construct a proper perplex number d such that $d \subseteq a$, $\|\Lambda(f, d)\|^2 \leq 0$, and $\|\mathrm{im}(\Lambda(f, d))\| < B$.

Implementation

1. Use procedure II:106 on $\langle f, \|\mathrm{re}(a)\| + \|\mathrm{im}(b)\|\rangle$ to construct $\langle G, q\rangle$.
2. Use procedure II:108 on $\langle f, a, \frac{B}{G}\rangle$ to construct $\langle c\rangle$ and show that:
   (a) $c \subseteq a$
   (b) $\|\mathrm{im}(c)\| \leq \frac{B}{G}$
   (c) $\|\Lambda(f, c)\|^2 \leq 0$.
3. **Use procedure q on $\langle c\rangle$ to show that $\|\mathrm{im}(\Lambda(f, c))\| \leq G\|\mathrm{im}(c)\| \leq G\frac{B}{G} = B$.**
4. **Yield the tuple $\langle c\rangle$.**

Declaration II:45(tue2502201328)

The notation $\mu_p(x)$, where x is a perplex number and p is a perplex polynomial, will be used as a shorthand for x if $\mathrm{im}(\Lambda(p, x)) > 0$ and $(x)^{-}$ if $\mathrm{im}(\Lambda(p, x)) < 0$.

Procedure II:110(tue2502201349)

Objective

Choose a perplex polynomial p and an increasing list of pairwise disjoint proper perplex numbers r such that $|r| = \deg(p)$ and $-\Lambda(p, r_i) \sim \pm j \sim \Lambda(p, (r_i)^{-})$ for $0 < i < |r|$. The objective of the following instructions is to construct a list of perplex numbers t such that $|t| = |r|$ and $\mu_\lambda(t_i) \subseteq r_i$ for $0 < i < |r|$, and a procedure $q(x)$ to show that $\Lambda(p, x) \supseteq p_{|t|}\prod_m^{[0:|t|]}(x - (t_m)^{\pm})$ when a perplex number x that is disjoint from r is chosen.

Implementation

1) If $\deg(p) = 0$, then do the following:
   a) Let $t = \langle\rangle$.
   b) Let $q(x)$ be the following procedure:
      i) Show that $\Lambda(p, x)$
      (1) $= p_0$
      (2) $\supseteq p_{|t|} \prod_m^{[0:|t|]}(x - (t_m)^{\pm})$.
   c) **Yield the tuple** $\langle t, q\rangle$**.**
2) Otherwise do the following:
   a) Let $z = \max(\Lambda(p, \mu_p(r))(k)^-) + \min(\Lambda(p, \mu_p(r))k)$.
   b) Let $y = \min(-(\mathrm{re}(z) - \mathrm{im}(z)), \mathrm{re}(z) + \mathrm{im}(z))$.
   c) Use procedure II:109 on $\langle p, r_0, \frac{1}{2}y\rangle$ to construct t_0 and show that:
      i) t_0 is a proper perplex number
      ii) $t_0 \subseteq r_0$
      iii) $\|\Lambda(p, t_0)\|^2 \leq 0$
      iv) $\|\mathrm{im}(\Lambda(p, t_0))\| < \frac{1}{2}y$.
   d) Hence show that $\Lambda(p, \mu_p(t_0)) \subseteq yj \subseteq z$.
   e) Let $d = \sum_m^{[0:|r|+1]} p_m \sum_n^{[0:m]} \lambda^n {t_0}^{m-1-n}$.
   f) For i in $[1 : |r|]$, do the following:
      i) Show that $\Lambda(p, \mu_p(t_0)) \subseteq z \subseteq \Lambda(p, \mu_p(r_i))$.
      ii) Hence show that $-(r_i - t_0)\Lambda(d, r_i)$
      (1) $= -\Lambda(\lambda - t_0, r_i)\Lambda(d, r_i)$
      (2) $= -\Lambda((\lambda - t_0)d, r_i)$
      (3) $= -(\Lambda(p, r_i) - \Lambda(p, t_0))$
      (4) $\sim -\Lambda(p, r_i)$
      (5) $\sim \pm j$
      (6) $\sim \Lambda(p, (r_i)^-)$
      (7) $\sim \Lambda(p, (r_i)^-) - \Lambda(p, t_0)$
      (8) $= \Lambda((\lambda - t_0)d, (r_i)^-)$
      (9) $= \Lambda(\lambda - t_0, (r_i)^-)\Lambda(d, (r_i)^-)$
      (10) $= ((r_i)^- - t_0)\Lambda(d, (r_i)^-)$
      iii) Hence show that $-\Lambda(d, r_i) \sim \pm j \sim \Lambda(d, (r_i)^-)$
      (1) given that $r_i - t_0 > 0$
      (2) and $(r_i)^- - t_0 > 0$.
   g) Use procedure II:110 on $\langle d, r_{[1:|r|]}\rangle$ to construct $\langle t_{[1:|r|]}, u\rangle$.
   h) Use procedure II:111 on $\langle d, r_{[1:|r|]}\rangle$ to construct $\langle t_{[1:|r|]}, w\rangle$.
   i) Let $q(x)$ be the following procedure:
      i) If $x > \mu_p(t_0)$, then do the following:
      (1) Using procedure u, show that $\Lambda(d, x)$
         (a) $\supseteq d_{|t|-1} \prod_m^{[1:|t|]}(x - (t_m)^{\pm})$
         (b) $= p_{|t|} \prod_m^{[1:|t|]}(x - (t_m)^{\pm})$.
      (2) Given that $x - \mu_p(t_0) > 0$, show that $\Lambda(p, x)$
         (a) $= \Lambda((\lambda - \mu_p(t_0))d, x) + \Lambda(p, \mu_p(t_0))$
         (b) $\supseteq \Lambda((\lambda - \mu_p(t_0))d, x)$
         (c) $= (x - \mu_p(t_0))\Lambda(d, x)$
         (d) $\supseteq (x - \mu_p(t_0))p_{|t|} \prod_m^{[1:|t|]}(x - (t_m)^{\pm})$
         (e) $= p_{|t|} \prod_m^{[0:|t|]}(x - (t_m)^{\pm})$.
      ii) Otherwise if $x < \mu_p(t_0)$, then do the following:
      (1) Using procedure w, show that $\Lambda(d, x)$
         (a) $\subseteq d_{|t|-1} \prod_m^{[1:|t|]}(x - (t_m)^{\pm})$
         (b) $= p_{|t|} \prod_m^{[1:|t|]}(x - (t_m)^{\pm})$.
      (2) Given that $x - \mu_p(t_0) < 0$, show that $\Lambda(p, x)$
         (a) $= \Lambda((\lambda - \mu_p(t_0))d, x) + \Lambda(p, \mu_p(t_0))$
         (b) $\supseteq \Lambda((\lambda - \mu_p(t_0))d, x)$
         (c) $= (x - \mu_p(t_0))\Lambda(d, x)$
         (d) $\supseteq (x - \mu_p(t_0))p_{|t|} \prod_m^{[1:|t|]}(x - (t_m)^{\pm})$
         (e) $= p_{|t|} \prod_m^{[0:|t|]}(x - (t_m)^{\pm})$.
   j) **Yield the tuple** $\langle t, q\rangle$**.**

Procedure II:111(thu2702201419)

Objective

Choose a perplex polynomial p and an increasing list of pairwise disjoint proper perplex numbers r such that $|r| = \deg(p)$ and $-\Lambda(p, r_i) \sim \pm j \sim \Lambda(p, (r_i)^-)$ for $0 < i < |r|$. The objective of the following instructions is to construct a list of perplex numbers t such that $|t| = |r|$ and $\mu_\lambda(t_i) \subseteq r_i$ for $0 < i < |r|$, and a procedure $q(x)$ to show that $\Lambda(p, x) \subseteq p_{|t|} \prod_m^{[0:|t|]}(x - (t_m)^\pm)$ when a perplex number x that is disjoint from r is chosen.

Implementation

Implementation is analogous to that of procedure II:110.

Procedure II:112(2.18)

Objective

Choose a polynomial $f \neq 0$ and pairs of rational numbers $(a_{\deg(f)}, b_{\deg(f)}), (a_{\deg(f)-1}, b_{\deg(f)-1}), \cdots, (a_0, b_0)$ in such a way that:

1. $a_{\deg(f)} < b_{\deg(f)} \leq a_{\deg(f)-1} < b_{\deg(f)-1} \leq \cdots \leq a_1 < b_1 \leq a_0 < b_0$.
2. $\operatorname{sgn}(\Lambda(f, a_i)) = -\operatorname{sgn}(\Lambda(f, b_i))$ for $i \in [0 : \deg(f) + 1]$.

The objective of the following instructions is to show that $1 = -1$.

Implementation

1. If $\deg(f) > 0$:
   (a) Let $B = \min_k^{[0:\deg(f)-1]} \min(|\Lambda(f, a_k)|, |\Lambda(f, b_k)|)$.
   (b) For $k \in [0 : \deg(f)]$, verify that $|\Lambda(f, a_k)| \geq B$.
   (c) Execute procedure II:109 on the formal polynomial f, interval $(a_{\deg(f)}, b_{\deg(f)})$, and target of B. Let the tuple $\langle d \rangle$ receive the result.
   (d) Verify that $|\Lambda(f, d)| < B$.
   (e) Let $h = f \operatorname{div}(\lambda - d)$.
   (f) Execute procedure II:97 on $\langle f, d \rangle$.
   (g) Hence verify that $f = (\lambda - d)h + f \bmod (\lambda - d) = (\lambda - d)h + \Lambda(f, d)$.
   (h) Hence verify that $0 \neq f - \Lambda(f, d) = (\lambda - d)h$.
   (i) Hence verify that $h \neq 0$.
   (j) Hence verify that $\deg(f) = \deg(f - \Lambda(f, d)) = \deg((\lambda - d)h) = \deg(\lambda - d) + \deg(h) = 1 + \deg(h)$.
   (k) Hence verify that $\deg(h) = \deg(f) - 1$.
   (l) For $k \in [0 : \deg(h) + 1]$, do the following:
      i. If $\Lambda(f, a_k) \geq B$, in-order verify that:
         A. $\Lambda(f, a_k) \geq B > |\Lambda(f, d)| \geq \Lambda(f, d)$.
         B. $\Lambda(f, a_k) - \Lambda(f, d) > 0$.
         C. $(a_k - d)\Lambda(h, a_k) > 0$.
         D. $\Lambda(h, a_k) > 0$**.**
         E. $\Lambda(f, b_k) \leq -B < -|\Lambda(f, d)| \leq \Lambda(f, d)$.
         F. $\Lambda(f, b_k) - \Lambda(f, d) < 0$.
         G. $(b_k - d)\Lambda(h, b_k) < 0$.
         H. $\Lambda(h, b_k) < 0$**.**
      ii. Otherwise, if $\Lambda(f, a_k) \leq -B$, do the following:
         A. **Using steps analogous to (ji), verify that $\Lambda(h, a_k) < 0$.**
         B. **Using steps analogous to (ji), verify that $\Lambda(h, b_k) > 0$.**
   (m) Execute procedure II:112 on h and $a_{\deg(h)} < b_{\deg(h)} \leq a_{\deg(h)-1} < b_{\deg(h)-1} \leq \cdots \leq a_1 < b_1 \leq a_0 < b_0$.
2. Otherwise, do the following:
   (a) Verify that $\deg(f) = 0$.
   (b) Therefore verify that $f = f_0 \neq 0$.
   (c) Therefore verify that $\operatorname{sgn}(f_0) = \operatorname{sgn}(\Lambda(f, a_0)) = -\operatorname{sgn}(\Lambda(f, b_0)) = -\operatorname{sgn}(f_0)$.
   (d) **Therefore verify that $1 = -1$.**
   (e) **Abort procedure.**

Procedure II:113(2.19)

Objective

Choose two lists of polynomials s, q in such a way that:

1. $|s| > 1$.

2. For i in $[0:|s|]$, $\deg(s_i) = i$.
3. For i in $[0:|s|]$, $\operatorname{sgn}((s_i)_i) = \operatorname{sgn}((s_m)_m)$.
4. For i in $[1:|s|-1]$, $s_{i-1} + s_{i+1} = q_i s_i$.

The objective of the following instructions is to construct lists of polynomials g, h such that $g_i s_{i+1} + h_i s_i = 1$ for i in $[0:|s|-1]$.

Implementation

1. Let $m = |s| - 1$
2. Let $g = h = \langle\rangle$.
3. If $m > 1$, do the following:
   (a) Verify that $q_{m-1}s_{m-1} - s_m = s_{m-2}$.
   (b) Execute procedure II:113 on $s_{[0:m]}$ and $q_{[1:m-1]}$ and let the tuple $\langle , , g, h\rangle$ receive.
   (c) Verify that $g_{m-2}s_{m-1} + h_{m-2}s_{m-2} = 1$.
   (d) Let $g_{m-1} = -h_{m-2}$.
   (e) Let $h_{m-1} = g_{m-2} + h_{m-2}q_{m-1}$.
   (f) Therefore verify that $g_{m-1}s_m + h_{m-1}s_{m-1}$
      i. $= g_{m-2}s_{m-1} + h_{m-2}(q_{m-1}s_{m-1} - s_m)$
      ii. $= g_{m-2}s_{m-1} + h_{m-2}s_{m-2}$
      iii. $= 1$.
4. Otherwise, if $m = 1$ do the following:
   (a) Let $g_0 = 0$.
   (b) Let $h_0 = \frac{1}{s_0}$.
   (c) **Therefore verify that** $g_0 s_1 + h_0 s_0 = 1$**.**
5. **Yield the tuple** $\langle s, q, g, h\rangle$**.**

Procedure II:114(fri3101200641)

Objective

Choose polynomials g, h, p, q and a rational number X such that $gp+hq = 1$. The objective of the following instructions is to construct a rational numbers a and a procedure $r(y,z)$ to show that $\Lambda(p,y)\Lambda(p,z) > 0$ when two rational numbers y, z such that $\|y\| \le X$, $\|z\| \le X$, $\|y - z\| \le a$, and $\Lambda(q,y)\Lambda(q,z) \le 0$ are chosen.

Implementation

1. Use procedure II:107 on $\langle p, X\rangle$ to construct $\langle a_1, r_1\rangle$.
2. Use procedure II:107 on $\langle q, X\rangle$ to construct $\langle a_2, r_2\rangle$.
3. Use procedure II:105 on $\langle g, X\rangle$ to construct $\langle a_3, r_3\rangle$.
4. Use procedure II:105 on $\langle h, X\rangle$ to construct $\langle a_4, r_4\rangle$.
5. Let $a = \frac{1}{a_1a_3 + a_2a_4 + 1}$.
6. Let $r(y, z)$ be the following procedure:
   (a) If $\Lambda(p,y)\Lambda(p,z) \le 0$, then do the following:
      i. Show that $\|\Lambda(p,y)\| \le a_1\|z - y\| \le a_1 a$ using procedure r_1.
      ii. Show that $\|\Lambda(q,y)\| \le a_2\|z - y\| \le a_2 a$ using procedure r_2.
      iii. Show that $\|\Lambda(g,y)\| \le a_3$ using procedure r_3.
      iv. Show that $\|\Lambda(h,y)\| \le a_4$ using procedure r_4.
      v. Given that $gp + hq = 1$, show that $\Lambda(gp, y) + \Lambda(h,y)\Lambda(q,y)$
         A. $= \Lambda(gp + hq, y)$
         B. $= \Lambda(1, y)$
         C. $= 1$.
      vi. Hence show that $\Lambda(gp, y)$
         A. $= 1 - \Lambda(h,y)\Lambda(q,y)$
         B. $\ge 1 - a_4a_2a$
         C. $= \frac{a_1a_3+1}{a_1a_3+a_2a_4+1}$
         D. $= (a_1a_3 + 1)a$
         E. $> a_1a_3a$
         F. $\ge \|\Lambda(p,y)\|\|\Lambda(g,y)\|$
         G. $\ge \Lambda(p,y)\Lambda(g,y)$
         H. $= \Lambda(pg, y)$.
      vii. Hence show that $0 > 0$.
      viii. **Abort procedure.**
   (b) Otherwise do the following:

i. Show that $\Lambda(p,y)\Lambda(p,z) > 0$.

7. **Yield the tuple** $\langle a, r\rangle$**.**

Procedure II:115(fri3101200730)

Objective

Choose polynomials g, h, j, p, q, r and a rational number X such that $hq+jr = 1$ and $p+r = gq$. The objective of the following instructions is to construct a rational number a and a procedure $t(y,z)$ to show that $\Lambda(p,y)\Lambda(r,y) < 0$ and $\Lambda(j,y) \neq 0$ when two rational numbers y, z such that $\|y\| \leq X$, $\|z\| \leq X$, $\|y-z\| \leq a$, and $\Lambda(q,y)\Lambda(q,z) \leq 0$ are chosen.

Implementation

1. Use procedure II:105 on $\langle h, X\rangle$ to construct $\langle a_1, t_1\rangle$.
2. Use procedure II:105 on $\langle g, X\rangle$ to construct $\langle a_2, t_2\rangle$.
3. Use procedure II:105 on $\langle j, X\rangle$ to construct $\langle a_3, t_3\rangle$.
4. Use procedure II:107 on $\langle q, X\rangle$ to construct $\langle a_4, t_4\rangle$.
5. Let $a = \frac{1}{(a_1+a_2a_3)a_4+1}$.
6. Let $t(y,z)$ be the following procedure:

(a) Show that $\|\Lambda(h,y)\| \leq a_1$ using procedure t_1.

(b) Show that $\|\Lambda(g,y)\| \leq a_2$ using procedure t_2.

(c) Show that $\|\Lambda(j,y)\| \leq a_3$ using procedure t_3.

(d) Show that $\|\Lambda(q,y)\| \leq a_4\|z-y\| \leq a_4 a$ using procedure t_4.

(e) Show that $jr = 1-hq$ given that $hq+jr = 1$.

(f) Hence show that $\|\Lambda(j,y)\|\|\Lambda(r,y)\|$

i. $= \|\Lambda(jr,y)\|$

ii. $= \|\Lambda(1-hq,y)\|$

iii. $= \|\Lambda(1,y)\| - \|\Lambda(h,y)\Lambda(q,y)\|$

iv. $\geq 1 - a_1a_4\|y-z\|$

v. $= 1 - a_1a_4a$

vi. $= \frac{a_2a_3a_4+1}{(a_1+a_2a_3)a_4+1}$

vii. $= (a_2a_3a_4+1)a$

viii. $> a_2a_3a_4a$

ix. $\geq \|\Lambda(q,y)\|\|\Lambda(g,y)\|\|\Lambda(j,y)\|$

x. $\geq \|\Lambda(qg,y)\|\|\Lambda(j,y)\|$.

(g) Hence show that $\|\Lambda(r,y)\| > \|\Lambda(qg,y)\| \geq 0$

i. given that $\Lambda(j,y) \neq 0$

ii. given that $\|\Lambda(j,y)\|\|\Lambda(r,y)\| > \|\Lambda(qg,y)\|\|\Lambda(j,y)\|$.

(h) Show that $p = gq - r$ given that $p+r = gq$.

(i) If $\Lambda(r,y) > 0$, then do the following:

i. Show that $\Lambda(p,y)$

A. $= \Lambda(gq-r,y)$

B. $= \Lambda(gq,y) - \Lambda(r,y)$

C. $\leq \|\Lambda(gq,y)\| - \|\Lambda(r,y)\|$

D. < 0.

ii. **Hence show that** $\Lambda(p,y)\Lambda(r,y) < 0$**.**

(j) Otherwise do the following:

i. Given that $\Lambda(r,y) < 0$, show that $\Lambda(p,y)$

A. $= \Lambda(gq-r,y)$

B. $= \Lambda(gq,y) - \Lambda(r,y)$

C. $\geq -\|\Lambda(gq,y)\| + \|\Lambda(r,y)\|$

D. > 0.

ii. **Hence show that** $\Lambda(p,y)\Lambda(r,y) < 0$**.**

7. **Yield the tuple** $\langle a, t\rangle$**.**

Procedure II:116(fri3101200807)

Objective

Choose polynomials g, h, j, p, q, r and a rational number X such that $hq+jr = 1$ and $p+r = gq$. The objective of the following instructions is to construct a rational number a and a procedure $t(y,z)$ to show that $\Lambda(p,y)\Lambda(r,y) < 0$,$\Lambda(p,z)\Lambda(r,z) < 0$,$\Lambda(r,y)\Lambda(r,z) > 0$, and $\Lambda(p,y)\Lambda(p,z) > 0$ when two rational numbers y, z such that $\|y\| \leq X$, $\|z\| \leq X$, $\|y-z\| \leq a$, and $\Lambda(q,y)\Lambda(q,z) \leq 0$ are chosen.

Implementation

1. Use procedure II:115 on $\langle g, h, j, p, q, r, X\rangle$ to construct $\langle a_1, t_1\rangle$.
2. Use procedure II:114 on $\langle j, h, r, q, X\rangle$ to construct $\langle a_2, t_2\rangle$.
3. Show that $(j + jg)q + (-j)p = 1$ given that $hq + jr = 1$ and $r = gq - p$.
4. Use procedure II:114 on $\langle -j, h+jg, p, q, X\rangle$ to construct $\langle a_3, t_3\rangle$.
5. Let $a = \min(a_1, a_2, a_3)$.
6. Let $t(y, z)$ be the following procedure:
   (a) **Show that** $\Lambda(p, y)\Lambda(r, y) < 0$ **using procedure** t_1**.**
   (b) **Show that** $\Lambda(r, y)\Lambda(r, z) > 0$ **using procedure** t_2**.**
   (c) **Show that** $\Lambda(p, y)\Lambda(p, z) > 0$ **using procedure** t_3**.**
   (d) **Hence show that** $\Lambda(p, z)\Lambda(r, z) = \frac{\Lambda(p,z)}{\Lambda(p,y)} \cdot \frac{\Lambda(r,z)}{\Lambda(r,y)}\Lambda(p, y)\Lambda(r, y) < 0$**.**
7. **Yield the tuple** $\langle a, t\rangle$**.**

Declaration II:46(2.10)

The notation $J_s(x)$, where s is a list of polynomials and x is a rational number, will be used as a shorthand for the number of changes observed when the list $H(\Lambda(s, x))$ is iterated through in order.

Procedure II:117(fri3101200839)

Objective

Choose polynomials g, h, j, p, q, r and a rational number X such that $hq + jr = 1$ and $p + r = gq$. The objective of the following instructions is to construct a rational number a and a procedure $t(y, z)$ to show that $J_{\langle p,q,r\rangle}(y) = J_{\langle p,q,r\rangle}(z) = 1$ when two rational numbers y, z such that $\|y\| \le X$, $\|z\| \le X$, $\|y - z\| \le a$, and $\Lambda(q, y)\Lambda(q, z) \le 0$ are chosen.

Implementation

1. Use procedure II:116 on $\langle g, h, j, p, q, r, X\rangle$ to construct $\langle a, t_1\rangle$.
2. Let $t(y, z)$ be the following procedure:
   (a) Use procedure t_1 to show that:
      i. $\Lambda(p, y)\Lambda(r, y) < 0$
      ii. $\Lambda(r, y)\Lambda(r, z) > 0$
      iii. $\Lambda(p, y)\Lambda(p, z) > 0$
      iv. $\Lambda(p, z)\Lambda(r, z) < 0$.
   (b) Now show that $H(\Lambda(p, y)) \le H(\Lambda(q, y)) \le H(\Lambda(r, y))$ or $H(\Lambda(r, y)) \le H(\Lambda(q, y)) \le H(\Lambda(p, y))$ given that $\Lambda(p, y)\Lambda(r, y) < 0$.
   (c) Hence using procedure II:26, show that $J_{\langle p,q,r\rangle}(y)$
      i. $= \|H(\Lambda(q, y))-H(\Lambda(p, y))\|+\|H(\Lambda(r, y))-H(\Lambda(q, y))\|$
      ii. $= \|H(\Lambda(r, y)) - H(\Lambda(p, y))\|$
      iii. $= 1$.
   (d) Also show that $H(\Lambda(p, z)) \le H(\Lambda(q, z)) \le H(\Lambda(r, z))$ or $H(\Lambda(r, z)) \le H(\Lambda(q, z)) \le H(\Lambda(p, z))$ given that $\Lambda(p, z)\Lambda(r, z) < 0$.
   (e) Hence using procedure II:26, show that $J_{\langle p,q,r\rangle}(z)$
      i. $= \|H(\Lambda(q, z))-H(\Lambda(p, z))\|+\|H(\Lambda(r, z))-H(\Lambda(q, z))\|$
      ii. $= \|H(\Lambda(r, z)) - H(\Lambda(p, z))\|$
      iii. $= 1$.
   (f) **Hence show that** $J_{\langle p,q,r\rangle}(y) = 1 = J_{\langle p,q,r\rangle}(z)$**.**
3. **Yield the tuple** $\langle a, t\rangle$**.**

Procedure II:118(fri3101201221)

Objective

Choose a list of polynomials s, a rational number r, and a natural number k such that $k < |s|$. The objective of the following instructions is to show that $J_s(r) = J_{s_{[0:k+1]}}(r) + J_{s_{[k:|s|]}}(r)$.

Implementation

1. Show that $J_s(r)$
   (a) $= \sum_t^{[0:|s|-1]} \|H(\Lambda(s_{t+1}, r)) - H(\Lambda(s_t, r))\|$
   (b) $= \sum_t^{[0:k]} \|H(\Lambda(s_{t+1})) - H(\Lambda(s_t, r))\|$
   (c) $= \sum_t^{[k:|s|-1]} \|H(\Lambda(s_{t+1}, r)) - H(\Lambda(s_t, r))\|$
   (d) $= J_{s_{[0:k+1]}}(r) + J_{s_{[k:|s|]}}(r)$.

Declaration II:47(fri3101201236)

The phrase "Sturm chain" will be used as a shorthand for a non-empty list of polynomials s such that:

1. For i in $[0:|s|]$, $\deg(s_i) = i$.
2. For i in $[0:|s|-1]$, $\mathrm{sgn}((s_i)_i) = \mathrm{sgn}_((s_{i+1})_{i+1})$
3. For i in $[1:|s|-1]$, $s_{i-1} + s_{i+1} \bmod s_i = 0$.

Procedure II:119(fri3101201247)

Objective

Choose a Sturm chain s, and a natural number k such that $0 < k \leq |s|$. The objective of the following instructions is to show that $s_{[0:k]}$ is also a Sturm chain.

Implementation

1. For i in $[0:k]$, show that $\deg(s_i) = i$.
2. For i in $[0:k-1]$, show that $\mathrm{sgn}((s_i)_i) = \mathrm{sgn}((s_{i+1})_{i+1})$.
3. For i in $[1:k-1]$, show that $s_{i-1} + s_{i+1} \bmod s_i = 0$.
4. **Hence show that $s_{[0:k]}$ is a Sturm chain.**

Procedure II:120(2.20)

Objective

Choose a Sturm chain s and a rational number X. The objective of the following instructions is to construct a rational number l and a procedure $u(c,d)$ to show that either $0 < 0$ or $|\mathrm{J}_s(d) - \mathrm{J}_s(c)| = \|\mathrm{H}(\Lambda(s_{|s|-1}, c)) - \mathrm{H}(\Lambda(s_{|s|-1}, d))\|$, when rational numbers c, d such that $|c| \leq X$, $|d| \leq X$, and $|d-c| \leq l$ are chosen.

Implementation

1. If $|s| > 2$, then do the following:
   (a) Use procedure II:120 on $\langle s_{[0:|s|-2]}, X\rangle$ to construct $\langle l_1, u_1\rangle$.
   (b) Use procedure II:120 on $\langle s_{[0:|s|-1]}, X\rangle$ to construct $\langle l_2, u_2\rangle$.
   (c) Use procedure II:113 on $\langle s_{[0:|s|-1]}\rangle$ to construct $\langle g, h\rangle$ and show that $\langle gs_{|s|-2} + hs_{|s|-3} = 1$.
   (d) Use procedure II:116 on $\langle (s_{|s|-1} + s_{|s|-3}) \operatorname{div} s_{|s|-2}, g, h, s_{|s|-1}, s_{|s|-2}, s_{|s|-3}, X\rangle$ to construct $\langle a_4, u_4\rangle$.
   (e) Use procedure II:117 on $\langle (s_{|s|-1} + s_{|s|-3}) \operatorname{div} s_{|s|-2}, g, h, s_{|s|-1}, s_{|s|-2}, s_{|s|-3}, X\rangle$ to construct $\langle a_5, u_5\rangle$.
   (f) Let $l = \min(l_1, l_2, a_4, a_5)$.
2. Otherwise do the following:
   (a) Let $l = 1$.
3. Let $u(c,d)$ be the following procedure:
   (a) If $|s| = 1$, then do the following:
      i. Show that $\|\mathrm{J}_s(d) - \mathrm{J}_s(c)\|$
         A. $= \|\sum_r^{[0:|s|-1]} \|\mathrm{H}(\Lambda(s_{r+1}, d)) - \mathrm{H}(\Lambda(s_r, d))\| - \sum_r^{[0:|s|-1]} \|\mathrm{H}(\Lambda(s_{r+1}, c)) - \mathrm{H}(\Lambda(s_r, c))\|\|$
         B. $= \|0 - 0\|$
         C. $= \|\mathrm{H}((s_{|s|-1})_0) - \mathrm{H}((s_{|s|-1})_0)\|$
         D. $= \|\mathrm{H}(\Lambda(s_{|s|-1}, c)) - \mathrm{H}(\Lambda(s_{|s|-1}, d))\|$.
   (b) Otherwise if $|s| = 2$, then do the following:
      i. Show that $\|\mathrm{J}_s(d) - \mathrm{J}_s(c)\|$
         A. $= \|\sum_r^{[0:|s|-1]} \|\mathrm{H}(\Lambda(s_{r+1}, d)) - \mathrm{H}(\Lambda(s_r, d))\| - \sum_r^{[0:|s|-1]} \|\mathrm{H}(\Lambda(s_{r+1}, c)) - \mathrm{H}(\Lambda(s_r, c))\|\|$
         B. $= \|\|\mathrm{H}(\Lambda(s_1, d)) - \mathrm{H}(\Lambda(s_0, d))\| - \|\mathrm{H}(\Lambda(s_1, c)) - \mathrm{H}(\Lambda(s_0, c))\|\|$
         C. $= \|\|\mathrm{H}(\Lambda(s_1, d)) - \mathrm{H}((s_0)_0)\| - \|\mathrm{H}(\Lambda(s_1, c)) - \mathrm{H}((s_0)_0)\|\|$
         D. $= \|\mathrm{H}(\Lambda(s_1, d)) - \mathrm{H}(\Lambda(s_1, c))\|$.
   (c) Otherwise if $\mathrm{H}(\Lambda(s_{|s|-2}, c)) = \mathrm{H}(\Lambda(s_{|s|-2}, d))$, then do the following:
      i. Use procedure u_2 to show that $\|\mathrm{J}_{s_{[0:|s|-1]}}(d) - \mathrm{J}_{s_{[0:|s|-1]}}(c)$
         A. $= \|\mathrm{H}(\Lambda(s_{|s|-2}, c)) - \mathrm{H}(\Lambda(s_{|s|-2}, d))\|$
         B. $= 0$.
      ii. Hence show that $\|\mathrm{J}_s(d) - \mathrm{J}_s(c)\|$
         A. $= \|(\mathrm{J}_{s_{[0:|s|-1]}}(d) + \mathrm{J}_{s_{[||s|-2:|s|]}}(d)) - (\mathrm{J}_{s_{[0:|s|-1]}}(c) + \mathrm{J}_{s_{[||s|-2:|s|]}}(c))\|$
         B. $= \|\mathrm{J}_{s_{[|s|-2:|s|]}}(c) - \mathrm{J}_{s_{[|s|-2:|s|]}}(d)\|$

C. $= \|\|\mathrm{H}(\Lambda(s_{|s|-1}, c)) - \mathrm{H}(\Lambda(s_{|s|-2}, c))\| - \|\mathrm{H}(\Lambda(s_{|s|-1}, d)) - \mathrm{H}(\Lambda(s_{|s|-2}, d))\|\|$

D. $= \|\mathrm{H}(\Lambda(s_{|s|-1}, c)) - \mathrm{H}(\Lambda(s_{|s|-1}, d))\|$.

(d) Otherwise do the following:

i. Show that $\mathrm{H}(\Lambda(s_{|s|-2}, c)) \neq \mathrm{H}(\Lambda(s_{|s|-2}, d))$.

ii. Show that $\Lambda(s_{|s|-1}, c)\Lambda(s_{|s|-1}, d) > 0$ and $\Lambda(s_{|s|-3}, c)\Lambda(s_{|s|-3}, d) > 0$ using procedure u_4.

iii. Hence show that $\mathrm{H}(\Lambda(s_{|s|-1}, c)) = \mathrm{H}(\Lambda(s_{|s|-1}, d))$ and $\mathrm{H}(\Lambda(s_{|s|-3}, c)) = \mathrm{H}(\Lambda(s_{|s|-3}, d))$.

iv. Use procedure u_1 to show that $\|\mathrm{J}_{s_{[0:|s|-2]}}(d) - \mathrm{J}_{s_{[0:|s|-2]}}(c)\| = \|\mathrm{H}(\Lambda(s_{|s|-3}, d)) - \mathrm{H}(\Lambda(s_{|s|-3}, c))\| = 0$ given that $\mathrm{H}(\Lambda(s_{|s|-3}, c)) = \mathrm{H}(\Lambda(s_{|s|-3}, d))$.

v. Use procedure u_5 to show that $\mathrm{J}_{s_{[|s|-3:|s|]}}(c) = \mathrm{J}_{s_{[|s|-3:|s|]}}(d) = 1$ given that $\Lambda(s_{|s|-2}, c)\Lambda(s_{|s|-2}, d) < 0$.

vi. Hence given that $\mathrm{H}(\Lambda(s_{|s|-1}, c)) = \mathrm{H}(\Lambda(s_{|s|-1}, d))$ show that $\|\mathrm{J}_s(d) - \mathrm{J}_s(c)\|$

A. $= \|(\mathrm{J}_{s_{[0:|s|-2]}}(d) + \mathrm{J}_{s_{[|s|-3:|s|]}}(d)) - (\mathrm{J}_{s_{[0:|s|-2]}}(c) + \mathrm{J}_{s_{[|s|-3:|s|]}}(c))\|$

B. $= \|0 + (1 - 1)\|$

C. $= 0$

D. $= \|\mathrm{H}(\Lambda(s_{|s|-1}, d)) - \mathrm{H}(\Lambda(s_{|s|-1}, c))\|$.

4. **Yield the tuple $\langle l, u\rangle$.**

Procedure II:121(2.21)

Objective

Choose a polynomial $p \neq 0$. Choose a rational number $k > 1 + \max_i^{[0:\deg(p)]} |\frac{p_i}{p_{\deg(p)}}|$. The objective of the following instructions is to show that $\operatorname{sgn}(\Lambda(p, k)) = \operatorname{sgn}(p_{\deg(p)})$.

Implementation

1. Let $n = \deg(p)$.
2. In reverse order verify the following:

(a) $\operatorname{sgn}(\Lambda(p, k)) = \operatorname{sgn}(p_{\deg(p)})$

(b) $\operatorname{sgn}(p_n k^n + p_{n-1}k^{n-1} + \cdots + p_0 k^0) = \operatorname{sgn}(p_n)$

(c) $\operatorname{sgn}(k^n + \frac{p_{n-1}}{p_n}k^{n-1} + \cdots + \frac{p_0}{p_n}k^0) = 1$

(d) $k^n + \frac{p_{n-1}}{p_n}k^{n-1} + \cdots + \frac{p_0}{p_n}k^0 > 0$

(e) $k^n > -(\frac{p_{n-1}}{p_n}k^{n-1} + \cdots + \frac{p_0}{p_n}k^0)$

(f) $k^n > |\frac{p_{n-1}}{p_n}k^{n-1} + \cdots + \frac{p_0}{p_n}k^0|$

(g) $k^n > |\max_i^{[0:n]} |\frac{p_i}{p_n}|(k^{n-1} + \cdots + k^0)|$

(h) $k^n > \max_i^{[0:n]} |\frac{p_i}{p_n}| \frac{k^n - 1}{k - 1}$

(i) $k^{n+1} - k^n > \max_i^{[0:n]} |\frac{p_i}{p_n}|(k^n - 1)$

(j) $k^{n+1} - (1 + \max_i^{[0:n]} |\frac{p_i}{p_n}|)k^n + \max_i^{[0:n]} |\frac{p_i}{p_n}| > 0$

(k) $k > 1 + \max_i^{[0:n]} |\frac{p_i}{p_n}|$

Procedure II:122(2.22)

Objective

Choose a polynomial $p \neq 0$. Choose a rational number $k < -(1 + \max_i^{[0:\deg(p)]} |\frac{p_i}{p_{\deg(p)}}|)$. The objective of the following instructions is to show that $\operatorname{sgn}(\Lambda(p, k)) = (-1)^{\deg(p)} \operatorname{sgn}(p_{\deg(p)})$.

Implementation

1. Let $t = \deg(p)$.
2. Let $q = \langle (-1)^{t-i} p_i \text{ for } i \in [0 : t+1]\rangle$.
3. Verify that $k < -(1 + \max_i^{[1:t+1]} |\frac{q_i}{q_{\deg(q)}}|)$.
4. Therefore verify that $-k > 1 + \max_i^{[0:t]} |\frac{q_i}{q_{\deg(q)}}|$.
5. Execute procedure II:121 on $\langle q, -k\rangle$.
6. Hence verify that $(-1)^t \operatorname{sgn}(\Lambda(p, k))$

(a) $= \operatorname{sgn}((-1)^t \Lambda(p, k))$

(b) $= \operatorname{sgn}((-1)^t \sum_i^{[0:t+1]} p_i k^i)$

(c) $= \operatorname{sgn}(\sum_i^{[0:t+1]} (-1)^i (-1)^{t-i} p_i k^i)$

(d) $= \operatorname{sgn}(\sum_i^{[0:t+1]} q_i (-k)^i)$

(e) $= \operatorname{sgn}(\Lambda(q, -k))$

(f) $= \operatorname{sgn}(q_t)$

(g) $= \operatorname{sgn}(p_t)$.

7. **Therefore verify that $\operatorname{sgn}(\Lambda(p, k)) = (-1)^t(-1)^t \operatorname{sgn}(\Lambda(p, k)) = (-1)^t \operatorname{sgn}(p_t)$.**

Procedure II:123(2.23)

Objective

Choose a list of polynomials, s, and rational numbers a, l, c such that $a < c$ and $l > 0$. The objective of the following instructions is to either show that $0 < 0$ or to construct a list of rational numbers, b, such that $a = b_0 < b_1 < \cdots < b_{|b|-1} = c$, $b_i - b_{i-1} \le l$ for i in $[1 : |b|]$, and $0 \notin \Lambda(s, b_i)$ for i in $[1 : |b| - 1]$.

Implementation

1. Let $e = \langle\langle\rangle, \langle\rangle, \cdots, \langle\rangle\rangle$.
2. Let $f = \sum_r^{[0:|s|]} \deg(s_r)$.
3. Let $b = \langle a\rangle$.
4. Let $d = b_1$.
5. While $d + l < c$, do the following:
   (a) Let $m = l$.
   (b) While $0 \in \Lambda(s, d + m)$ and $\sum|e| \le f$, do the following:
      i. Let $0 \le i < |s|$ be an integer such that $\Lambda(s_i, d + m) = 0$.
      ii. Append $d + m$ onto e_i.
      iii. Set $m = \frac{m}{2}$
   (c) If $\sum|e| > f$, then do the following:
      i. If $|e_i| \le \deg(s_i)$ for $0 \le i < |s|$, then do the following:
         A. Verify that $\sum|e| \le f$.
         B. Therefore using (c), verify that $\sum|e| \le f < \sum|e|$.
         C. **Abort procedure.**
      ii. Otherwise, do the following:
         A. Let $0 \le i < |s|$ be an integer such that $|e_i| > \deg(s_i)$.
         B. Execute procedure II:104 on s_i and a sorted e_i.
         C. **Abort procedure.**
   (d) Otherwise, do the following:
      i. **Verify that** $0 \notin \Lambda(s, d + m)$**.**
      ii. Append $d + m$ onto b.
      iii. **Verify that** $0 < b_{|b|-1} - b_{|b|-2} = m \le l$**.**
      iv. Set d to $d + m$.
      v. Using (5), verify that $d < c$.
6. Verify that $d < c$.
7. Verify that $d + l \ge c$.
8. **Therefore verify that** $0 < c - d \le l$**.**
9. Append c onto b.
10. **Yield** $\langle b\rangle$**.**

Procedure II:124(2.24)

Objective

Execute procedure II:113 and let $\langle s, q, g, h\rangle$ receive. Let $m = |s| - 1$. The objective of the following instructions is to either show that $0 < 0$ or to construct two lists of rational numbers c, d such that $c_0 < d_0 \le c_1 < d_1 \le \cdots \le c_{m-1} < d_{m-1}$ and $0 \ne \operatorname{sgn}(\Lambda(s_m, c_i)) = -\operatorname{sgn}(\Lambda(s_m, d_i))$ for i in $[0 : m]$.

Implementation

1. Let $U = 1 + \max_i^{[0:|s|]} \left(1 + \max_j^{[1:i+1]} |\frac{(s_i)_{i-j}}{(s_i)_i}|\right)$
2. Using procedure II:121, verify that $J(U) = 0$.
3. Using procedure II:122, verify that $J(-U) = m$.
4. Execute procedure II:120 on the tuple $\langle s, q, U\rangle$ and let $\langle l, u\rangle$ receive.
5. Execute procedure II:123 on s with endpoints $-U, U$ and a step size of l and let $\langle e\rangle$ receive the result.
6. Let $c = d = \langle\rangle$.
7. For $i = 1$ to $i = |e| - 1$:
   (a) Execute procedure u on the tuple $\langle e_{i-1}, e_i\rangle$.
   (b) If $\mathrm{J}_m(e_{i-1}) \ne \mathrm{J}_m(e_i)$, then do the following:
      i. Append e_{i-1} to c.
      ii. Append e_i to d.
      iii. Verify that $0 \ne |\mathrm{J}_s(d_{|d|-1}) - \mathrm{J}_s(c_{|c|-1})| = [\operatorname{sgn}(\Lambda(s_{|s|-1}, c_{|c|-1})) \ne \operatorname{sgn}(\Lambda(s_{|s|-1}, d_{|d|-1}))]$.

iv. Therefore verify that $\operatorname{sgn}(s_m(c_{|c|-1})) \neq \operatorname{sgn}(s_m(d_{|d|-1}))$.

v. Therefore verify that $|J_m(d_{|d|-1}) - J_m(c_{|c|-1})| = 1$.

vi. Also verify that $0 \notin \Lambda(s, c_{|c|-1})$.

vii. Hence verify that $\Lambda(s_m, c_{|c|-1}) \neq 0$.

viii. Also verify that $0 \notin \Lambda(s, d_{|d|-1})$.

ix. Hence verify that $\Lambda(s_m, d_{|d|-1}) \neq 0$.

x. **Therefore verify that** $0 \neq \operatorname{sgn}(s_m(c_{|c|-1})) = -\operatorname{sgn}(s_m(d_{|d|-1}))$**.**

xi. **Also verify that** $d_{|d|-2} \leq c_{|c|-1} < d_{|d|-1}$**.**

8. If $|c| = |d| < m$, then do the following:

(a) Verify that each change of $J_m(x)$ over the course of (7) was by 1.

(b) Verify that $J_m(x)$ changed less than m times over the course of (12).

(c) Therefore verify that $|J_m(U) - J_m(-U)| < m$.

(d) Therefore using (2) and (3), verify that $m = |J_m(U) - J_m(-U)| < m$.

(e) **Abort procedure.**

9. Otherwise, do the following:

(a) **Verify that** $m \leq |c| = |d|$**.**

(b) **Yield the tuple** $\langle c, d \rangle$**.**

Procedure II:125(2.26)

Objective

Choose two lists of polynomials s, q and a non-negative integer k in such a way that, letting $m = |s| - 1$,

1. $k < m$.

2. For $k \leq i \leq m$, $\deg(s_i) = i$.

3. For $k < i < m$, $s_{i-1} + s_{i+1} = q_i s_i$.

Let $\deg(0) = -1$. The objective of the following instructions is to construct polynomials g, h such that $s_k = g s_{m-1} + h s_m$, $\deg(g) = m - 1 - k$, and $\deg(h) = m - 2 - k$.

Implementation

1. If $k < m - 2$, do the following:

(a) Verify that $s_k + s_{k+2} = q_{k+1} s_{k+1}$.

(b) Therefore verify that $s_k = q_{k+1} s_{k+1} - s_{k+2}$.

(c) Execute procedure II:125 on $s, q, k+1$ and let the tuple $\langle g_1, h_1 \rangle$ receive.

(d) Verify that $s_{k+1} = g_1 s_{m-1} + h_1 s_m$.

(e) Verify that $\deg(g_1) = m - 1 - (k+1) = m - k - 2$.

(f) Verify that $\deg(h_1) = m - 2 - (k+1) = m - k - 3$.

(g) Execute procedure II:125 on $s, q, k+2$ and let the tuple $\langle g_2, h_2 \rangle$ receive.

(h) Verify that $s_{k+2} = g_2 s_{m-1} + h_2 s_m$.

(i) Verify that $\deg(g_2) = m - 1 - (k+2) = m - k - 3$.

(j) Verify that $\deg(h_2) = m - 2 - (k+2) = m - k - 4$.

(k) Let $g = q_{k+1} g_1 - g_2$.

(l) **Verify that** $\deg(g) = \max(1 + (m-k-2), m-k-3) = m - 1 - k$**.**

(m) Let $h = q_{k+1} h_1 - h_2$.

(n) **Verify that** $\deg(h) = \max(1 + (m-k-3), m-k-4) = m - 2 - k$**.**

(o) **Verify that** $s_k = q_{k+1}(g_1 s_{m-1} + h_1 s_m) - (g_2 s_{m-1} + h_2 s_m) = (q_{k+1} g_1 - g_2) s_{m-1} + (q_{k+1} h_1 - h_2) s_m = g s_{m-1} + h s_m$**.**

2. Otherwise, if $k = m - 2$ do the following:

(a) Verify that $s_{m-2} + s_m = q_{m-1} s_{m-1}$.

(b) Let $g = q_{m-1}$.

(c) **Verify that** $\deg(g) = 1 = m - 1 - k$**.**

(d) Let $h = -1$.

(e) **Verify that** $\deg(h) = 0 = m - 2 - k$**.**

(f) **Therefore verify that** $s_k = s_{m-2} = q_{m-1} s_{m-1} - s_m = g s_{m-1} + h s_m$**.**

3. Otherwise, if $k = m - 1$ do the following:

(a) Let $g = 1$.

(b) **Verify that** $\deg(g) = 0 = m - 1 - k$**.**

(c) Let $h = 0$.

(d) **Verify that** $\deg(h) = -1 = m - 2 - k$**.**

(e) **Verify that** $s_k = s_{m-1} = gs_{m-1} + hs_m$**.**

4. **Yield the tuple** $\langle g, h \rangle$**.**

Part III

Complex Arithmetic

Chapter 9

Complex Arithmetic

Declaration III:0(3.19)

The phrase "complex number" will be used as a shorthand for an ordered pair of rational numbers.

Declaration III:1(3.20)

The phrase "the real part of a" and the notation $\mathrm{re}(a)$, where a is a complex number, will be used as a shorthand for the first entry of a.

Declaration III:2(3.21)

The phrase "the imaginary part of a" and the notation $\mathrm{im}(a)$, where a is a complex number, will be used as a shorthand for the second entry of a.

Declaration III:3(3.22)

The phrase "$a = b$", where a, b are complex numbers, will be used as a shorthand for "$\mathrm{re}(a) = \mathrm{re}(b)$ and $\mathrm{im}(a) = \mathrm{im}(b)$".

Procedure III:0(3.68)

Objective

Choose a complex number a. The objective of the following instructions is to show that $a = a$.

Implementation

1. Show that $\mathrm{re}(a) = \mathrm{re}(a)$.
2. Show that $\mathrm{im}(a) = \mathrm{im}(a)$.
3. **Hence show that** $a = a$.

Procedure III:1(3.69)

Objective

Choose two complex numbers a, b such that $a = b$. The objective of the following instructions is to show that $b = a$.

Implementation

1. Show that $\mathrm{re}(b) = \mathrm{re}(a)$ given that $\mathrm{re}(a) = \mathrm{re}(b)$.
2. Show that $\mathrm{im}(b) = \mathrm{im}(a)$ given that $\mathrm{im}(a) = \mathrm{im}(b)$.
3. **Hence show that** $b = a$.

Procedure III:2(3.70)

Objective

Choose three complex numbers a, b, c such that $a = b$ and $b = c$. The objective of the following instructions is to show that $a = c$.

Implementation

1. Show that $\mathrm{re}(a) = \mathrm{re}(c)$
   (a) given that $\mathrm{re}(a) = \mathrm{re}(b)$
   (b) and $\mathrm{re}(b) = \mathrm{re}(c)$.
2. Show that $\mathrm{im}(a) = \mathrm{im}(c)$
   (a) given that $\mathrm{im}(a) = \mathrm{im}(b)$
   (b) and $\mathrm{im}(b) = \mathrm{im}(c)$.
3. **Hence verify that** $a = c$.

Declaration III:4(3.23)

The notation $a+b$, where a, b are complex numbers, will be used as a shorthand for the pair $\langle \mathrm{re}(a)+\mathrm{re}(b), \mathrm{im}(a)+\mathrm{im}(b)\rangle$.

Procedure III:3(3.71)

Objective

Choose two complex numbers a, b, c, d such that $a = c$ and $b = d$. The objective of the following instructions is to show that $a + b = c + d$.

Implementation

1. Using declaration III:3, show that
   (a) $\mathrm{re}(a) = \mathrm{re}(c)$
   (b) $\mathrm{im}(a) = \mathrm{im}(c)$
   (c) $\mathrm{re}(b) = \mathrm{re}(d)$
   (d) $\mathrm{im}(b) = \mathrm{im}(d)$.
2. Hence show that $a + b$
   (a) $= \langle \mathrm{re}(a), \mathrm{im}(a)\rangle + \langle \mathrm{re}(b), \mathrm{im}(b)\rangle$
   (b) $= \langle \mathrm{re}(a) + \mathrm{re}(b), \mathrm{im}(a) + \mathrm{im}(b)\rangle$
   (c) $= \langle \mathrm{re}(c) + \mathrm{re}(d), \mathrm{im}(c) + \mathrm{im}(d)\rangle$
   (d) $= \langle \mathrm{re}(c), \mathrm{im}(c)\rangle + \langle \mathrm{re}(d), \mathrm{im}(d)\rangle$
   (e) $= c + d$.

Procedure III:4(3.72)

Objective

Choose three complex numbers a, b, c. The objective of the following instructions is to show that $(a + b) + c = a + (b + c)$.

Implementation

1. Show that $(a + b) + c$
   (a) $= \langle \mathrm{re}(a)+\mathrm{re}(b), \mathrm{im}(a)+\mathrm{im}(b)\rangle+\langle \mathrm{re}(c), \mathrm{im}(c)\rangle$
   (b) $= \langle (\mathrm{re}(a) + \mathrm{re}(b)) + \mathrm{re}(c), (\mathrm{im}(a) + \mathrm{im}(b)) + \mathrm{im}(c)\rangle$
   (c) $= \langle \mathrm{re}(a) + (\mathrm{re}(b) + \mathrm{re}(c)), \mathrm{im}(a) + (\mathrm{im}(b) + \mathrm{im}(c))\rangle$
   (d) $= \langle \mathrm{re}(a), \mathrm{im}(a)\rangle+\langle \mathrm{re}(b)+\mathrm{re}(c), \mathrm{im}(b)+\mathrm{im}(c)\rangle$
   (e) $= a + (b + c)$.

Procedure III:5(3.73)

Objective

Choose two complex numbers a, b. The objective of the following instructions is to show that $a + b = b + a$.

Implementation

1. Show that $a + b$
   (a) $= \langle \mathrm{re}(a) + \mathrm{re}(b), \mathrm{im}(a) + \mathrm{im}(b)\rangle$
   (b) $= \langle \mathrm{re}(b) + \mathrm{re}(a), \mathrm{im}(b) + \mathrm{im}(a)\rangle$
   (c) $= b + a$.

Declaration III:5(3.24)

The notation a, where a is a rational number, will contextually be used as a shorthand for the pair $\langle a, 0\rangle$.

Procedure III:6(3.74)

Objective

Choose a complex number a. The objective of the following instructions is to show that $0 + a = a$.

Implementation

1. Show that $0 + a$
   (a) $= \langle 0, 0\rangle + \langle \mathrm{re}(a), \mathrm{im}(a)\rangle$
   (b) $= \langle 0 + \mathrm{re}(a), 0 + \mathrm{im}(a)\rangle$
   (c) $= \langle \mathrm{re}(a), \mathrm{im}(a)\rangle$
   (d) $= a$.

Declaration III:6(3.25)

The notation $-a$, where a is a complex number, will be used as a shorthand for the pair $\langle -\mathrm{re}(a), -\mathrm{im}(a)\rangle$.

Procedure III:7(3.75)

Objective

Choose a complex number a. The objective of the following instructions is to show that $-a + a = 0$.

Implementation

1. Show that $-a+a$

   (a) $=(-a)+a$

   (b) $=\langle -\operatorname{re}(a), -\operatorname{im}(a)\rangle + \langle \operatorname{re}(a), \operatorname{im}(a)\rangle$

   (c) $=\langle -\operatorname{re}(a)+\operatorname{re}(a), -\operatorname{im}(a)+\operatorname{im}(a)\rangle$

   (d) $=\langle 0,0\rangle$

   (e) $=0.$

Declaration III:7(3.26)

The notation ab, where a,b are complex numbers, will be used as a shorthand for the pair $\langle \operatorname{re}(a)\operatorname{re}(b)-\operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b)+\operatorname{im}(a)\operatorname{re}(b)\rangle$.

Procedure III:8(3.76)

Objective

Choose four complex numbers a,b,c,d such that $a=c$ and $b=d$. The objective of the following instructions is to show that $ab=cd$.

Implementation

1. Using declaration III:3, show that

   (a) $\operatorname{re}(a)=\operatorname{re}(c)$

   (b) $\operatorname{im}(a)=\operatorname{im}(c)$

   (c) $\operatorname{re}(b)=\operatorname{re}(d)$

   (d) $\operatorname{im}(b)=\operatorname{im}(d)$.

2. Hence show that ab

   (a) $=\langle \operatorname{re}(a), \operatorname{im}(a)\rangle\langle \operatorname{re}(b), \operatorname{im}(b)\rangle$

   (b) $=\langle \operatorname{re}(a)\operatorname{re}(b)-\operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b)+\operatorname{im}(a)\operatorname{re}(b)\rangle$

   (c) $=\langle \operatorname{re}(c)\operatorname{re}(d)-\operatorname{im}(c)\operatorname{im}(d), \operatorname{re}(c)\operatorname{im}(d)+\operatorname{im}(c)\operatorname{re}(d)\rangle$

   (d) $=\langle \operatorname{re}(c), \operatorname{im}(c)\rangle\langle \operatorname{re}(d), \operatorname{im}(d)\rangle$

   (e) $=cd.$

Procedure III:9(3.77)

Objective

Choose three complex numbers a,b,c. The objective of the following instructions is to show that $(ab)c=a(bc)$.

Implementation

1. Show that $(ab)c$

   (a) $=\langle \operatorname{re}(a)\operatorname{re}(b)-\operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b)+\operatorname{im}(a)\operatorname{re}(b)\rangle\langle \operatorname{re}(c), \operatorname{im}(c)\rangle$

   (b) $=\langle (\operatorname{re}(a)\operatorname{re}(b)-\operatorname{im}(a)\operatorname{im}(b))\operatorname{re}(c)-(\operatorname{re}(a)\operatorname{im}(b)+\operatorname{im}(a)\operatorname{re}(b))\operatorname{im}(c), (\operatorname{re}(a)\operatorname{re}(b)-\operatorname{im}(a)\operatorname{im}(b))\operatorname{im}(c)+(\operatorname{re}(a)\operatorname{im}(b)+\operatorname{im}(a)\operatorname{re}(b))\operatorname{re}(c)\rangle$

   (c) $=\langle \operatorname{re}(a)(\operatorname{re}(b)\operatorname{re}(c)-\operatorname{im}(b)\operatorname{im}(c))-\operatorname{im}(a)(\operatorname{re}(b)\operatorname{im}(c)+\operatorname{im}(b)\operatorname{re}(c)), \operatorname{re}(a)(\operatorname{re}(b)\operatorname{im}(c)+\operatorname{im}(b)\operatorname{re}(c))+\operatorname{im}(a)(\operatorname{re}(b)\operatorname{re}(c)-\operatorname{im}(b)\operatorname{im}(c))\rangle$

   (d) $=\langle \operatorname{re}(a), \operatorname{im}(a)\rangle\langle \operatorname{re}(b)\operatorname{re}(c)-\operatorname{im}(b)\operatorname{im}(c), \operatorname{re}(b)\operatorname{im}(c)+\operatorname{im}(b)\operatorname{re}(c)\rangle$

   (e) $=a(bc).$

Procedure III:10(3.78)

Objective

Choose two complex numbers a,b. The objective of the following instructions is to show that $ab=ba$.

Implementation

1. Show that ab

   (a) $=\langle \operatorname{re}(a)\operatorname{re}(b)-\operatorname{im}(a)\operatorname{im}(b), \operatorname{re}(a)\operatorname{im}(b)+\operatorname{im}(a)\operatorname{re}(b)\rangle$

   (b) $=\langle \operatorname{re}(b)\operatorname{re}(a)-\operatorname{im}(b)\operatorname{im}(a), \operatorname{re}(b)\operatorname{im}(a)+\operatorname{im}(b)\operatorname{re}(a)\rangle$

   (c) $=ba.$

Procedure III:11(3.79)

Objective

Choose a complex number a. The objective of the following instructions is to show that $1a=a$.

Implementation

1. Show that $1a$

   (a) $=\langle 1,0\rangle\langle \operatorname{re}(a), \operatorname{im}(a)\rangle$

   (b) $=\langle 1\operatorname{re}(a)-0\operatorname{im}(a), 1\operatorname{im}(a)+0\operatorname{re}(a)\rangle$

   (c) $=\langle \operatorname{re}(a), \operatorname{im}(a)\rangle$

   (d) $=a.$

Procedure III:12(3.82)

Objective

Choose three complex numbers a, b, c. The objective of the following instructions is to show that $a(b+c) = ab + ac$.

Implementation

1. $a(b+c)$
   (a) $= \langle \mathrm{re}(a), \mathrm{im}(a)\rangle\langle \mathrm{re}(b) + \mathrm{re}(c), \mathrm{im}(b) + \mathrm{im}(c)\rangle$
   (b) $= \langle \mathrm{re}(a)(\mathrm{re}(b)+\mathrm{re}(c)) - \mathrm{im}(a)(\mathrm{im}(b)+\mathrm{im}(c)), \mathrm{re}(a)(\mathrm{im}(b) + \mathrm{im}(c)) + \mathrm{im}(a)(\mathrm{re}(b) + \mathrm{re}(c))\rangle$
   (c) $= \langle(\mathrm{re}(a)\,\mathrm{re}(b) - \mathrm{im}(a)\,\mathrm{im}(b)) + (\mathrm{re}(a)\,\mathrm{re}(c) - \mathrm{im}(a)\,\mathrm{im}(c)), (\mathrm{re}(a)\,\mathrm{im}(b) + \mathrm{im}(a)\,\mathrm{re}(b)) + (\mathrm{re}(a)\,\mathrm{im}(c) + \mathrm{im}(a)\,\mathrm{re}(c))\rangle$
   (d) $= \langle \mathrm{re}(a)\,\mathrm{re}(b) - \mathrm{im}(a)\,\mathrm{im}(b), \mathrm{re}(a)\,\mathrm{im}(b) + \mathrm{im}(a)\,\mathrm{re}(b)\rangle + \langle \mathrm{re}(a)\,\mathrm{re}(c) - \mathrm{im}(a)\,\mathrm{im}(c), \mathrm{re}(a)\,\mathrm{im}(c) + \mathrm{im}(a)\,\mathrm{re}(c)\rangle$
   (e) $= ab + ac$.

Declaration III:8(3.02)

The notation $(a)^-$, where a is a complex number, will be used as a shorthand for $\langle \mathrm{re}(a), -\mathrm{im}(a)\rangle$.

Procedure III:13(3.00)

Objective

Choose two complex numbers a, b. The objective of the following instructions is to show that $(a+b)^- = (a)^- + (b)^-$.

Implementation

1. Show that $(a+b)^-$
   (a) $= \langle \mathrm{re}(a+b), -\mathrm{im}(a+b)\rangle$
   (b) $= \langle \mathrm{re}(a) + \mathrm{re}(b), -\mathrm{im}(a) - \mathrm{im}(b)\rangle$
   (c) $= (a)^- + (b)^-$.

Procedure III:14(3.01)

Objective

Choose two complex numbers a, b. The objective of the following instructions is to show that $(ab)^- = (a)^-(b)^-$.

Implementation

1. Show that $(ab)^-$
   (a) $= \langle \mathrm{re}(ab), -\mathrm{im}(ab)\rangle$
   (b) $= \langle \mathrm{re}(a)\,\mathrm{re}(b) - \mathrm{im}(a)\,\mathrm{im}(b)), -\mathrm{re}(a)\,\mathrm{im}(b) - \mathrm{im}(a)\,\mathrm{re}(b)\rangle$
   (c) $= \langle \mathrm{re}(a), -\mathrm{im}(a)\rangle\langle \mathrm{re}(b), -\mathrm{im}(b)\rangle$
   (d) $= (a)^-(b)^-$.

Declaration III:9(3.03)

The notation $\|a\|^2$, where a is a complex number, will be used as a shorthand for $\mathrm{re}(a)^2 + \mathrm{im}(a)^2$.

Procedure III:15(3.02)

Objective

Choose a complex number a. The objective of the following instructions is to show that $a(a)^- = \|a\|^2$.

Implementation

1. **Show that** $a(a)^- = \|a\|^2$**.**

Procedure III:16(3.04)

Objective

Choose a list of complex numbers a. The objective of the following instructions is to show that $\|\sum_r^{[0:|a|]} a_r\|^2 \leq |a| \sum_r^{[0:|a|]} \|a_r\|^2$.

Implementation

1. Show that $\|\sum_r^{[0:|a|]} a_r\|^2$
   (a) $= \sum_r^{[0:|a|]} \sum_k^{[0:|a|]} a_r(a_k)^-$
   (b) $= \sum_r^{[0:|a|]} \|a_r\|^2 + 2\sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} (\mathrm{re}(a_r)\,\mathrm{re}(a_k) + \mathrm{im}(a_r)\,\mathrm{im}(a_k))$
   (c) $= \sum_r^{[0:|a|]} \|a_r\|^2 + \sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} (\mathrm{re}(a_r)^2 - (\mathrm{re}(a_r) - \mathrm{re}(a_k))^2 + \mathrm{re}(a_k)^2 + \mathrm{im}(a_r)^2 - (\mathrm{im}(a_r) - \mathrm{im}(a_k))^2 + \mathrm{im}(a_k)^2)$
   (d) $\leq \sum_r^{[0:|a|]} \|a_r\|^2 + \sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} (\mathrm{re}(a_r)^2 + \mathrm{re}(a_k)^2 + \mathrm{im}(a_r)^2 + \mathrm{im}(a_k)^2)$
   (e) $= \sum_r^{[0:|a|]} \|a_r\|^2 + \sum_r^{[0:|a|]} \sum_k^{[r+1:|a|]} (\|a_r\|^2 + \|a_k\|^2)$
   (f) $= \sum_r^{[0:|a|]} \|a_r\|^2 + \frac{1}{2} \sum_r^{[0:|a|]} \sum_k^{[0:r]^\frown[r+1:|a|]} (\|a_r\|^2 + \|a_k\|^2)$

(g) $= \sum_r^{[0:|a|]} \|a_r\|^2 + \frac{1}{2}(\sum_r^{[0:|a|]}(|a|-1)\|a_r\|^2 + \sum_k^{[0:|a|]}(|a|-1)\|a_k\|^2)$

(h) $= \sum_r^{[0:|a|]} \|a_r\|^2 + \sum_r^{[0:|a|]}(|a|-1)\|a_r\|^2$

(i) $= |a| \sum_r^{[0:|a|]} \|a_r\|^2$

Procedure III:17(3.05)

Objective

Choose a list of complex numbers a. The objective of the following instructions is to show that $\frac{\|a_0\|^2}{|a|} - \sum_r^{[1:|a|]} \|a_r\|^2 \leq \|a_0 - \sum_r^{[1:|a|]} a_r\|^2$.

Implementation

1. Using procedure III:16, show that $\|a_0\|^2$
   (a) $= \|\sum_r^{[1:|a|]} a_r + (a_0 - \sum_r^{[1:|a|]} a_r)\|^2$
   (b) $\leq |a| \sum_r^{[1:|a|]} \|a_r\|^2 + |a| \|a_0 - \sum_r^{[1:|a|]} a_r\|^2$
2. **Therefore show that** $\frac{\|a_0\|^2}{|a|} - \sum_r^{[1:|a|]} \|a_r\|^2 \leq \|a_0 - \sum_r^{[1:|a|]} a_r\|^2$**.**

Procedure III:18(3.04aa)

Objective

Choose a list of complex numbers a and a list of rational numbers b such that $|a| = |b|$ and $\|a_i\|^2 \leq {b_i}^2$ for each $i \in [0 : |a|]$. The objective of the following instructions is to show that $\|\sum_r^{[0:|a|]} a_r\|^2 \leq (\sum_r^{[0:|b|]} b_r)^2$.

Implementation

1. If $|a| = 0$, then do the following:
   (a) **Show that** $\|\sum_i^{[0:|a|]} a_i\|^2 = \|0\|^2 = (\sum_i^{[0:|b|]} b_i)^2$**.**
2. Otherwise do the following:
   (a) Show that $|a| > 0$.
   (b) Show that $\|\sum_i^{[1:|a|]} a_i\|^2 \leq (\sum_i^{[1:|b|]} b_i)^2$ using procedure III:18 on $a_{[1:|a|]}$ and $b_{[1:|b|]}$.
   (c) Show that $\mathrm{re}((a_0)^- \sum_i^{[1:|a|]} a_i)^2$
      i. $\leq \|(a_0)^- \sum_i^{[1:|a|]} a_i\|^2$
      ii. $= \|(a_0)^-\|^2 \|\sum_i^{[1:|a|]} a_i\|^2$
      iii. $\leq {b_0}^2 (\sum_i^{[1:|a|]} b_i)^2$.
   (d) Hence show that $\|\sum_i^{[0:|a|]} a_i\|^2$
      i. $= (a_0 + \sum_i^{[1:|a|]} a_i)((a_0 + \sum_i^{[1:|a|]} a_i)^-)$
      ii. $= \|a_0\|^2 + a_0(\sum_i^{[1:|a|]} a_i)^- + (a_0)^- \sum_i^{[1:|a|]} a_i + \|\sum_i^{[1:|a|]} a_i\|^2$
      iii. $\leq {b_0}^2 + ((a_0)^- \sum_i^{[1:|a|]} a_i)^- + (a_0)^- \sum_i^{[1:|a|]} a_i + (\sum_i^{[1:|a|]} b_i)^2$
      iv. $= {b_0}^2 + 2\,\mathrm{re}((a_0)^- \sum_i^{[1:|a|]} a_i) + (\sum_i^{[1:|a|]} b_i)^2$
      v. $\leq {b_0}^2 + 2b_0 \sum_i^{[1:|a|]} b_i + (\sum_i^{[1:|a|]} b_i)^2$
      vi. $= (b_0 + \sum_i^{[1:|a|]} b_i)^2$
      vii. $= (\sum_i^{[0:|a|]} b_i)^2$.

Procedure III:19(sat1708191238)

Objective

Choose two complex numbers a, d and two rational numbers b, c such that $\|a\|^2 \leq b^2 < c^2 \leq \|d\|^2$. The objective of the following instructions is to show that $\|d - a\|^2 \geq (c - b)^2$.

Implementation

1. Show that $\mathrm{re}(\frac{a}{d})^2$
   (a) $= \mathrm{re}(\frac{a(d)^-}{\|d\|^2})^2 = \frac{\mathrm{re}(a(d)^-)^2}{\|d\|^4} \leq \frac{\|a(d)^-\|^2}{\|d\|^4}$
   (b) $= \frac{\|a\|^2\|d\|^2}{\|d\|^4} = \frac{\|a\|^2}{\|d\|^2} \leq \frac{b^2}{c^2} = (\frac{b}{c})^2$.
2. Hence show that $\mathrm{re}(\frac{a}{d}) \leq \frac{b}{c} < 1$.
3. Hence show that $\|d - a\|^2$
   (a) $= \|\frac{d-a}{d}\|^2 \|d\|^2$
   (b) $= (\mathrm{re}(1 - \frac{a}{d})^2 + \mathrm{im}(1 - \frac{a}{d})^2)\|d\|^2$
   (c) $\geq \mathrm{re}(1 - \frac{a}{d})^2 \|d\|^2$
   (d) $= (1 - \mathrm{re}(\frac{a}{d}))^2 \|d\|^2$
   (e) $\geq (1 - \frac{b}{c})^2 c^2$
   (f) $= (c - b)^2$.

Declaration III:10(3.27)

The notation $\frac{1}{a}$, where a is a complex number, will be used as a shorthand for the pair $\frac{1}{\|a\|^2}(a)^-$.

Procedure III:20(3.81)

Objective

Choose a complex number a such that $a \neq 0$. The objective of the following instructions is to show that $\frac{1}{a}a = 1$.

Implementation

1. Show that $\mathrm{re}(a) \neq \mathrm{re}(0) = 0$ or $\mathrm{im}(a) \neq \mathrm{im}(0) = 0$ using declaration III:3.
2. Hence show that $\|a\|^2 = \mathrm{re}(a)^2 + \mathrm{im}(a)^2 > 0$.
3. Hence show that $\frac{1}{a}a$
   (a) $= (\frac{1}{\|a\|^2}(a)^-)a$
   (b) $= \frac{1}{\|a\|^2}((a)^- a)$
   (c) $= \frac{1}{\|a\|^2}\|a\|^2$
   (d) $= 1$.

Declaration III:11(3.28)

The notation i will be used as a shorthand for $\langle 0, 1\rangle$.

Procedure III:21(3.03)

Objective

Choose an integer a. The objective of the following instructions is to show that $i^{4a} = 1$, $i^{4a+1} = i$, $i^{4a+2} = -1$, and $i^{4a+3} = -i$.

Implementation

1. Show that $i^2 = -1$.
2. Hence show that $i^4 = (-1)^2 = 1$.
3. **Hence show that**
   (a) $i^{4a} = (i^4)^a = 1^a = 1$
   (b) $i^{4a+1} = i^{4a}i = 1i = i$
   (c) $i^{4a+2} = i^{4a+1}i = i^2 = -1$
   (d) $i^{4a+3} = i^{4a+2}i = (-1)i = -i$.

Procedure III:22(sun2107190636)

Objective

Choose a non-negative integer a and a complex number x. The objective of the following instructions is to show that $(1+x)^a = \sum_r^{[0:a+1]} \binom{a}{r} x^r$.

Implementation

Instructions are analogous to those of procedure I:84.

Declaration III:12(mon1908191749)

The notation $a \equiv b$ (err c_1) (err c_2)$\cdots$ (err c_n) will be used as a shorthand for $\|b-a\|^2 \leq \|c_1\|^2 \leq \|c_2\|^2 \leq \cdots \leq \|c_n\|^2$.

Procedure III:23(mon1908191916)

Objective

Choose four complex numbers a, b, c, d in such a way that $a \equiv b$ (err c) and $\|c\|^2 \leq \|d\|^2$. The objective of the following instructions is to show that $a \equiv b$ (err c) (err d).

Implementation

1. Show that $\|b-a\| \leq \|c\|^2 \leq \|d\|^2$.
2. **Hence show that** $a \equiv b$ (err c) (err d) **using declaration III:12.**

Procedure III:24(mon1908191825)

Objective

Choose three complex numbers a, b, c and two non-negative rational numbers d, e in such a way that $a \equiv b$ (err d) and $b \equiv c$ (err e). The objective of the following instructions is to show that $a \equiv c$ (err $d+e$).

Implementation

1. Show that $\|b-a\|^2 \leq \|d\|^2 = d^2$.
2. Show that $\|c-b\|^2 \leq \|e\|^2 = e^2$.
3. Hence show that $\|c-a\|^2 = \|(c-b)+(b-a)\|^2 \leq (e+d)^2$ using procedure III:18.
4. **Hence show that** $a \equiv c$ (err $e+d$) **using declaration III:12.**

Procedure III:25(mon1908191839)

Objective

Choose four complex numbers a, b, c, d and two non-negative rational numbers e, f in such a way that $a \equiv b$ (err e) and $c \equiv d$ (err f). The objective of the following instructions is to show that $a + c \equiv b + d$ (err $e + f$).

Implementation

1. Show that $\|b - a\|^2 \le \|e\|^2 = e^2$.
2. Show that $\|d - c\|^2 \le \|f\|^2 = f^2$.
3. Hence show that $\|(b + d) - (a + c)\|^2 = \|(b - a) + (d - c)\|^2 \le (e + f)^2$ using procedure III:18.
4. **Hence show that $a + c \equiv b + d$ (err $e + f$) using declaration III:12.**

Procedure III:26(mon1908191849)

Objective

Choose three complex numbers a, b, c in such a way that $a \equiv b$ (err c). The objective of the following instructions is to show that $-a \equiv -b$ (err c).

Implementation

1. Show that $\|(-b) - (-a)\|^2 = \|b - a\| \le \|c\|^2$.
2. **Hence show that $-a \equiv -b$ (err c) using declaration III:12.**

Procedure III:27(mon1908191857)

Objective

Choose four complex numbers a, b, c, d in such a way that $a \equiv b$ (err c). The objective of the following instructions is to show that $ad \equiv bd$ (err cd).

Implementation

1. Show that $\|b - a\|^2 \le \|c\|^2$.
2. Hence show that $\|bd - ad\|^2 \le \|cd\|^2$.
3. **Hence show that $ad \equiv bd$ (err cd) using declaration III:12.**

Procedure III:28(mon1908191905)

Objective

Choose two complex numbers a, b, c in such a way that $a \neq 0$, $b \neq 0$, and $a \equiv b$ (err c). The objective of the following instructions is to show that $\frac{1}{a} \equiv \frac{1}{b}$ (err $\frac{c}{ab}$).

Implementation

1. Show that $\|b - a\| \le \|c\|^2$.
2. Hence show that $\|\frac{1}{b} - \frac{1}{a}\|^2 = \|\frac{a-b}{ba}\|^2 \le \|\frac{c}{ba}\|^2$.
3. **Hence show that $\frac{1}{a} \equiv \frac{1}{b}$ (err $\frac{c}{ab}$) using declaration III:12.**

Chapter 10

Exponential and Trigonometric Functions

Declaration III:13(3.05)

The notation $\exp_n(a)$, where a is a complex number, will be used as a shorthand for $(1+\frac{a}{n})^n$.

Procedure III:29(3.08)

Objective

Choose a rational number a and a positive integer n such that $-n < a < 1$. The objective of the following instructions is to show that $\exp_n(a) \leq \frac{1}{1-a}$.

Implementation

1. Using procedure II:30, show that $\exp_n(a)$

   (a) $= (\frac{n+a}{n})^n$

   (b) $= (\frac{n}{n+a})^{-n}$

   (c) $= \frac{1}{(1+\frac{-a}{n+a})^n}$

   (d) $\leq \frac{1}{1+\frac{-an}{n+a}}$

   (e) $\leq \frac{1}{1-a}$.

Procedure III:30(3.09)

Objective

Choose a rational number a and a positive integer n such that $a > -n$. The objective of the following instructions is to show that $\frac{\exp_{n+1}(a)}{\exp_n(a)} \geq 1$.

Implementation

1. Using procedure II:30, show that $\frac{\exp_{n+1}(a)}{\exp_n(a)}$

   (a) $= \frac{(\frac{n+1+a}{n+1})^n}{(\frac{n+a}{n})^n}(1+\frac{a}{n+1})$

   (b) $= (\frac{(n+1+a)n}{(n+1)(n+a)})^n(1+\frac{a}{n+1})$

   (c) $= (\frac{n^2+n+na}{n^2+an+n+a})^n(1+\frac{a}{n+1})$

   (d) $= (1-\frac{a}{(n+1)(n+a)})^n(1+\frac{a}{n+1})$

   (e) $\geq (1-\frac{an}{(n+1)(n+a)})(1+\frac{a}{n+1})$

   (f) $= 1+\frac{a(n+a)}{(n+1)(n+a)}-\frac{an}{(n+1)(n+a)}-\frac{a^2n}{(n+1)^2(n+a)}$

   (g) $= 1+\frac{a^2}{(n+1)(n+a)}-\frac{a^2n}{(n+1)^2(n+a)}$

   (h) $= 1+\frac{a^2}{(n+1)^2(n+a)}$

   (i) ≥ 1

Procedure III:31(3.10)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct positive rational numbers a, b such that $a > 1$, and a procedure, $p(x, r, n)$, to show that $(1+\frac{x}{n})^r \leq a^2$ when given a rational number x and a non-negative integers r, n such that $r \leq n$, $n \geq b$ and $x^2 \leq X^2$ are chosen.

Implementation

1. Let $a = 2^{\lceil X \rceil}$.
2. Let $b = X$.
3. Let $p(x, r, n)$ be the following procedure:
   (a) Show that $0 \le 1 + \frac{x}{n} \le 2$
      i. given that $-1 \le \frac{x}{n} \le 1$
      ii. given that $-X \le x \le X$
      iii. given that $x^2 \le X^2$.
   (b) Hence using procedure III:29 and procedure III:30, show that $(1 + \frac{x}{n})^r$
      i. $\le (1 + \frac{X}{n})^r$
      ii. $\le \exp_n(X)$
      iii. $\le (1 + \frac{X}{2\lceil X \rceil n})^{2\lceil X \rceil n}$
      iv. $= ((1 + \frac{\frac{X}{2\lceil X \rceil}}{n})^n)^{2\lceil X \rceil}$
      v. $= \exp_n(\frac{X}{2\lceil X \rceil})^{2\lceil X \rceil}$
      vi. $\le (\frac{1}{1 - \frac{X}{2\lceil X \rceil}})^{2\lceil X \rceil}$
      vii. $\le 2^{2\lceil X \rceil}$
      viii. $= a^2$.
4. **Yield the tuple** $\langle a, b, p \rangle$**.**

Procedure III:32(3.11)

Objective

Choose a rational number $X \le 0$. The objective of the following instructions is to construct two rational numbers $a > 0, b$, and a procedure $p(x, r, n)$ to show that $(1 + \frac{x}{n})^r \ge a^2$ when a rational number x and non-negative integers r, n such that $X \le x \le 0$, $r \le n$, and $n > b$ are chosen.

Implementation

1. Use procedure III:31 on $\langle -2X \rangle$ to construct $\langle c, d, q \rangle$.
2. Let $a = c^{-1}$.
3. Let $b = \max(-2X, d)$.
4. Let $p(x, r, n)$ be the following procedure:
   (a) Show that $0 \le -2x \le -2X$
      i. given that $2X \le 2x \le 0$
      ii. given that $X \le x \le 0$.
   (b) Show that $(1 + \frac{-2x}{n})^r \le c^2$ using procedure q.
   (c) Show that $\frac{n}{2} \le n + x < n$
      i. given that $-\frac{n}{2} \le x \le 0$
      ii. given that $n > b \ge -2X \ge -2x \ge 0$.
   (d) Hence show that $(1 + \frac{x}{n})^r$
      i. $= (\frac{n+x}{n})^r$
      ii. $= (\frac{n}{n+x})^{-r}$
      iii. $= (1 - \frac{x}{n+x})^{-r}$
      iv. $\ge (1 - \frac{x}{\frac{1}{2}n})^{-r}$
      v. $= (1 - \frac{2x}{n})^{-r}$
      vi. $= ((1 + \frac{-2x}{n})^r)^{-1}$
      vii. $\ge (c^2)^{-1}$
      viii. $= a^2$.
5. **Yield the tuple** $\langle a, b, p \rangle$**.**

Procedure III:33(3.12)

Objective

Choose a rational number $X \ge 0$. The objective of the following instructions is to construct two rational numbers $a > 0, b$, and a procedure $p(x, r, n)$ to show that $(1 + \frac{x}{n})^r \ge a^2$ when a rational number x and non-negative integers r, n such that $x^2 \le X^2$, $r \le n$, and $n > b$ are chosen.

Implementation

1. Execute procedure III:32 on $\langle -X \rangle$ and let $\langle c, b, q \rangle$ receive.
2. Let $a = \min(1, c)$.
3. Let $p(x, r, n)$ be the following procedure:
   (a) If $x < 0$, then do the following:
      i. Show that $-X \le x \le 0$ given that $x^2 \le X^2$.
      ii. **Hence show that** $(1 + \frac{x}{n})^r \ge c^2 \ge a^2$ **using procedure** q**.**
   (b) Otherwise do the following:
      i. Verify that $x \ge 0$.

ii. **Show that** $(1+\frac{x}{n})^r \geq 1+\frac{rx}{n} \geq 1 \geq a^2$ **using procedure II:30.**

4. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:34(3.13)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct positive rational numbers a, b such that $a > 1$, and a procedure, $p(x, r, n)$, to show that $\|(1+\frac{x}{n})^r\|^2 \leq a^2$ when a complex number x and non-negative integers r, n such that $\|x\|^2 \leq X^2$, $r \leq n$, and $n > b$ are chosen.

Implementation

1. Let $c = 2X + X^2$.
2. Execute procedure III:31 on $\langle c\rangle$ and let $\langle a, b, q\rangle$.
3. Let $p(x, r, n)$ be the following procedure:

(a) Let $y = 2|\mathrm{re}(x)| + \|x\|^2$.

(b) Show that $|y| = y \leq 2X + X^2 = c$

i. given that $|\mathrm{re}(x)| \leq X$

ii. given that $|\mathrm{re}(x)|^2 \leq \|x\|^2 \leq X^2$.

(c) Hence show that $(1+\frac{y}{n})^r \leq a^2$ using procedure q.

(d) Now using procedure III:15 show that $\|(1+\frac{x}{n})^r\|^2$

i. $= (1+\frac{x}{n})^r((1+\frac{x}{n})^r)^-$

ii. $= (1+\frac{x}{n})^r(1+\frac{(x)^-}{n})^r$

iii. $= (1+\frac{2\,\mathrm{re}(x)}{n}+\frac{\|x\|^2}{n^2})^r$

iv. $\leq (1+\frac{2|\mathrm{re}(x)|}{n}+\frac{\|x\|^2}{n^2})^r$

v. $\leq (1+\frac{2|\mathrm{re}(x)|+\|x\|^2}{n})^r$

vi. $= (1+\frac{y}{n})^r$

vii. $\leq a^2$.

4. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:35(3.14)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, b and a procedure, $p(x, r, n)$, to show that $\|(1+\frac{x}{n})^r\|^2 \geq a^2$ when a rational number x and non-negative integers r, n such that $\|x\|^2 \leq X^2$, $r \leq n$ and $n > b$ are chosen.

Implementation

1. Let $c = 2X + X^2$.
2. Execute procedure III:33 on $\langle c\rangle$ and let $\langle a, d, q\rangle$ receive.
3. Let $b = \max(c, d)$.
4. Let $p(x, r, n)$ be the following procedure:

(a) Let $y = 2|\mathrm{re}(x)| + \|x\|^2$.

(b) Verify that $|-y| = y \leq 2X + X^2 = c$.

(c) Hence show that $(1+\frac{-y}{n})^r \geq a^2$ using procedure q.

(d) Also, show that $n > b \geq c \geq y$.

(e) Hence show that $\|(1+\frac{x}{n})^r\|^2$

i. $= (1+\frac{x}{n})^r((1+\frac{x}{n})^r)^-$

ii. $= (1+\frac{x}{n})^r(1+\frac{(x)^-}{n})^r$

iii. $= (1+\frac{2\,\mathrm{re}(x)}{n}+\frac{\|x\|^2}{n^2})^r$

iv. $\geq (1-\frac{2|\mathrm{re}(x)|}{n}-\frac{\|x\|^2}{n^2})^r$

v. $\geq (1-\frac{2|\mathrm{re}(x)|+\|x\|^2}{n})^r$

vi. $= (1+\frac{-y}{n})^r$

vii. $\geq a^2$.

5. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:36(3.15)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct rational numbers a, b such that $a > 0$, and a procedure, p, to show that $\exp_n(x+y) \equiv \exp_n(x)\exp_n(y)$ (err $\frac{axy}{n}$) (err $\frac{aX^2}{n}$) when two complex numbers x, y and a positive integer $n > b$ such that $\|x\|^2 \leq X^2$, $\|y\|^2 \leq X^2$ are chosen.

Implementation

1. Execute procedure III:34 on $\langle 2X\rangle$ and let $\langle c, b, q\rangle$ receive.
2. Let $a = c^3$.
3. Let $p(x, y, n)$ be the following procedure:
   (a) Using procedure q, show that $\exp_n(x+y) \equiv \exp_n(x)\exp_n(y)$
      i. (err $\exp_n(x)\exp_n(y) - \exp_n(x+y)$)
      ii. (err $(1+\frac{x}{n})^n(1+\frac{y}{n})^n - (1+\frac{x+y}{n})^n$)
      iii. (err $(1+\frac{x+y}{n}+\frac{xy}{n^2})^n - (1+\frac{x+y}{n})^n$)
      iv. (err $\frac{xy}{n^2}\sum_r^{[0:n]}(1+\frac{x+y}{n}+\frac{xy}{n^2})^r(1+\frac{x+y}{n})^{n-1-r}$)
      v. (err $\frac{xy}{n^2}\sum_r^{[0:n]}(1+\frac{x}{n})^r(1+\frac{y}{n})^r(1+\frac{x+y}{n})^{n-1-r}$)
      vi. (err $\frac{xy}{n^2}\sum_r^{[0:n]} c^3$)
      vii. (err $\frac{axy}{n}$)
      viii. (err $\frac{aX^2}{n}$).
4. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:37(thu2507191359)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct rational numbers a, b such that $a > 0$ and a procedure $p(x, y, n)$ to show that $\exp_n(x-y) \equiv \frac{\exp_n(x)}{\exp_n(y)}$ (err $\frac{a}{n}$) when two complex numbers x, y and a positive integer n such that $\|x\|^2 \leq X$, $\|y\|^2 \leq X$, and $n > b$ are chosen.

Implementation

1. Execute procedure III:36 on $\langle X\rangle$ and let $\langle c, d, q\rangle$ receive.
2. Execute procedure III:35 on $\langle X\rangle$ and let $\langle e, f, r\rangle$ receive.
3. Execute procedure III:34 on $\langle X\rangle$ and let $\langle g, h, t\rangle$ receive.
4. Let $b = \max(d, f, h)$.
5. Let $a = c(1+\frac{g}{e})X^2$.
6. Let $p(x, y, n)$ be the following procedure:
   (a) Using procedures q, r, t, show that $\exp_n(x-y)$
      i. $\equiv \exp_n(x)\exp_n(-y)$ (err $\frac{cX^2}{n}$)
      ii. $= \exp_n(x)\frac{\exp_n(y)\exp_n(-y)}{\exp_n(y)}$
      iii. $\equiv \exp_n(x)\frac{\exp_n(0)}{\exp_n(y)}$ (err $\frac{g}{e}\cdot\frac{cX^2}{n}$)
      iv. $= \frac{\exp_n(x)}{\exp_n(y)}$.
   (b) **Hence show that** $\exp_n(x-y) \equiv \frac{\exp_n(x)}{\exp_n(y)}$ (err $\frac{cX^2}{n}+\frac{gcX^2}{en}$) (err $\frac{a}{n}$)**.**
7. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:38(3.16)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct positive rational numbers a, b and a procedure, $p(x, k, n)$, to show that $\exp_n(kx) \equiv \exp_n(x)^k$ (err $\frac{ak}{n}$) when a complex number x, and non-negative integers k, n such that $n > b$ and $\|kx\|^2 \leq X^2$ are chosen.

Implementation

1. Execute procedure III:34 on $\langle X\rangle$ and let $\langle c, d, q\rangle$ receive.
2. Execute procedure III:36 on $\langle X\rangle$ and let $\langle e, f, t\rangle$ receive.
3. Let $a = ecX^2$
4. Let $b = \max(d, f)$.
5. Let $p(x, k, n)$ be the following procedure:
   (a) If $k > 0$, then for $r \in [1:k]$ do the following:
      i. Show that $\|xr\|^2 \leq \|kx\|^2 \leq X^2$.
      ii. Hence show that $\|\exp_{nr}(xr)\|^2 \leq c^2$ using procedure q.
      iii. Hence show that $\|\exp_n(x)^r\|^2 = \|(1+\frac{x}{n})^{nr}\|^2 = \|(1+\frac{xr}{nr})^{nr}\|^2 = \|\exp_{nr}(xr)\|^2 \leq c^2$
   (b) Hence using procedure t, show that $\exp_n(kx)$
      i. $= \exp_n(x)^0\exp_n(kx)$
      ii. $\equiv \exp_n(x)^1\exp_n((k-1)x)$ (err $\frac{ceX^2}{n}$)

iii. $\equiv \exp_n(x)^2 \exp_n((k-2)x)$ (err $\frac{ceX^2}{n}$)

iv. $\vdots$

v. $\equiv \exp_n(x)^k \exp_n((k-k)x)$ (err $\frac{ceX^2}{n}$)

vi. $= \exp_n(x)^k$.

(c) **Hence show that** $\exp_n(kx) \equiv \exp_n(x)^k$ (err $\frac{kceX^2}{n}$) (err $\frac{ak}{n}$)**.**

6. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:39(thu2507191307)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct positive rational numbers a, b, and a procedure $p(x, y, n)$ to show that $\exp_n(y) \equiv \exp_n(x)$ (err $a(x-y)$) when two complex numbers x, y and a positive integer $n > b$ such that $\|x\|^2 \leq X$ and $\|y\|^2 \leq X$ are chosen.

Implementation

1. Execute procedure III:34 on $\langle X\rangle$ and let $\langle c, b, q\rangle$ receive.
2. Let $a = c^2$.
3. Let $p(x, y, n)$ be the following procedure:

(a) Using procedure q, show that $\exp_n(x) \equiv \exp_n(y)$

i. (err $\exp_n(y) - \exp_n(x)$)

ii. (err $(1+\frac{y}{n})^n - (1+\frac{x}{n})^n$)

iii. (err $(\frac{y}{n}-\frac{x}{n})\sum_r^{[0:n]}(1+\frac{y}{n})^r(1+\frac{x}{n})^{n-1-r}$)

iv. (err $(y-x)(\frac{1}{n}\sum_r^{[0:n]} c^2)$)

v. (err $a(y-x)$).

4. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:40(3.21)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, N, and a procedure, $p(x, n)$, to show that $\exp_n(x) \equiv \sum_r^{[0:n+1]} \frac{x^r}{r!}$ (err $\frac{a}{n}$) when a complex number x and an integer $n > N$ such that $\|x\|^2 \leq X^2$ are chosen.

Implementation

1. Let $N = \lfloor X \rfloor + 1$.
2. Let $a = X^2(\sum_r^{[0:N]} \frac{X^r}{r!} + \frac{X^N}{N!} \cdot \frac{1}{1-\frac{X}{N}})$.
3. Let $p(x, n)$ be the following procedure:

(a) Using procedure II:29, procedure III:16, procedure II:28, and procedure II:30, show that $\exp_n(x) \equiv \sum_r^{[0:n+1]} \frac{x^r}{r!}$

i. (err $\sum_r^{[0:n+1]} \frac{x^r}{r!} - \exp_n(x)$)

ii. (err $\sum_r^{[0:n+1]} \frac{x^r}{r!} - \sum_r^{[0:n+1]} \frac{n^{\underline{r}}}{r!} \cdot \frac{x^r}{n^r}$)

iii. (err $\sum_r^{[1:n+1]}(1-\frac{n^{\underline{r}}}{n^r})\frac{x^r}{r!}$)

iv. (err $\sum_r^{[1:n+1]}(1-\frac{n^{\underline{r}}}{n^r})\frac{X^r}{r!}$)

v. (err $\sum_r^{[2:n+1]}(1-\frac{(n-r+1)^r}{n^r})\frac{X^r}{r!}$)

vi. (err $\sum_r^{[2:n+1]}(1-(1-\frac{r-1}{n})^r)\frac{X^r}{r!}$)

vii. (err $\sum_r^{[2:n+1]}(1-(1-\frac{(r-1)r}{n}))\frac{X^r}{r!}$)

viii. (err $\sum_r^{[2:n+1]} \frac{(r-1)r}{n}\frac{X^r}{r!}$)

ix. (err $\frac{1}{n}\sum_r^{[2:n+1]} \frac{X^r}{(r-2)!}$)

x. (err $\frac{X^2}{n}\sum_r^{[0:n-1]} \frac{X^r}{r!}$)

xi. (err $\frac{X^2}{n}(\sum_r^{[0:N]} \frac{X^r}{r!} + \sum_r^{[N:n-1]} \frac{X^r}{r!})$)

xii. (err $\frac{X^2}{n}(\sum_r^{[0:N]} \frac{X^r}{r!} + \sum_r^{[N:n-1]} \frac{X^r}{N!N^{r-N}})$)

xiii. (err $\frac{X^2}{n}(\sum_r^{[0:N]} \frac{X^r}{r!} + \frac{X^N}{N!}\sum_r^{[N:n-1]} \frac{X^{r-N}}{N^{r-N}})$)

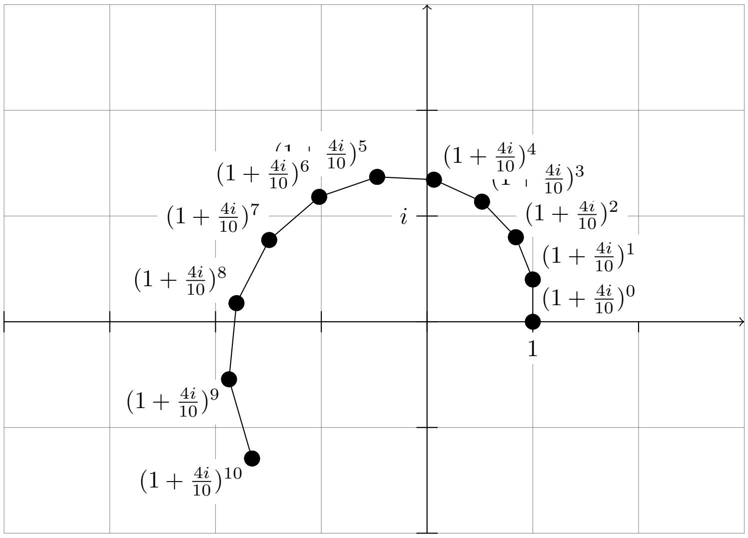
xiv. (err $\frac{X^2}{n}(\sum_r^{[0:N]} \frac{X^r}{r!} + \frac{X^N}{N!}\sum_r^{[0:n-N-1]} \frac{X^r}{N^r})$)

xv. (err $\frac{X^2}{n}(\sum_r^{[0:N]} \frac{X^r}{r!} + \frac{X^N}{N!} \cdot \frac{1}{1-\frac{X}{N}})$)

xvi. (err $\frac{a}{n}$).

4. **Yield the tuple** $\langle a, N, p\rangle$**.**

Figure III:0



A plot of the list of complex numbers $(1+\frac{4i}{10})^{[0:11]}$. Notice that each multiplication of a complex number by $1+\frac{4i}{10}$ results in an anti-clockwise rotation about the origin and a small radial movement outwards. This can be seen to reflect the computation $(1+\frac{4i}{10})a = 1a + \frac{4}{10}(ai)$ after one notes that ai is perpendicular to a. Also note that each line segment has a length of roughly $\frac{4}{10}$ units. Hence the entire path has a length of approximately $10 * \frac{4}{10} = 4$ units.

Declaration III:14(3.17)

The notation $\cos_n(z)$, where z is a complex number and n is a positive integer, will be used as a shorthand for $\frac{\exp_n(iz)+\exp_n(-iz)}{2}$.

Procedure III:41(3.22)

Objective

Choose a rational number x and a positive integer n. The objective of the following instructions is to show that $\mathrm{re}(\exp_n(ix)) = \cos_n(x)$.

Implementation

1. Show that $\mathrm{re}(\exp_n(ix))$

   (a) $= \frac{\exp_n(ix)+(\exp_n(ix))^-}{2}$

   (b) $= \frac{\exp_n(ix)+\exp_n((ix)^-)}{2}$

   (c) $= \frac{\exp_n(ix)+\exp_n(-ix)}{2}$

   (d) $= \cos_n(x)$.

Declaration III:15(3.18)

The notation $\sin_n(z)$, where z is a complex number and n is a positive integer, will be used as a shorthand for $\frac{\exp_n(iz)-\exp_n(-iz)}{2i}$.

Procedure III:42(3.23)

Objective

Choose a rational number x and a positive integer n. The objective of the following instructions is to show that $\mathrm{im}(\exp_n(ix)) = \sin_n(x)$.

Implementation

1. Show that $\mathrm{im}(\exp_n(ix))$

   (a) $= \frac{\exp_n(ix)-(\exp_n(ix))^-}{2i}$

   (b) $= \frac{\exp_n(ix)-\exp_n((ix)^-)}{2i}$

   (c) $= \frac{\exp_n(ix)-\exp_n(-ix)}{2i}$

   (d) $= \sin_n(x)$.

Procedure III:43(3.24)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, b, and a procedure, $p(x, y, n)$, to show that $\cos_n(x+y) \equiv \cos_n(x)\cos_n(y) - \sin_n(x)\sin_n(y)$ (err $\frac{axy}{n}$) (err $\frac{aX^2}{n}$) when two complex numbers x, y and a positive integer $n > b$ such that $\|x\|^2 \leq X^2$ and $\|y\|^2 \leq X^2$ are chosen.

Implementation

1. Execute procedure III:36 on $\langle X\rangle$ and let $\langle a, b, q\rangle$ receive.
2. Let $p(x, y, n)$ be the following procedure:
   (a) Using procedure q, show that $\cos_n(x+y)$
      i. $= \frac{1}{2}(\exp_n(i(x+y)) + \exp_n(-i(x+y)))$
      ii. $\equiv \frac{1}{2}(\exp_n(ix)\exp_n(iy) + \exp_n(-i(x+y)))$ (err $\frac{a(ix)(iy)}{2n}$)
      iii. $\equiv \frac{1}{2}(\exp_n(ix)\exp_n(iy) + \exp_n(-ix)\exp_n(-iy))$ (err $\frac{a(-ix)(-iy)}{2n}$)
      iv. $= \frac{1}{4}(\exp_n(ix)\exp_n(iy) + \exp_n(-ix)\exp_n(-iy)) + \frac{1}{4}(\exp_n(ix)\exp_n(iy) + \exp_n(-ix)\exp_n(-iy))$
      v. $= \frac{1}{4}(\exp_n(ix)(\exp_n(iy) + \exp_n(-iy)) + (\exp_n(-ix) - \exp_n(ix))\exp_n(-iy)) + \frac{1}{4}((\exp_n(ix) - \exp_n(-ix))\exp_n(iy) + \exp_n(-ix)(\exp_n(iy) + \exp_n(-iy)))$
      vi. $= \frac{1}{2}\exp_n(ix)\cos_n(y) + \frac{1}{2i}\sin_n(x)\exp_n(-iy) - \frac{1}{2i}\sin_n(x)\exp_n(iy) + \frac{1}{2}\exp_n(-ix)\cos_n(y)$
      vii. $= \cos_n(x)\cos_n(y) - \sin_n(x)\sin_n(y)$
   (b) **Hence show that** $\cos_n(x+y) \equiv \cos_n(x)\cos_n(y) - \sin_n(x)\sin_n(y)$ (err $\frac{axy}{n}$) (err $\frac{aX^2}{n}$).
3. **Yield the tuple** $\langle a, b, p\rangle$.

Procedure III:44(3.25)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, b, and a procedure, $p(x, y, n)$, to show that $\sin_n(x+y) \equiv \sin_n(x)\cos_n(y) - \cos_n(x)\sin_n(y)$ (err $\frac{axy}{n}$) (err $\frac{aX^2}{n}$) when two complex numbers x, y and a positive integer $n > b$ such that $\|x\|^2 \leq X^2$ and $\|y\|^2 \leq X^2$ are chosen.

Implementation

Implementation is analogous to that of procedure III:43.

Procedure III:45(3.26)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, b, and a procedure, $p(x, n)$, to show that $\cos_n(x)^2 + \sin_n(x)^2 \equiv 1$ (err $\frac{a\|x\|^2}{n}$) (err $\frac{aX^2}{n}$) when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > b$ are chosen.

Implementation

1. Execute procedure III:36 on $\langle X\rangle$ and let $\langle a, b, q\rangle$ receive.
2. Let $p(x, n)$ be the following procedure:
   (a) Using procedure q, show that $\cos_n(x)^2 + \sin_n(y)^2$
      i. $= \frac{1}{4}(\exp_n(ix) + \exp_n(-ix))^2 + \frac{1}{4i^2}(\exp_n(ix) - \exp_n(-ix))^2$
      ii. $= \frac{1}{4}(\exp_n(ix)^2 + 2\exp_n(ix)\exp_n(-ix) + \exp_n(-ix)^2 - \exp_n(ix)^2 + 2\exp_n(ix)\exp_n(-ix) - \exp_n(-ix)^2)$
      iii. $= \exp_n(ix)\exp_n(-ix)$
      iv. $\equiv 1$ (err $\frac{a(-ix)(ix)}{n}$).
   (b) **Hence show that** $\cos_n(x)^2 + \sin_n(y)^2 \equiv 1$ (err $\frac{a\|x\|^2}{n}$) (err $\frac{aX^2}{n}$).
3. **Yield the tuple** $\langle a, b, p\rangle$.

Procedure III:46(sat0308190647)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, b, and a procedure, $p(x, y, n)$, to show that $\|x\exp_n(iy)\|^2 \equiv \|x\|^2$ (err $\frac{a\|x\|^2\|y\|^2}{n}$) (err $\frac{a\|x\|^2X^2}{n}$) when a complex number x, a rational number y, and a positive integer n such that $\|y\|^2 \leq X^2$ and $n > b$ are chosen.

Implementation

1. Execute procedure III:45 on $\langle X\rangle$ and let $\langle a, b, q\rangle$ receive.
2. Let $p(x, y, n)$ be the following procedure:
   (a) Using procedure q, procedure III:41, and procedure III:42, show that $\|x\exp_n(iy)\|^2$
      i. $= \|x\|^2\|\exp_n(iy)\|^2$
      ii. $= \|x\|^2\|\cos_n(y) + i\sin_n(y)\|^2$
      iii. $= \|x\|^2(\cos_n(y)^2 + \sin_n(y)^2)$

iv. $\equiv \|x\|^2 \cdot 1$ (err $\|x\|^2 \cdot \frac{a\|y\|^2}{n}$).

(b) **Hence show that** $\|x \exp_n(iy)\|^2 \equiv \|x\|^2$ (err $\frac{a\|xy\|^2}{n}$) (err $\frac{a\|x\|^2X^2}{n}$)**.**

Procedure III:47(3.29)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, N, and a procedure, $p(x, n)$, to show that $\cos_n(x) \equiv \sum_r^{[0:\lceil \frac{n}{2} \rceil]} \frac{(-1)^r x^{2r}}{(2r)!}$ (err $\frac{a}{n}$) when a complex number x and an integer $n > N$ such that $\|x\|^2 \leq X^2$ is chosen.

Implementation

1. Execute procedure III:40 on $\langle X \rangle$ and let $\langle a, N, q \rangle$ receive.
2. Let $p(x, n)$ be the following procedure:

(a) Using procedure q, show that $\cos_n(x)$

i. $= \frac{\exp_n(ix)}{2} + \frac{\exp_n(-ix)}{2}$

ii. $\equiv \frac{1}{2} \sum_r^{[0:n+1]} \frac{(ix)^r}{r!} + \frac{\exp_n(-ix)}{2}$ (err $\frac{a}{2n}$)

iii. $\equiv \frac{1}{2} \sum_r^{[0:n+1]} \frac{(ix)^r}{r!} + \frac{1}{2} \sum_r^{[0:n+1]} \frac{(-ix)^r}{r!}$ (err $\frac{a}{2n}$)

iv. $= \sum_r^{[0:n+1]} \frac{(i^r + (-i)^r) x^r}{2(r!)}$

v. $= \sum_r^{[0:n+1]} \frac{[r \bmod 2 = 0](-1)^{\frac{r}{2}} x^r}{r!}$

vi. $= \sum_r^{[0:\lceil \frac{n}{2} \rceil]} \frac{(-1)^r x^{2r}}{(2r)!}$.

(b) **Hence show that** $\cos_n(x) \equiv \sum_r^{[0:\lceil \frac{n}{2} \rceil]} \frac{(-1)^r x^{2r}}{(2r)!}$ (err $\frac{a}{n}$)**.**

Procedure III:48(3.30)

Objective

Choose a rational number $X \geq 0$. The objective of the following instructions is to construct two rational numbers a, N, and a procedure, $p(x, n)$, to show that $\sin_n(x) \equiv \sum_r^{[0:\lfloor \frac{n+1}{2} \rfloor]} \frac{(-1)^r x^{2r+1}}{(2r+1)!}$ (err $\frac{a}{n}$) when a complex number x and an integer $n > N$ such that $\|x\|^2 \leq X^2$ is chosen.

Implementation

Implementation is analogous to that of procedure III:47.

Chapter 11

Binomial and Mercator Series

Declaration III:16(sun2107190610)

The notation $(1+x)_n^a$, where x, a are complex numbers and n is a positive integer, will be used as a shorthand for $\sum_r^{[0:n]} \binom{a}{r} x^r$.

Procedure III:49(sun2107190619)

Objective

Choose a complex number x and two non-negative integers a, n such that $n > a$. The objective of the following instructions is to show that $(1+x)_n^a = (1+x)^a$.

Implementation

1. Using procedure III:22, show that $(1+x)_n^a =$
   (a) $= \sum_r^{[0:n]} \binom{a}{r} x^r$
   (b) $= \sum_r^{[0:n]} \frac{a^{\underline{r}}}{r!} x^r$
   (c) $= \sum_r^{[0:a+1]} \frac{a^{\underline{r}}}{r!} x^r + \sum_r^{[a+1:n]} \frac{a^{\underline{r}}}{r!} x^r$
   (d) $= \sum_r^{[0:a+1]} \frac{a^{\underline{r}}}{r!} x^r + \sum_r^{[a+1:n]} \frac{0}{r!} x^r$
   (e) $= \sum_r^{[0:a+1]} \binom{a}{r} x^r$
   (f) $= (1+x)^a$.

Procedure III:50(sun2107190640)

Objective

Choose two complex numbers x, y and a positive integer N. The objective of the following instructions is to show that $\binom{x+y}{N} = \sum_k^{N+1} \binom{x}{k} \binom{y}{N-k}$.

Implementation

1. If $N = 0$, then do the following:
   (a) Show that $\binom{x+y}{N} = 1 = \sum_k^{[0:N+1]} \binom{x}{k} \binom{y}{N-k}$.
2. Otherwise do the following:
   (a) Show that $N > 0$.
   (b) Show that $\binom{x+y-1}{N-1} = \sum_k^{[0:N]} \binom{x-1}{k} \binom{y}{N-1-k}$ using procedure III:50.
   (c) Show that $\binom{x+y-1}{N-1} = \sum_k^{[0:N]} \binom{x}{k} \binom{y-1}{N-1-k}$ using procedure III:50.
   (d) Hence show that $\binom{x+y}{N}$
      i. $= \frac{x+y}{N} \binom{x+y-1}{N-1}$
      ii. $= \frac{x}{N} \binom{x+y-1}{N-1} + \frac{y}{N} \binom{x+y-1}{N-1}$
      iii. $= \frac{x}{N} \sum_k^{[0:N]} \binom{x-1}{k} \binom{y}{N-1-k} + \frac{y}{N} \sum_k^{[0:N]} \binom{x}{k} \binom{y-1}{N-1-k}$
      iv. $= \frac{x}{N} \sum_k^{[1:N+1]} \binom{x-1}{k-1} \binom{y}{N-k} + \frac{y}{N} \sum_k^{[0:N]} \binom{x}{k} \binom{y-1}{N-1-k}$
      v. $= \sum_k^{[0:N+1]} \frac{k}{N} \binom{x}{k} \binom{y}{N-k} + \sum_k^{[0:N+1]} \frac{N-k}{N} \binom{x}{k} \binom{y}{N-k}$
      vi. $= \sum_k^{[0:N+1]} \binom{x}{k} \binom{y}{N-k}$.

Procedure III:51(sun2107191133)

Objective

Choose complex numbers a, b, x and a natural number n. The objective of the following instructions is to show that $(1+x)_n^a (1+x)_n^b - (1+x)_n^{a+b} = \sum_k^{[1:n]} \sum_r^{[k:n]} \binom{a}{k+n-1-r} \binom{b}{r} x^{k+n-1}$.

Implementation

1. Show that $(1+x)^a_n(1+x)^b_n-(1+x)^{a+b}_n$

 (a) $=(\sum_k^{[0:n]}\binom{a}{k}x^k)(\sum_r^{[0:n]}\binom{b}{r}x^r)-\sum_k^{[0:n]}\binom{a+b}{k}x^k$

 (b) $=\sum_k^{[0:n]}\sum_r^{[0:n]}\binom{a}{k}\binom{b}{r}x^{k+r}-\sum_k^{[0:n]}\binom{a+b}{k}x^k$

 (c) $=\sum_k^{[0:n]}\sum_r^{[0:k+1]}\binom{a}{k-r}\binom{b}{r}x^k+\sum_k^{[n:2n-1]}\sum_r^{[k-n+1:n]}\binom{a}{k-r}\binom{b}{r}x^k-\sum_k^{[0:n]}\binom{a+b}{k}x^k$

 (d) $=\sum_k^{[0:n]}\binom{a+b}{k}x^k+\sum_k^{[1:n]}\sum_r^{[k:n]}\binom{a}{k+n-1-r}\binom{b}{r}x^{k+n-1}-\sum_k^{[0:n]}\binom{a+b}{k}x^k$

 (e) $=\sum_k^{[1:n]}\sum_r^{[k:n]}\binom{a}{k+n-1-r}\binom{b}{r}x^{k+n-1}$.

Procedure III:52(sun2107191247)

Objective

Choose two rational numbers $A>0$ and $0<X<1$. The objective of the following instructions is to construct rational numbers $Y>0$, $0<Z<1$ and a procedure $p(a,x,n)$ to show that $\|\binom{a}{n}x^n\|^2\leq(YZ^n)^2$ when complex numbers a,x such that $\|a+1\|^2<A^2$ and $\|x\|^2<X^2$ are chosen.

Implementation

1. Let $e=\frac{AX}{1-X}-1$.
2. Let $d=\lfloor\frac{AX}{1-X}\rfloor$.
3. Show that $d>e>-1$.
4. Let $Z=(1+\frac{A}{d+1})X$.
5. Show that $0<Z<(1+\frac{A}{e+1})X=1$.
6. Let $Y=Z^{-d}\prod_k^{[0:d]}\frac{(A+k+1)X}{k+1}=Z^{-d}\prod_k^{[0:d]}X(1+\frac{A}{k+1})$.
7. Let $p(a,x,n)$ be the following procedure:

 (a) Show that $|\mathrm{re}(a+1)|\leq A$ given that $\mathrm{re}(a+1)^2\leq\|a+1\|^2\leq A^2$.

 (b) Hence show that $\|\binom{a}{n}x^n\|^2$

  i. $=\|\frac{a^{\underline{n}}}{n!}x^n\|^2$

  ii. $=\|\prod_k^{[0:n]}(\frac{a+1-(k+1)}{k+1}\cdot x)\|^2$

  iii. $=\prod_k^{[0:n]}\frac{\|(a+1)-(k+1)\|^2\|x\|^2}{(k+1)^2}$

  iv. $=\prod_k^{[0:n]}\frac{(\|a+1\|^2-2\,\mathrm{re}(a+1)(k+1)+(k+1)^2)\|x\|^2}{(k+1)^2}$

  v. $\leq\prod_k^{[0:n]}\frac{(A^2+2A(k+1)+(k+1)^2)X^2}{(k+1)^2}$

  vi. $=(\prod_k^{[0:n]}\frac{(A+k+1)X}{k+1})^2$

  vii. $=(\prod_k^{[0:n]}X(1+\frac{A}{k+1}))^2$.

 (c) If $n\leq d$, then do the following:

  i. Show that $\|\binom{a}{n}x^n\|^2$

   A. $\leq(\prod_k^{[0:n]}X(1+\frac{A}{k+1}))^2$

   B. $=(\prod_k^{[0:d]}X(1+\frac{A}{k+1}))^2(\prod_k^{[n:d]}X(1+\frac{A}{k+1}))^{-2}$

   C. $\leq(\prod_k^{[0:d]}X(1+\frac{A}{k+1}))^2(X(1+\frac{A}{d+1}))^{-2(d-n)}$

   D. $=Y^2Z^{2n}$.

 (d) Otherwise do the following:

  i. Show that $\|\binom{a}{n}x^n\|^2$

   A. $\leq(\prod_k^{[0:n]}X(1+\frac{A}{k+1}))^2$

   B. $=(\prod_k^{[0:d]}X(1+\frac{A}{k+1}))^2(\prod_k^{[d:n]}X(1+\frac{A}{k+1}))^2$

   C. $\leq(\prod_k^{[0:d]}X(1+\frac{A}{k+1}))^2(X(1+\frac{A}{d+1}))^{2(n-d)}$

   D. $=Y^2Z^{2n}$.

8. **Yield the tuple $\langle Y,Z,p\rangle$.**

Procedure III:53(wed2407191422)

Objective

Choose a rational number $0<X<1$ and a positive integer k. The objective of the following instructions is to construct rational numbers $Y>0$, $0<Z<1$ and a procedure $p(x,n)$ to show that $\|n^kx^n\|^2\leq(YZ^n)^2$ when a complex number x such that $\|x\|^2\leq X^2$ is chosen.

Implementation

1. Let $e=\frac{k}{1-X}-1$.
2. Let $d=\lfloor\frac{k}{1-X}\rfloor$.
3. Show that $d>e>k-1$.
4. Let $Z=(1+\frac{1}{d})^kX$.
5. Show that $Z<(1+\frac{1}{e})^kX$.

6. Now show that $0 < Z < (1+\frac{1}{e})^k X \leq \frac{1+\frac{1}{e}}{1-(k-1)\frac{1}{e}} \cdot X = 1$ using procedure II:31.
7. Let $Y = Z^{-d} X \prod_r^{[1:d]} X(1+\frac{1}{r})^k$.
8. Let $p(x, n)$ be the following procedure:
   (a) Show that $\|n^k x^n\|^2$
      i. $\leq \|x \prod_r^{[1:n]} x \cdot \frac{(r+1)^k}{r^k}\|^2$
      ii. $= \|x\|^2 \prod_r^{[1:n]} \|x\|^2 (\frac{(r+1)^k}{r^k})^2$
      iii. $\leq X^2 \prod_r^{[1:n]} ((1+\frac{1}{r})^k X)^2$.
   (b) If $n \leq d$, then do the following:
      i. Show that $\|n^k x^n\|^2$
         A. $\leq X^2 (\prod_r^{[1:n]} X(1+\frac{1}{r})^k)^2$
         B. $= X^2 (\prod_r^{[1:d]} X(1+\frac{1}{r})^k)^2 \cdot (\prod_r^{[n:d]} X(1+\frac{1}{r})^k)^{-2}$
         C. $\leq X^2 (\prod_r^{[1:d]} X(1+\frac{1}{r})^k)^2 (X(1+\frac{1}{d})^k)^{-2(d-n)}$
         D. $= Y^2 Z^{2n}$.
   (c) Otherwise do the following:
      i. Show that $\|n^k x^n\|^2$
         A. $\leq X^2 (\prod_r^{[1:n]} X(1+\frac{1}{r})^k)^2$
         B. $= X^2 (\prod_r^{[1:d]} X(1+\frac{1}{r})^k)^2 (\prod_r^{[d:n]} X(1+\frac{1}{r})^k)^2$
         C. $\leq X^2 (\prod_r^{[1:d]} X(1+\frac{1}{r})^k)^2 (X(1+\frac{1}{d})^k)^{2(n-d)}$
         D. $= Y^2 Z^{2n}$.
9. **Yield the tuple** $\langle Y, Z, p \rangle$.

Procedure III:54(wed2407191521)

Objective

Choose two rational numbers $A > 0$, $1 > X > 0$. The objective of the following instructions is to construct rational numbers $D > 0$, $0 < G < 1$, and a procedure $p(x, a, b, n)$ to show that $(1+x)_n^{a+b} \equiv (1+x)_n^a (1+x)_n^b$ (err DG^n) when $\|x\|^2 \leq X$, and $\|a\|^2, \|b\|^2 < A$.

Implementation

1. Execute procedure III:52 on $\langle A, X \rangle$ and let $\langle B, C, q \rangle$ receive.
2. Execute procedure III:53 on $\langle C, 1 \rangle$ and let $\langle F, G, t \rangle$ receive.
3. Let $D = \frac{B^2 F}{1-C}$.
4. Let $p(x, a, b, n)$ be the following procedure:
   (a) For each $r \in [1:n]$, do the following:
      i. Show that $\|\binom{a}{r} x^r\|^2 \leq (BC^r)^2$ using procedure q.
      ii. Show that $\|\binom{b}{r} x^r\|^2 \leq (BC^r)^2$ using procedure q, .
   (b) Show that $\|nC^n\|^2 \leq (FG^n)^2$ using procedure t.
   (c) Hence show that $(1+x)_n^{a+b} \equiv (1+x)_n^a (1+x)_n^b$
      i. (err $(1+x)_n^a (1+x)_n^b - (1+x)_n^{a+b}$)
      ii. (err $\sum_k^{[1:n]} \sum_r^{[k:n]} \binom{a}{k+n-1-r} \binom{b}{r} x^{k+n-1}$)
      iii. (err $\sum_k^{[1:n]} \sum_r^{[k:n]} \binom{a}{k+n-1-r} x^{k+n-1-r} \binom{b}{r} x^r$)
      iv. (err $\sum_k^{[1:n]} \sum_r^{[k:n]} BC^{k+n-1-r} BC^r$)
      v. (err $B^2 C^n \sum_k^{[1:n]} \sum_r^{[k:n]} C^{k-1}$)
      vi. (err $B^2 C^n \sum_r^{[1:n]} \sum_k^{[1:r+1]} C^{k-1}$)
      vii. (err $B^2 C^n \sum_r^{[1:n]} \frac{1}{1-C}$)
      viii. (err $\frac{B^2}{1-C} \cdot nC^n$)
      ix. (err $\frac{B^2 F}{1-C} G^n$)
      x. (err DG^n).
5. **Yield the tuple** $\langle D, G, p \rangle$.

Procedure III:55(wed2407191611)

Objective

Choose two rational numbers $A > 0$, $1 > X > 0$. The objective of the following instructions is to construct a rational number D and a procedure $p(x, n, a, k)$ to show that $\|((1+x)_n^a)^k\|^2 < D^2$ when complex numbers x, a and positive integers n, k such that $\|x\|^2 < X^2$ and $\|ka\|^2 < A^2$.

Implementation

1. Execute procedure III:34 on $\langle \frac{ABX}{1-C} \rangle$ and let $\langle E, N, t \rangle$ receive.
2. Execute procedure III:52 on $\langle A+1, X \rangle$ and let $\langle B, C, q \rangle$ receive.
3. Let $D = \max(E, (1 + \frac{ABX}{1-C})^{\lfloor N \rfloor})$.
4. Let $p(x, n, a, k)$ be the following procedure:
   (a) For each $r \in [1:n]$, do the following:
      i. Show that $\|a\|^2 \le \|ka\|^2 \le A^2$.
      ii. Show that $\|a-1\|^2 \le (A+1)^2$.
      iii. Hence show that $\|\binom{a-1}{r-1}x^{r-1}\|^2 \le (BC^r)^2$ using procedure q.

   (b) Hence show that $\|k \sum_r^{[1:n]} \binom{a}{r} x^r\|^2$
      i. $= \|k \sum_r^{[1:n]} \frac{a}{r} \binom{a-1}{r-1} x^r\|^2$
      ii. $= \|kax \sum_r^{[1:n]} \frac{1}{r} \binom{a-1}{r-1} x^{r-1}\|^2$
      iii. $\le (AX \sum_r^{[1:n]} BC^{r-1})^2$
      iv. $\le (\frac{ABX}{1-C})^2$.

   (c) If $k > N$, then do the following:
      i. Hence using procedure t, show that $\|((1+x)_n^a)^k\|^2$
         A. $= \|(\sum_r^{[0:n]} \binom{a}{r} x^r)^k\|^2$
         B. $= \|(1 + \sum_r^{[1:n]} \binom{a}{r} x^r)^k\|^2$
         C. $= \|\exp_k(k \sum_r^{[1:n]} \binom{a}{r} x^r)\|^2$
         D. $\le E^2$
         E. $\le D^2$.

   (d) Otherwise do the following:
      i. Show that $\|\sum_r^{[1:n]} \binom{a}{r} x^r)^k\|^2$
         A. $\le \|k \sum_r^{[1:n]} \binom{a}{r} x^r\|^2$
         B. $\le (\frac{ABX}{1-C})^2$.
      ii. Hence show that $\|((1+x)_n^a)^k\|^2$
         A. $= (\|(1+x)_n^a\|^2)^k$
         B. $= (\|1 + \sum_r^{[1:n]} \binom{a}{r} x^r\|^2)^k$
         C. $\le (1 + \frac{ABX}{1-C})^{2k}$
         D. $\le D^2$.
5. **Yield** $\langle D, p \rangle$.

Procedure III:56(tue2008190712)

Objective

Choose two rational numbers $A > 0$, $1 > X > 0$. The objective of the following instructions is to construct positive rational numbers D, N, and a procedure $p(x, a, n)$ to show that $\|(1+x)_n^a\|^2 \ge D^2$ when complex numbers x, a and an integer n such that $\|x\|^2 \le X^2$, $\|a\| \le A^2$, and $n > N$ are chosen.

Implementation

1. Execute procedure III:54 on $\langle A, X \rangle$ and let $\langle a_1, b_1, p_1 \rangle$ receive.
2. Execute procedure III:53 on $\langle b_1, 1 \rangle$ and let $\langle a_2, b_2, p_2 \rangle$ receive.
3. Execute procedure III:55 on $\langle A, X \rangle$ and let $\langle a_3, p_3 \rangle$ receive.
4. Let $D = \frac{1}{2a_3}$.
5. Let $N = 2a_1a_2$.
6. Let $p(x, a, n)$ be the following procedure:
   (a) Show that $\|n{b_1}^n\|^2 \le (a_2{b_2}^n)^2 \le {a_2}^2$ using procedure p_2.
   (b) Hence show that $(a_1{b_1}^n)^2 \le (\frac{a_1a_2}{n})^2$.
   (c) Show that $\|((1+x)_n^{-a})^1\|^2 \le {a_3}^2$ using procedure p_3.
   (d) Using procedure p_1, show that $\|(1+x)_n^{-a}(1+x)_n^a - 1\|^2$
      i. $= \|(1+x)_n^{-a}(1+x)_n^a - (1+x)_n^{-a+a}\|^2$
      ii. $\le (a_1{b_1}^n)^2$.
   (e) Hence using procedure III:17, show that $\frac{1}{2} - \|(1+x)_n^{-a}(1+x)_n^a\|^2$
      i. $= \frac{1}{2}\|1\|^2 - \|(1+x)_n^{-a}(1+x)_n^a\|^2$
      ii. $\le \|1 - (1+x)_n^{-a}(1+x)_n^a\|^2$
      iii. $\le (a_1{b_1}^n)^2$
      iv. $\le (\frac{a_1a_2}{n})^2$
      v. $\le \frac{1}{4}$.
   (f) Hence show that $(\frac{1}{2})^2$
      i. $\le \|(1+x)_n^{-a}(1+x)_n^a\|^2$

ii. $\leq {a_3}^2 \|(1+x)^a_n\|^2$.

(g) **Hence show that** $D^2 \leq \|(1+x)^a_n\|^2$**.**

7. **Yield the tuple** $\langle D, N, p\rangle$**.**

Procedure III:57(tue2008190849)

Objective

Choose two rational numbers $A > 0$ and $1 > X > 0$. The objective of the following instructions is to construct positive rational numbers B, C, D, and a procedure $p(x, a, b, n)$ to show that $(1+x)^{a-b}_n \equiv \frac{(1+x)^a_n}{(1+x)^b_n}$ (err BC^n) when complex numbers x, a, b and an integer n such that $\|x\|^2 \leq X^2$, $\|a\|^2 \leq A^2$, $\|b\|^2 \leq A^2$, and $n > D$ are chosen.

Implementation

1. Execute procedure III:54 on $\langle A, X\rangle$ and let $\langle a_1, C, p_1\rangle$ receive.
2. Execute procedure III:56 on $\langle A, X\rangle$ and let $\langle a_2, D, p_2\rangle$ receive.
3. Execute procedure III:55 on $\langle A, X\rangle$ and let $\langle a_3, p_3\rangle$ receive.
4. Let $B = (1 + \frac{a_3}{a_2})a_1$.
5. Let $p(x, a, b, n)$ be the following procedure:

(a) Using procedures p_1, p_2, p_3, show that $(1+x)^{a-b}_n$

i. $\equiv (1+x)^a_n(1+x)^{-b}_n$ (err $a_1 C^n$)

ii. $= (1+x)^a_n \frac{(1+x)^b_n(1+x)^{-b}_n}{(1+x)^b_n}$

iii. $\equiv ((1+x)^a_n)^1 \frac{(1+x)^{b-b}_n}{(1+x)^b_n}$ (err $a_3\frac{a_1C^n}{a_2}$)

iv. $= \frac{(1+x)^a_n}{(1+x)^b_n}$

(b) **Hence show that** $(1+x)^{a-b}_n \equiv \frac{(1+x)^a_n}{(1+x)^b_n}$ (err $(1+\frac{a_3}{a_2})a_1C^n$) (err BC^n)**.**

6. **Yield the tuple** $\langle B, C, D, p\rangle$**.**

Procedure III:58(wed2407191627)

Objective

Choose two rational numbers $A > 0$, $1 > X > 0$. The objective of the following instructions is to construct rational numbers $G > 0$, $0 < C < 1$, and a procedure $p(x, n, a, k)$ to show that $(1+x)^{ka}_n \equiv ((1+x)^a_n)^k$ (err GkC^n) when a non-negative integer k and complex numbers x, a such that $\|x\|^2 \leq X^2$ and $\|ka\|^2 < A^2$ are chosen.

Implementation

1. Execute procedure III:55 on $\langle A, X\rangle$ and let $\langle D, t\rangle$ receive.
2. Execute procedure III:54 on $\langle A, X\rangle$ and let $\langle B, C, q\rangle$ receive.
3. Let $G = DB$.
4. Let $p(x, n, a, k)$ be the following procedure:

(a) Hence using procedures t, q, show that $(1+x)^{ka}_n$

i. $= ((1+x)^a_n)^0(1+x)^{ka}_n$

ii. $\equiv ((1+x)^a_n)^1(1+x)^{(k-1)a}_n$ (err DBC^n)

iii. $\equiv ((1+x)^a_n)^2(1+x)^{(k-2)a}_n$ (err DBC^n)

iv. $\vdots$

v. $\equiv ((1+x)^a_n)^k(1+x)^{(k-k)a}_n$ (err DBC^n)

vi. $= ((1+x)^a_n)^k$.

(b) **Hence show that** $(1+x)^{ka}_n \equiv ((1+x)^a_n)^k$ (err $kDBC^n$) (err GkC^n)**.**

5. **Yield the tuple** $\langle G, C, D, p\rangle$**.**

Procedure III:59(sun0812190858)

Objective

Choose two non-negative rational numbers a, b and two non-negative integers r, n such that $b < r < n - a - 1$. The objective of the following instructions is to show that $\text{sgn}(\binom{b}{r}\binom{a}{n-r}) = \text{sgn}(\binom{b}{r+1}\binom{a}{n-r-1})$.

Implementation

1. Show that $\text{sgn}(\frac{b-r}{r+1} \cdot \frac{n-r}{a-n+r+1}) = 1$

(a) given that $\frac{b-r}{r+1} \cdot \frac{n-r}{a-n+r+1} > 0$

(b) given that $\frac{b-r}{(a+1)-(n-r)} > 0$

(c) given that $r > b$ and $n - r > a + 1$.

2. Hence show that $\text{sgn}(\binom{b}{r+1}\binom{a}{n-r-1})$

(a) $= \text{sgn}(\frac{b-r}{r+1}\binom{b}{r} \cdot \frac{n-r}{a-n+r+1}\binom{a}{n-r})$

(b) $= \text{sgn}(\frac{b-r}{r+1} \cdot \frac{n-r}{a-n+r+1})\,\text{sgn}(\binom{b}{r}\binom{a}{n-r})$

(c) $= \mathrm{sgn}(\binom{b}{r}\binom{a}{n-r})$.

Procedure III:60(sun0812190920)

Objective

Choose two non-negative rational numbers a, b and an integer $n \geq \lceil a \rceil + \lceil b \rceil$. The objective of the following instructions is to show that $\sum_r^{[0:n+1]} \|\binom{b}{r}\binom{a}{n-r}\| = \sum_r^{[0:\lceil b \rceil]} \|\binom{b}{r}\binom{a}{n-r}\| + \|\sum_r^{[\lceil b \rceil:\lceil n-a \rceil]} \binom{b}{r}\binom{a}{n-r}\| + \sum_r^{[\lceil n-a \rceil:n+1]} \|\binom{b}{r}\binom{a}{n-r}\|$.

Implementation

1. Verify that $\lceil b \rceil \leq \lfloor n-a \rfloor$.
2. For r in $[\lceil b \rceil : \lfloor n-a \rfloor]$, do the following:
   (a) Show that $\mathrm{sgn}(\binom{b}{r}\binom{a}{n-r}) = \mathrm{sgn}(\binom{b}{r+1}\binom{a}{n-r-1})$ using procedure III:59.
3. Hence show that $\sum_r^{[\lceil b \rceil:\lceil n-a \rceil]} \|\binom{b}{r}\binom{a}{n-r}\| = \|\sum_r^{[\lceil b \rceil:\lceil n-a \rceil]} \binom{b}{r}\binom{a}{n-r}\|$.
4. Hence show that $\sum_r^{[0:n+1]} \|\binom{b}{r}\binom{a}{n-r}\|$
   (a) $= \sum_r^{[0:\lceil b \rceil]} \|\binom{b}{r}\binom{a}{n-r}\| + \sum_r^{[\lceil b \rceil:\lceil n-a \rceil]} \|\binom{b}{r}\binom{a}{n-r}\| + \sum_r^{[\lceil n-a \rceil:n+1]} \|\binom{b}{r}\binom{a}{n-r}\|$
   (b) $= \sum_r^{[0:\lceil b \rceil]} \|\binom{b}{r}\binom{a}{n-r}\| + \|\sum_r^{[\lceil b \rceil:\lceil n-a \rceil]} \binom{b}{r}\binom{a}{n-r}\| + \sum_r^{[\lceil n-a \rceil:n+1]} \|\binom{b}{r}\binom{a}{n-r}\|$.

Procedure III:61(wed2407191824)

Objective

Choose a rational number $A > 0$. The objective of the following instructions is to construct rational numbers $M > 1$, $N > 0$, and a procedure $p(a, n)$ to show that $\|\binom{a}{n}\|^2 \leq (\frac{M}{n})^{2(\lceil a \rceil)}$ and $\frac{M}{n} < 1$ when a rational number $-1 < a < A$ and an integer $n > N$ are chosen.

Implementation

1. Let $M = 2A$.
2. Let $N = 2A$.
3. Let $p(a, n)$ be the following procedure:
   (a) Show that $\frac{2a}{n} < \frac{2A}{2A} = 1$
      i. given that $n > N = 2A > 2a$
      ii. and $-1 < a < A$.
   (b) Show that $n - \lfloor a \rfloor > n - a > n - \frac{n}{2} = \frac{n}{2}$
      i. given that $\frac{n}{2} > a$
      ii. given that $n > N = 2A > 2a$.
   (c) Hence show that $\|\binom{a}{n}\|^2$
      i. $= \|\frac{a^{\underline{n}}}{n!}\|^2$
      ii. $= \|\prod_k^{[0:n]} \frac{a-k}{k+1}\|^2$
      iii. $= \prod_k^{[0:n]} \frac{(a-k)^2}{(k+1)^2}$
      iv. $= \prod_k^{[0:\lceil a \rceil]} (k-a)^2 \cdot \prod_k^{[0:n]} \frac{(k+\lfloor a \rfloor+1-a)^2}{(k+1)^2} \cdot \prod_k^{[n-\lceil a \rceil:n]} \frac{1}{(k+1)^2}$
      v. $\leq (a^{\lceil a \rceil} \cdot 1^n \cdot (\frac{1}{n-\lfloor a \rfloor})^{\lceil a \rceil})^2$
      vi. $= (\frac{a}{n-\lfloor a \rfloor})^{2(\lceil a \rceil)}$
      vii. $\leq (\frac{2a}{n})^{2(\lceil a \rceil)}$
      viii. $\leq (\frac{M}{n})^{2(\lceil a \rceil)}$.
4. **Yield the tuple $\langle M, N, p \rangle$.**

Procedure III:62(sun0812191002)

Objective

Choose a positive integer A. The objective of the following instructions is to construct a rational number B, an integer N, and a procedure $p(a, b, n)$ to show that $\sum_r^{[0:n+1]} \|\binom{b}{r}\binom{a}{n-r}\| \leq \frac{B}{n}$ when non-negative rational numbers a, b, and an integer n such that $a < A$, $b < A$, and $n > N$ are chosen.

Implementation

1. Execute procedure III:61 on $\langle A \rangle$ and let $\langle M, Q, q \rangle$ receive.
2. Let $N = \max(2A, Q + A)$.
3. Let $B = M^A(M^A + 8A!A)$.
4. Let $p(a, b, n)$ be the following procedure:
   (a) Show that $n > N \geq Q$.
   (b) Now show that $\|\binom{a+b}{n}\| \leq (\frac{M}{n})^{\lceil a+b \rceil} \leq \frac{M^{\lceil A+b \rceil}}{n} \leq \frac{M^{A+\lceil b \rceil}}{n} \leq \frac{M^{2A}}{n}$ using procedure q.
   (c) For r in $[0 : \lceil b \rceil]$, do the following:
      i. Show that $n - r \geq N - \lceil b \rceil \geq Q + A - A = Q$.

ii. Now show that $\|\binom{a}{n-r}\|^2 \le (\frac{M}{n-r})^{2\lceil a\rceil} \le (\frac{M^A}{r})^2 \le (\frac{M^A}{n-\lfloor a\rfloor})^2 \le (\frac{M^A}{n-A})^2 \le (\frac{M^A}{n-\frac{1}{2}N})^2 \le (\frac{M^A}{\frac{1}{2}n})^2 = (\frac{2M^A}{n})^2$ using procedure q.

(d) For r in $[\lceil n-a\rceil : n+1]$, do the following:

i. Show that $r \ge \lceil n-a\rceil = n-\lfloor a\rfloor \ge N-\lfloor a\rfloor \ge Q+A-A = Q$.

ii. Now show that $\|\binom{b}{r}\|^2 \le (\frac{M}{r})^{2\lceil b\rceil} \le (\frac{M^A}{r})^2 \le (\frac{2M^A}{n})^2$ using procedure q.

(e) Hence using procedure III:60, show that $\sum_r^{[0:n+1]}\|\binom{b}{r}\binom{a}{n-r}\|$

i. $= \sum_r^{[0:\lceil b\rceil]}\|\binom{b}{r}\binom{a}{n-r}\| + \|\sum_r^{[\lceil b\rceil:\lceil n-a\rceil]}\binom{b}{r}\binom{a}{n-r}\| + \sum_r^{[\lceil n-a\rceil:n+1]}\|\binom{b}{r}\binom{a}{n-r}\|$

ii. $= \sum_r^{[0:\lceil b\rceil]}\|\binom{b}{r}\binom{a}{n-r}\| + \|\sum_r^{[0:n+1]}\binom{b}{r}\binom{a}{n-r} - \sum_r^{[0:\lceil b\rceil]}\binom{b}{r}\binom{a}{n-r} - \sum_r^{[\lceil n-a\rceil:n+1]}\binom{b}{r}\binom{a}{n-r}\| + \sum_r^{[\lceil n-a\rceil:n+1]}\|\binom{b}{r}\binom{a}{n-r}\|$

iii. $= 2\sum_r^{[0:\lceil b\rceil]}\|\binom{b}{r}\binom{a}{n-r}\| + \|\sum_r^{[0:n+1]}\binom{b}{r}\binom{a}{n-r}\| + 2\sum_r^{[\lceil n-a\rceil:n+1]}\|\binom{b}{r}\binom{a}{n-r}\|$

iv. $= \|\binom{a+b}{n}\| + 2(\sum_r^{[0:\lceil b\rceil]}\|\binom{b}{r}\binom{a}{n-r}\| + \sum_r^{[\lceil n-a\rceil:n+1]}\|\binom{b}{r}\binom{a}{n-r}\|)$

v. $\le \frac{M^{2A}}{n} + 2(\sum_r^{[0:\lceil b\rceil]} A!\frac{2M^A}{n} + \sum_r^{[\lceil n-a\rceil:n+1]} \frac{2M^A}{n}A!)$

vi. $\le \frac{M^A}{n}(M^A + 8\frac{A!A}{n})$

vii. $= \frac{B}{n}$.

5. **Yield the tuple $\langle B, N, p\rangle$.**

Procedure III:63(thu2507190646)

Objective

Choose a rational number $1 > X \ge 0$. The objective of the following instructions is to construct rational numbers $B > 0$, $N > 0$, and a procedure $p(x,a,b,n)$ to show that $(1+x)_n^{a+b} \equiv (1+x)_n^a(1+x)_n^b$ (err $\frac{B}{n}$) when a complex number x, two positive rational numbers a, b, and a positive integer n such that $\|x\|^2 \le 1$, $\mathrm{re}(x) \ge -X$, $a < 1$, $b < 1$, and $n > N$ are chosen.

Implementation

1. Execute procedure III:62 on $\langle 1\rangle$ and let $\langle M, N, q\rangle$ receive.
2. Let $B = \frac{2M}{1-X}$.
3. Let $p(x,a,b,n)$ be the following procedure:

(a) For $r \in [1:n]$, for $k \in [0:r]$, show that $\binom{a}{k+1+n-r}(-1)^{k+1} - \binom{a}{k+n-r}(-1)^k$

i. $= (-1)^{k+1}(\binom{a}{k+1+n-r} + \binom{a}{k+n-r})$

ii. $= (-1)^{k+1}\binom{a+1}{k+1+n-r}$

iii. $= (-1)^{-(k+1)}\|\binom{a+1}{k+1+n-r}\|(-1)^{k+1+n-r}$

iv. $= \|\binom{a+1}{k+1+n-r}\|(-1)^{n-r}$.

(b) Now show that $\sum_r^{[0:n+1]}\|\binom{b}{r}\binom{a}{n-r}\| \le \frac{M}{n}$ using procedure q.

(c) Show that $\|x+1\|^2 = \mathrm{re}(x+1)^2 + \mathrm{im}(x)^2 \ge (1-X)^2$.

(d) Hence using procedure III:51, show that $(1+x)_n^{a+b} \equiv (1+x)_n^a(1+x)_n^b$

i. (err $(1+x)_n^a(1+x)_n^b - (1+x)_n^{a+b}$)

ii. (err $\sum_k^{[1:n]}\sum_r^{[k:n]}\binom{a}{k+n-1-r}\binom{b}{r}x^{k+n-1}$)

iii. (err $x^n\sum_r^{[1:n]}\binom{b}{r}\sum_k^{[0:r]}\binom{a}{k+n-r}x^k$)

iv. (err $x^n\sum_r^{[1:n]}\binom{b}{r}\sum_k^{[0:r]}(\binom{a}{k+1+n-r}(-1)^{k+1}\cdot\frac{(-x)^{k+1}}{-x-1} - \binom{a}{k+n-r}(-1)^k\cdot\frac{(-x)^k}{-x-1} - \frac{(-x)^{k+1}}{-x-1}(\binom{a}{k+1+n-r}(-1)^{k+1} - \binom{a}{k+n-r}(-1)^k)))$

v. (err $\frac{x^n}{x+1}\sum_r^{[1:n]}\binom{b}{r}(\binom{a}{n}x^r - \binom{a}{n-r} - \sum_k^{[0:r]}(-x)^{k+1}(\binom{a}{k+1+n-r}(-1)^{k+1} - \binom{a}{k+n-r}(-1)^k)))$

vi. (err $\frac{1}{1-X}\sum_r^{[1:n]}\|\binom{b}{r}\|(\|\binom{a}{n}\| + \|\binom{a}{n-r}\| + \sum_k^{[0:r]}\|\binom{a}{k+1+n-r}(-1)^{k+1} - \binom{a}{k+n-r}(-1)^k\|)$)

vii. (err $\frac{1}{1-X}\sum_r^{[1:n]}\|\binom{b}{r}\|(\|\binom{a}{n}\| + \|\binom{a}{n-r}\| + \|\sum_k^{[0:r]}(\binom{a}{k+1+n-r}(-1)^{k+1} - \binom{a}{k+n-r}(-1)^k)\|)$)

viii. (err $\frac{1}{1-X}\sum_r^{[1:n]}\|\binom{b}{r}\|(\|\binom{a}{n}\| + \|\binom{a}{n-r}\| + \|\binom{a}{n}(-1)^r - \binom{a}{n-r}\|)$)

ix. (err $\frac{2}{1-X}\sum_r^{[1:n]}\|\binom{b}{r}\|\|\binom{a}{n-r}\|$)

x. (err $\frac{B}{n}$).

4. **Yield the tuple $\langle B, N, p\rangle$.**

Procedure III:64(thu2507191017)

Objective

Choose a rational number $0 \le X < 1$. The objective of the following instructions is to construct a positive rational number D such that $D > 1$, and a procedure $p(x, n, a, k)$ to show that $\|((1+x)_n^a)^k\|^2 < D^2$ when a complex number x, a rational number a, and positive integers n, k such that $\|x\|^2 \le 1$, $\mathrm{re}(x) \ge -X$, and $(ka)^2 < 1$ are chosen.

Implementation

1. Execute procedure III:34 on $\langle \frac{2}{1-X}\rangle$ and let $\langle E, N, q\rangle$ receive.
2. Let $D = \max(E, (1 + \frac{2}{1-X})^{\lfloor N \rfloor})$.
3. Let $p(x, n, a, k)$ be the following procedure:

(a) For $t \in [1 : n]$, show that $\binom{a}{t+1}(-1)^{t+1} - \binom{a}{t}(-1)^t$

i. $= (-1)^{t+1}(\binom{a}{t+1} + \binom{a}{t})$

ii. $= (-1)^{t+1} \cdot \frac{(a+1)^{\underline{t+1}}}{(t+1)!}$

iii. > 0.

(b) Hence show that $\|k \sum_t^{[1:n]} \binom{a}{t} x^t\|^2$

i. $= \|k \sum_t^{[1:n]}(\binom{a}{t+1}(-1)^{t+1} \cdot \frac{(-x)^{t+1}}{-x-1} - \binom{a}{t}(-1)^t \cdot \frac{(-x)^t}{-x-1} - \frac{(-x)^{t+1}}{-x-1}(\binom{a}{t+1}(-1)^{t+1} - \binom{a}{t}(-1)^t))\|^2$

ii. $= \frac{k^2}{\|x+1\|^2}\|\binom{a}{n}x^n - \binom{a}{1}x^1 - \sum_t^{[1:n]}(-x)^{t+1}(\binom{a}{t+1}(-1)^{t+1} - \binom{a}{t}(-1)^t)\|^2$

iii. $\le \frac{k^2}{(\mathrm{re}(x)+1)^2+\mathrm{im}(x)^2}(|\binom{a}{n}| + a + \sum_t^{[1:n]}|\binom{a}{t+1}(-1)^{t+1} - \binom{a}{t}(-1)^t|)^2$

iv. $\le \frac{k^2}{(1-X)^2}(|\binom{a}{n}| + a + \sum_t^{[1:n]}(\binom{a}{t+1}(-1)^{t+1} - \binom{a}{t}(-1)^t))^2$

v. $= \frac{k^2}{(1-X)^2}(|\binom{a}{n}| + a + \binom{a}{n}(-1)^n - \binom{a}{1}(-1)^1)^2$

vi. $= \frac{k^2}{(1-X)^2}(|\binom{a}{n}| + a - |\binom{a}{n}| + a)^2$

vii. $= (\frac{2ak}{1-X})^2$

viii. $\le (\frac{2}{1-X})^2$.

(c) If $k > N$, then do the following:

i. Using procedure q, show that $\|((1+x)_n^a)^k\|^2$

A. $= \|(\sum_t^{[0:n]} \binom{a}{t} x^t)^k\|^2$

B. $= \|(1 + \sum_t^{[1:n]} \binom{a}{t} x^t)^k\|^2$

C. $= \|\exp_k(k \sum_t^{[1:n]} \binom{a}{t} x^t)\|^2$

D. $\le E^2$.

E. $\le D^2$.

(d) Otherwise do the following:

i. Show that $\|\sum_t^{[1:n]} \binom{a}{t} x^t\|^2$

A. $\le \|k \sum_t^{[1:n]} \binom{a}{t} x^t\|^2$

B. $\le (\frac{2}{1-X})^2$.

ii. Hence show that $\|((1+x)_n^a)^k\|^2$

A. $= (\|(1+x)_n^a\|^2)^k$

B. $= (\|1 + \sum_t^{[1:n]} \binom{a}{t} x^t\|^2)^k$

C. $\le (1 + \frac{2}{1-X})^{2k}$

D. $\le D^2$.

4. **Yield the tuple $\langle D, p\rangle$.**

Procedure III:65(thu2507190752)

Objective

Choose a rational number $0 \le X < 1$. The objective of the following instructions is to construct positive rational numbers G, N and a procedure $p(x, n, a, k)$ to show that $(1+x)_n^{ka} \equiv ((1+x)_n^a)^k$ (err $\frac{Gk}{n}$) when positive integers n, k, a rational number a, and a complex number x such that $\|x\|^2 \le 1$, $\mathrm{re}(x) \ge -X$, $k > 1$, $0 < ka \le 1$, and $n > N$ are chosen.

Implementation

1. Execute procedure III:64 on $\langle X\rangle$ and let $\langle D, t\rangle$ receive.
2. Execute procedure III:63 on $\langle X\rangle$ and let $\langle B, N, q\rangle$ receive.
3. Let $G = DB$.
4. Let $p(x, n, a, k)$ be the following procedure:

(a) Using procedures t, q, show that $(1+x)_n^{ka}$

i. $= ((1+x)^{a}_{n})^{0}(1+x)^{ka}_{n}$

ii. $\equiv ((1+x)^{a}_{n})^{1}(1+x)^{(k-1)a}_{n}$ (err $D\frac{B}{n}$)

iii. $\equiv ((1+x)^{a}_{n})^{2}(1+x)^{(k-2)a}_{n}$ (err $D\frac{B}{n}$)

iv. $\vdots$

v. $\equiv ((1+x)^{a}_{n})^{k}(1+x)^{(k-k)a}_{n}$ (err $D\frac{B}{n}$)

vi. $= ((1+x)^{a}_{n})^{k}$.

(b) **Hence show that** $(1+x)^{ka}_{n} \equiv ((1+x)^{a}_{n})^{k}$ (err $\frac{DBk}{n}$) (err $\frac{Gk}{n}$)**.**

5. **Yield the tuple** $\langle G, D, N, p\rangle$**.**

Procedure III:66(fri2607191210)

Objective

Choose a rational number $1 > X \geq 0$. The objective of the following instructions is to construct positive rational numbers a, c such that $b > 1$, and a procedure $p(x, n, k)$ to show that $\exp_n(n((1+x)^{\frac{1}{n}}_{k} - 1)) \equiv 1 + x$ (err $\frac{an}{k}$) when a complex number x, and positive integers n, k such that $\|x\|^2 \leq 1$, $\mathrm{re}(x) \geq -X$, $n > 1$, and $k > c$ are chosen.

Implementation

1. Execute procedure III:65 on $\langle X\rangle$ and let $\langle a, c, p_1\rangle$ receive.
2. Let $p(x, n, k)$ be the following procedure:

(a) Using procedure p_1 and procedure III:49, show that $\exp_n(n((1+x)^{\frac{1}{n}}_{k} - 1))$

i. $= (1 + \frac{1}{n}(n((1+x)^{\frac{1}{n}}_{k} - 1)))^n$

ii. $= ((1+x)^{\frac{1}{n}}_{k})^n$

iii. $\equiv (1+x)^{1}_{k}$ (err $\frac{an}{k}$)

iv. $= (1+x)^1$

v. $= 1 + x$.

(b) **Hence show that** $\exp_n(n((1+x)^{\frac{1}{n}}_{k} - 1)) \equiv 1 + x$ (err $\frac{an}{k}$)**.**

3. **Yield the tuple** $\langle a, c, p\rangle$**.**

Procedure III:67(fri2607191243)

Objective

Choose a rational number $1 > X \geq 0$. The objective of the following instructions is to construct a rational number $a > 0$ and a procedure $p(x, n, k)$ to show that $\|n((1+x)^{\frac{1}{n}}_{k} - 1)\|^2 \leq a^2$ when positive integers n, k, and a complex number x such that $\|x\|^2 \leq 1$ and $\mathrm{re}(x) \geq -X$ are chosen.

Implementation

1. Let $a = \frac{2}{1-X}$.
2. Let $p(x, n, k)$ be the following procedure:

(a) Show that $\|n((1+x)^{\frac{1}{n}}_{k} - 1)\|^2$

i. $= \|n(\sum_r^{[0:k]} \binom{\frac{1}{n}}{r} x^r - 1)\|^2$

ii. $= \|n \sum_r^{[1:k]} \binom{\frac{1}{n}}{r}(-1)^r(-x)^r\|^2$

iii. $= n^2\|\sum_r^{[1:k]}((\binom{\frac{1}{n}}{r+1}(-1)^{r+1} \cdot \frac{(-x)^{r+1}}{-x-1} - \binom{\frac{1}{n}}{r}(-1)^r \cdot \frac{(-x)^r}{-x-1} - ((\binom{\frac{1}{n}}{r+1}(-1)^{r+1} - \binom{\frac{1}{n}}{r}(-1)^r)\frac{(-x)^{r+1}}{-x-1})\|^2$

iv. $= \frac{n^2}{\|x+1\|^2}\|\binom{\frac{1}{n}}{k}x^k - \binom{\frac{1}{n}}{1}x^1 - \sum_r^{[1:k]}((\binom{\frac{1}{n}}{r+1}(-1)^{r+1} - \binom{\frac{1}{n}}{r}(-1)^r)(-x)^{r+1}\|^2$

v. $\leq \frac{n^2}{\|x+1\|^2}\|\binom{\frac{1}{n}}{k}(-1)^{k-1} + \frac{1}{n} + \sum_r^{[1:k]}((\binom{\frac{1}{n}}{r+1}(-1)^{r+1} - \binom{\frac{1}{n}}{r}(-1)^r)\|^2$

vi. $= \frac{n^2}{(\mathrm{re}(x)+1)^2+\mathrm{im}(x)^2}(\binom{\frac{1}{n}}{k}(-1)^{k-1} + \frac{1}{n} + \binom{\frac{1}{n}}{k}(-1)^k - \binom{\frac{1}{n}}{1}(-1)^1)^2$

vii. $\leq \frac{n^2}{(1-X)^2}(\frac{2}{n})^2$

viii. $= a^2$.

3. **Yield the tuple** $\langle a, p\rangle$**.**

Declaration III:17(fri0108191325)

The notation $\omega(r)$ will be used as a shorthand notation for $\frac{1}{r}(1 - \prod_t^{[1:r]}(1 - \frac{1}{nt}))$.

Procedure III:68(thu0108191318)

Objective

Choose two positive integers r, n such that $r > 1$. The objective of the following instructions is to show that $\frac{\omega(r+1)}{\omega(r)} \leq 1$.

Implementation

1. Using procedure II:30, show that $\frac{\omega(r+1)}{\omega(r)}$

(a) $= \frac{\frac{1}{r+1}(1-\prod_t^{[1:r+1]}(1-\frac{1}{nt}))}{\frac{1}{r}(1-\prod_t^{[1:r]}(1-\frac{1}{nt}))}$

(b) $= \frac{r}{r+1} \cdot \frac{1-(1-\frac{1}{nr})\prod_t^{[1:r]}(1-\frac{1}{nt})}{1-\prod_t^{[1:r]}(1-\frac{1}{nt})}$

(c) $= \frac{r}{r+1}\left(1+\frac{\frac{1}{nr}\prod_t^{[1:r]}(1-\frac{1}{nt})}{1-\prod_t^{[1:r]}(1-\frac{1}{nt})}\right)$

(d) $= \frac{r}{r+1}\left(1+\frac{\frac{1}{nr}}{(\prod_t^{[1:r]}(1-\frac{1}{nt}))^{-1}-1}\right)$

(e) $\leq \frac{r}{r+1}\left(1+\frac{\frac{1}{nr}}{(1-\frac{1}{n(r-1)})^{-(r-1)}-1}\right)$

(f) $= \frac{r}{r+1}\left(1+\frac{\frac{1}{nr}}{(1+\frac{1}{nr-n-1})^{r-1}-1}\right)$

(g) $\leq \frac{r}{r+1}\left(1+\frac{\frac{1}{nr}}{(1+\frac{1}{n(r-1)})^{r-1}-1}\right)$

(h) $\leq \frac{r}{r+1}\left(1+\frac{\frac{1}{nr}}{1+\frac{r-1}{n(r-1)}-1}\right)$

(i) $= \frac{r}{r+1}(1+\frac{1}{r})$

(j) $= 1$.

Declaration III:18(fri2607191453)

The notation $\ln_k(1+x)$ will be used as a shorthand for $\sum_r^{[1:k]}\frac{(-1)^{r-1}}{r}x^r$.

Procedure III:69(fri2607191450)

Objective

Choose a rational number $1 > X \geq 0$. The objective of the following instructions is to construct a positive rational number a and a procedure $p(x, n, k)$ to show that $\ln_k(1+x) \equiv n((1+x)_k^{\frac{1}{n}}-1)$ (err $\frac{a}{n}$) when positive integers n, k and a complex number x such that $\|x\|^2 \leq 1$ and $\mathrm{re}(x) \geq -X$ are chosen.

Implementation

1. Let $a = \frac{1}{1-X}$.
2. Let $p(x, n, k)$ be the following procedure:

(a) For $r \in [2:k]$, show that $\frac{\omega(r+1)}{\omega(r)} \leq 1$ using procedure III:68.

(b) Also show that $\|x+1\|^2 \geq \mathrm{re}(x+1)^2 + \mathrm{im}(x)^2 \geq (1-X)^2$.

(c) Hence show that $\ln_k(1+x) \equiv n((1+x)_k^{\frac{1}{n}}-1)$

i. (err $\ln_k(1+x) - n((1+x)_k^{\frac{1}{n}}-1)$)

ii. (err $\sum_r^{[1:k]}\frac{(-1)^{r-1}}{r}x^r - n(\sum_r^{[0:k]}\binom{\frac{1}{n}}{r}x^r - 1)$)

iii. (err $\sum_r^{[1:k]}\frac{(-1)^{r-1}}{r}x^r - n\sum_r^{[1:k]}\binom{\frac{1}{n}}{r}x^r$)

iv. (err $\sum_r^{[1:k]}\frac{(-1)^{\underline{r-1}}}{r!}x^r - \sum_r^{[1:k]}\frac{(\frac{1}{n}-1)^{\underline{r-1}}}{r!}x^r$)

v. (err $\sum_r^{[1:k]}\frac{1}{r!}((-1)^{\underline{r-1}} - (\frac{1}{n}-1)^{\underline{r-1}})x^r$)

vi. (err $\sum_r^{[1:k]}\frac{(-1)^{\underline{r-1}}}{r!}(1-\frac{(\frac{1}{n}-1)^{\underline{r-1}}}{(-1)^{\underline{r-1}}})x^r$)

vii. (err $\sum_r^{[1:k]}\frac{(-1)^{r-1}}{r}(1-\prod_t^{[1:r]}\frac{\frac{1}{n}-t}{-t})x^r$)

viii. (err $\sum_r^{[1:k]}\omega(r)(-x)^r$)

ix. (err $\sum_r^{[1:k]}(\omega(r+1)\cdot\frac{(-x)^{r+1}}{-x-1} - \omega(r)\cdot\frac{(-x)^r}{-x-1} - (\omega(r+1)-\omega(r))\cdot\frac{(-x)^{r+1}}{-x-1})$)

x. (err $\frac{1}{x+1}(\omega(k)(-x)^k - \omega(1)(-x)^1 - \sum_r^{[1:k]}(\omega(r+1)-\omega(r))(-x)^{r+1})$)

xi. (err $\frac{1}{x+1}(\omega(k)+\omega(1)+\sum_r^{[2:k]}(\omega(r)-\omega(r+1))+\omega(2)-\omega(1))$)

xii. (err $\frac{1}{1-X}(\omega(k)-\omega(k)+\omega(2)+\omega(2)+\omega(1)-\omega(1))$)

xiii. (err $\frac{a}{n}$).

3. **Yield the tuple $\langle a, p\rangle$.**

Procedure III:70(fri2607191736)

Objective

Choose a rational number $1 > X \geq 0$. The objective of the following instructions is to construct a rational number $a > 0$ and a procedure $p(x, k)$ to show that $\|\ln_k(1+x)\|^2 \leq a^2$ when a positive integer k and a complex number x such that $\|x\|^2 \leq 1$ and $\mathrm{re}(x) \geq -X$ are chosen.

Implementation

1. Let $a = \frac{2}{1-X}$.
2. Let $p(x, k)$ be the following procedure:

(a) Show that $\|\ln_k(1+x)\|^2$

i. $= \|\sum_r^{[1:k]}\frac{(-1)^{r-1}}{r}x^r\|^2$

ii. $= \|\sum_r^{[1:k]}\frac{1}{r}(-x)^r\|^2$

iii. $= \|\sum_r^{[1:k]}(\frac{1}{r+1}\cdot\frac{(-x)^{r+1}}{-x-1} - \frac{1}{r}\cdot\frac{(-x)^r}{-x-1} - (\frac{1}{r+1} - \frac{1}{r})\cdot\frac{(-x)^{r+1}}{-x-1})\|^2$

iv. $= \frac{1}{\|x+1\|^2}\|\frac{1}{k}(-x)^k - \frac{1}{1}(-x)^1 - \sum_r^{[1:k]}(\frac{1}{r+1} - \frac{1}{r})(-x)^{r+1}\|^2$

v. $\leq \frac{1}{\|x+1\|^2}(\frac{1}{k} + 1 + \sum_r^{[1:k]}(\frac{1}{r} - \frac{1}{r+1}))^2$

vi. $= \frac{1}{\|x+1\|^2}(\frac{1}{k} + 1 - \frac{1}{k} + 1)^2$

vii. $= \frac{4}{(\mathrm{re}(x)+1)^2+\mathrm{im}(x)^2}$

viii. $\leq a^2$

3. **Yield the tuple** $\langle a, p\rangle$**.**

Procedure III:71(fri2607191801)

Objective

Choose a rational number $1 > X \geq 0$. The objective of the following instructions is to construct positive rational numbers a, c, d, e such that $b > 1$, and a procedure $p(x, n, k)$ to show that $\exp_n(\ln_k(1+x)) \equiv 1+x$ (err $\frac{an}{k} + \frac{c}{n}$) when positive integers n, k, and a complex number x such that $\|x\|^2 \leq 1$, $\mathrm{re}(x) \geq -X$, $k > d$, and $n > e$ are chosen.

Implementation

1. Execute procedure III:67 on $\langle X\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Execute procedure III:70 on $\langle X\rangle$ and let $\langle a_2, p_2\rangle$ receive.
3. Execute procedure III:39 on $\langle \max(a_1, a_2)\rangle$ and let $\langle a_3, e, p_3\rangle$ receive.
4. Execute procedure III:69 on $\langle X\rangle$ and let $\langle a_4, p_4\rangle$ receive.
5. Execute procedure III:66 on $\langle X\rangle$ and let $\langle a, d, p_5\rangle$ receive.
6. Let $c = a_4a_3$.
7. Let $p(x, n, k)$ be the following procedure:

(a) Show that $\|n((1+x)_k^{\frac{1}{n}} - 1)\|^2 \leq {a_1}^2$ using procedure p_1.

(b) Show that $\|\ln_k(1+x)\|^2 \leq {a_2}^2$ using procedure p_2.

(c) Show that $\|\ln_k(1+x) - n((1+x)_k^{\frac{1}{n}} - 1)\|^2 \leq (\frac{a_4}{n})^2$ using procedure p_4.

(d) Now using procedures p_3, p_5, show that $\exp_n(\ln_k(1+x))$

i. $\equiv \exp_n(n((1+x)_k^{\frac{1}{n}} - 1))$

A. (err $a_3(\ln_k(1+x) - n((1+x)_k^{\frac{1}{n}} - 1)))$

B. (err $a_3 \cdot \frac{a_4}{n}$)

ii. $\equiv 1 + x$ (err $\frac{an}{k}$)

(e) **Hence show that** $\exp_n(\ln_k(1+x)) \equiv 1 + x$ (err $\frac{a_3a_4}{n} + \frac{an}{k}$) (err $\frac{c}{n} + \frac{an}{k}$)**.**

8. **Yield the tuple** $\langle a, c, d, e, p\rangle$**.**

Chapter 12

Gregory-Leibniz Series

Declaration III:19(3.33)

The notation τ_n, where n is a positive integer, will be used as a shorthand for $8\,\mathrm{im}(\ln_n(1+i))$.

Procedure III:72(3.47)

Objective

Choose a positive integer k. The objective of the following instructions is to show that $\tau_k = 8\sum_r^{[0:\lfloor\frac{k}{2}\rfloor]} \frac{(-1)^r}{2r+1}$.

Implementation

1. Using declaration III:19, show that τ_k
   (a) $= 8\,\mathrm{im}(\sum_r^{[1:k]} \frac{(-1)^{r-1}}{r} i^r)$
   (b) $= 8\,\mathrm{im}(\sum_r^{[0:\lfloor\frac{k}{2}\rfloor]} \frac{(-1)^{2r}}{2r+1} i^{2r+1})$
   (c) $= 8\sum_r^{[0:\lfloor\frac{k}{2}\rfloor]} \frac{i^{2r}}{2r+1}$
   (d) $= 8\sum_r^{[0:\lfloor\frac{k}{2}\rfloor]} \frac{(-1)^r}{2r+1}$.

Procedure III:73(3.49)

Objective

The objective of the following instructions is to construct positive rational numbers a, b such that $a \geq 4$, and a procedure, $p(n)$, to show that $\tau_n \geq a$ when a positive integer $n \geq b$ is chosen.

Implementation

1. Let $a = \frac{16}{3}$.
2. **Show that** $a \geq 4$**.**
3. Let $b = 4$.
4. Let $p(n)$ be the following procedure:
   (a) Let $d = n \operatorname{div} 4$.
   (b) Let $g = n \bmod 4$.
   (c) Hence show that $n = 4d + g$.
   (d) If $g = 0$ or $g = 1$, then do the following:
      i. Using procedure III:72, show that τ_n
         A. $= 8\sum_r^{[0:\lfloor\frac{4d+g}{2}\rfloor]} \frac{(-1)^r}{2r+1}$
         B. $= 8\sum_r^{[0:2d]} \frac{(-1)^r}{2r+1}$
         C. $= 8(1 - \frac{1}{3} + \sum_r^{[2:2d]} \frac{(-1)^r}{2r+1})$
         D. $= \frac{16}{3} + 8\sum_r^{[1:d]}(\frac{1}{4r+1} - \frac{1}{4r+3})$
         E. $\geq \frac{16}{3}$.
   (e) Otherwise do the following:
      i. Show that $g = 2$ or $g = 3$.
      ii. Hence show that τ_n
         A. $= 8\sum_r^{[0:\lfloor\frac{4d+g}{2}\rfloor]} \frac{(-1)^r}{2r+1}$
         B. $= 8\sum_r^{[0:2d+1]} \frac{(-1)^r}{2r+1}$
         C. $= 8(1 - \frac{1}{3} + \sum_r^{[0:2d]} \frac{(-1)^r}{2r+1} + \frac{(-1)^{2d}}{4d+1})$
         D. $\frac{16}{3} + 8\sum_r^{[1:d]}(\frac{1}{4r+1} - \frac{1}{4r+3}) + \frac{8}{4d+1}$
         E. $\geq \frac{16}{3}$.
5. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:74(3.50)

Objective

The objective of the following instructions is to construct rational numbers a, b such that $a \geq 4$ and $a^2 < 48$, and a procedure, $p(n)$, to show that $\tau_n \leq a$ when a positive integer n such that $n \geq b$ is chosen.

Implementation

1. Let $a = \frac{2104}{315}$.
2. **Show that** $a \geq 4$**.**
3. **Show that** $a^2 = \frac{4426816}{99225} < 48$**.**
4. Let $b = 10$.
5. Let $p(n)$ be the following procedure:
   (a) Let $d = n \operatorname{div} 4$.
   (b) Let $g = n \bmod 4$.
   (c) Hence verify that $n = 4d + g$.
   (d) If $g = 0$ or $g = 1$, then do the following:
      i. Show that τ_n
         A. $= 8 \sum_r^{[0:\lfloor \frac{n}{2} \rfloor]} \frac{(-1)^r}{2r+1}$
         B. $= 8 \sum_r^{[0:5]} \frac{(-1)^r}{2r+1} + 8 \sum_r^{[5:\lfloor \frac{4d+g}{2} \rfloor]} \frac{(-1)^r}{2r+1}$
         C. $= a + 8 \sum_r^{[5:2d]} \frac{(-1)^r}{2r+1}$
         D. $= a + 8 \sum_r^{[5:2d-1]} \frac{(-1)^r}{2r+1} + \frac{8(-1)^{2d-1}}{4d-1}$
         E. $= a - 8 \sum_r^{[3:d]} (\frac{1}{4r-1} - \frac{1}{4r+1}) - \frac{8}{4d-1}$
         F. $\leq a$.
   (e) Otherwise do the following:
      i. Show that $g = 2$ or $g = 3$.
      ii. Hence show that τ_n
         A. $= 8 \sum_r^{[0:\lfloor \frac{n}{2} \rfloor]} \frac{(-1)^r}{2r+1}$
         B. $= 8 \sum_r^{[0:5]} \frac{(-1)^r}{2r+1} + 8 \sum_r^{[5:\lfloor \frac{4d+g}{2} \rfloor]} \frac{(-1)^r}{2r+1}$
         C. $= a + 8 \sum_r^{[5:2d+1]} \frac{(-1)^r}{2r+1}$
         D. $= a - 8 \sum_r^{[2:d]} (\frac{1}{4r+3} - \frac{1}{4r+5})$
         E. $\leq a$.
6. **Yield the tuple** $\langle a, b, p \rangle$**.**

Procedure III:75(3.53)

Objective

The objective of the following instructions is to construct positive rational numbers a, c, d, e, and a procedure $p(n, k)$ to show that $\exp_n(\frac{1}{4}\tau_k i) \equiv i$ (err $\frac{an}{k} + \frac{c}{n}$) when integers k, n such that $n > e$ and $k > d$ are chosen.

Implementation

1. Execute procedure III:70 on $\langle 0 \rangle$ and let $\langle a_1, p_1 \rangle$ receive.
2. Execute procedure III:37 on $\langle a_1 \rangle$ and let $\langle a_2, b_2, p_2 \rangle$ receive.
3. Execute procedure III:35 on $\langle a_1 \rangle$ and let $\langle a_3, b_3, p_3 \rangle$ receive.
4. Execute procedure III:71 on $\langle 0 \rangle$ and let $\langle a_4, c_4, d, e_4, p_4 \rangle$ receive.
5. Let $a = \frac{2a_4}{a_3}$.
6. Let $c = \frac{2c_4}{a_3} + a_2$.
7. Let $e = \max(b_2, b_3, e_4)$.
8. Let $p(n, k)$ be the following procedure:
   (a) Show that $\|\ln_k(1+i)\|^2 \leq {a_1}^2$ using procedure p_1.
   (b) Hence using procedures p_2, p_3, p_4, show that $\exp_n(\frac{1}{4}\tau_k i)$
      i. $= \exp_n(2 \operatorname{im}(\ln_k(1+i))i)$
      ii. $= \exp_n(\ln_k(1+i) - (\ln_k(1+i))^-)$
      iii. $\equiv \frac{\exp_n(\ln_k(1+i))}{\exp_n((\ln_k(1+i))^-)}$ (err $\frac{a_2}{n}$)
      iv. $\equiv \frac{1+i}{\exp_n((\ln_k(1+i))^-)}$ (err $\frac{1}{a_3}(\frac{a_4 n}{k} + \frac{c_4}{n})$)
      v. $= \frac{1+i}{(\exp_n(\ln_k(1+i)))^-}$
      vi. $\equiv \frac{1+i}{(1+i)^-}$
         A. (err $\frac{(1+i)(\frac{a_4 n}{k} + \frac{c_4}{n})}{(\exp_n(\ln_k(1+i)))^- \cdot (1+i)^-}$)
         B. (err $\frac{1}{a_3}(\frac{a_4 n}{k} + \frac{c_4}{n})$)
      vii. $= i$.
   (c) **Hence show that** $\exp_n(\frac{1}{4}\tau_k i) \equiv i$ (err $\frac{a_2}{n} + \frac{2}{a_3}(\frac{a_4 n}{k} + \frac{c_4}{n})$) (err $\frac{an}{k} + \frac{c}{n}$)**.**
9. **Yield the tuple** $\langle a, c, d, e, p \rangle$**.**

Procedure III:76(3.54)

Objective

The objective of the following instructions is to construct positive rational numbers a, c, d, e such that $b > 1$, and a procedure, $p(n, k)$, to show that $\exp_n(-\frac{1}{4}\tau_k i) \equiv -i$ (err $\frac{an}{k} + \frac{c}{n}$) when integers k, n such that $n > e$ and $k > d$ are chosen.

Implementation

Implementation is analogous to that of procedure III:75.

Procedure III:77(mon2608190753)

Objective

Choose a rational number $X \geq 0$ and an integer $K \geq 0$. The objective of the following instructions is to construct a rational number a, and a procedure $p(x, y, k)$ to show that $x^k \equiv y^k$ (err $a(x-y)$) when two complex numbers x, y and a non-negative integer k such that $\|x\|^2 \leq X^2$, $\|y\|^2 \leq X^2$, and $k \leq K$ are chosen.

Implementation

1. Let $a = K \max(1, X)^{K-1}$.
2. Let $p(x, y, k)$ be the following procedure:
   (a) Show that $x^k \equiv y^k$
      i. (err $y^k - x^k$)
      ii. (err $(y-x)\sum_r^{[0:k]} x^r y^{k-1-r}$)
      iii. (err $(y-x)\sum_r^{[0:k]} X^{k-1}$)
      iv. (err $(y-x)KX^{k-1}$)
      v. (err $a(y-x)$)
3. **Yield the tuple $\langle a, p \rangle$.**

Procedure III:78(3.55)

Objective

Choose an integer $K \geq 0$. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(n, m, k)$, to show that $\exp_n(\frac{k}{4}\tau_m i) \equiv i^k$ (err $\frac{an}{m} + \frac{b}{n}$) when a non-negative integer k and two positive integers n, m such that $k \leq K$, $n > c$, and $m > d$ are chosen.

Implementation

1. Execute procedure III:74 and let $\langle a_1, d, p_1 \rangle$ receive.
2. Execute procedure III:38 on $\langle (\frac{a_1}{4})^2 \rangle$ and let $\langle a_2, b_2, p_2 \rangle$ receive.
3. Execute procedure III:75 and let $\langle a_3, b_3, c_3, p_3 \rangle$ receive.
4. Execute procedure III:34 on $\langle (\frac{a_1}{4})^2 \rangle$ and let $\langle a_4, b_4, p_4 \rangle$ receive.
5. Execute procedure III:77 on $\langle \max(1, \frac{a_1}{4}), K \rangle$ and let $\langle a_5, p_5 \rangle$ receive.
6. Let $a = a_3 a_5$.
7. Let $b = a_2 K + b_3 a_5$.
8. Let $c = \max(b_2, b_4, c_3)$.
9. Let $p(n, k, m)$ be the following procedure:
   (a) Show that $\tau_m \leq a_1$ using procedure p_1.
   (b) Hence show that $\|\frac{1}{4}\tau_m i\|^2 = \|\frac{1}{4}\tau_m\|^2 \leq (\frac{a_1}{4})^2$.
   (c) Hence show that $\|\exp_n(\frac{1}{4}\tau_m i) - i\|^2 \leq (\frac{a_3 n}{m} + \frac{b_3}{n})^2$ using procedure p_3.
   (d) Hence show that $\|\exp_n(\frac{1}{4}\tau_m i)\|^2 \leq a_4$ using procedure p_4.
   (e) Hence using procedures p_2, p_5, show that $\exp_n(\frac{k}{4}\tau_m i)$
      i. $\equiv \exp_n(\frac{1}{4}\tau_m i)^k$
         A. (err $\frac{a_2 k}{n}$)
         B. (err $\frac{a_2 K}{n}$)
      ii. $\equiv i^k$
         A. (err $a_5(\exp_n(\frac{1}{4}\tau_m i) - i)$)
         B. (err $a_5(\frac{a_3 n}{m} + \frac{b_3}{n})$)
   (f) **Hence show that** $\exp_n(\frac{k}{4}\tau_m i) \equiv i^k$ (err $\frac{a_2 K}{n} + a_5(\frac{a_3 n}{m} + \frac{b_3}{n})$) (err $\frac{an}{m} + \frac{b}{n}$)**.**
10. **Yield the tuple $\langle a, b, c, d, p \rangle$.**

Procedure III:79(3.56)

Objective

Choose an integer $K \geq 0$. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(n, m, k)$, to show that $\exp_n(\frac{k}{4}\tau_m i) \equiv i^k$ (err $\frac{an}{m} + \frac{b}{n}$) when an integer k and two positive integers n, m such that $|k| \leq K$, $n > c$, and $m > d$ are chosen.

Implementation

Implementation is an extension of that of procedure III:78 using procedure III:76.

Procedure III:80(3.57)

Objective

Choose an integer $K \geq 0$. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(n, m, k)$, to show that $\cos_n(\frac{k}{4}\tau_m) \equiv \frac{i^k+(-i)^k}{2}$ (err $\frac{an}{m} + \frac{b}{n}$) when an integer k and two positive integers n, m such that $|k| \leq K$, $n > c$, and $m > d$ are chosen.

Implementation

1. Execute procedure III:79 on $\langle K\rangle$ and let $\langle a, b, c, d, q\rangle$ receive.
2. Let $p(n, m, k)$ be the following procedure:
   (a) Using procedure q, show that $\cos_n(\frac{k}{4}\tau_m)$
      i. $= \frac{\exp_n(\frac{k}{4}\tau_m i)+\exp_n(-\frac{k}{4}\tau_m i)}{2}$
      ii. $= \frac{\exp_n(\frac{k}{4}\tau_m i)}{2} + \frac{\exp_n(-\frac{k}{4}\tau_m i)}{2}$
      iii. $\equiv \frac{i^k}{2} + \frac{\exp_n(-\frac{k}{4}\tau_m i)}{2}$ (err $\frac{1}{2}(\frac{an}{m} + \frac{b}{n})$)
      iv. $\equiv \frac{i^k}{2} + \frac{i^{-k}}{2}$ (err $\frac{1}{2}(\frac{an}{m} + \frac{b}{n})$)
      v. $= \frac{i^k+i^{-k}}{2}$.
   (b) **Hence show that** $\cos_n(\frac{k}{4}\tau_m) \equiv \frac{i^k+i^{-k}}{2}$ (err $\frac{an}{m} + \frac{b}{n}$)**.**
3. **Yield the tuple** $\langle a, b, c, d, p\rangle$**.**

Procedure III:81(3.58)

Objective

Choose an integer $K \geq 0$. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(n, m, k)$, to show that $\sin_n(\frac{k}{4}\tau_m) \equiv \frac{i^k-(-i)^k}{2i}$ (err $\frac{an}{m} + \frac{b}{n}$) when an integer k and two positive integers n, m such that $|k| \leq K$, $n > c$, and $m > d$ are chosen.

Implementation

Implementation is analogous to that of procedure III:80.

Procedure III:82(3.59)

Objective

Choose two integers $X \geq 0, K \geq 0$. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(x, n, m, k)$, to show that $\exp_n(x + \frac{k}{4}\tau_m i) \equiv i^k \exp_n(x)$ (err $\frac{an}{m} + \frac{b}{n}$) when an integer k and two positive integers n, m such that $\|x\|^2 \leq X$, $|k| \leq K$, $n > c$, and $m > d$ are chosen.

Implementation

1. Execute procedure III:74 and let $\langle a_1, b_1, p_1\rangle$ receive.
2. Let $H = \max(X, \frac{Ka_1}{4})$.
3. Execute procedure III:36 on $\langle H\rangle$ and let $\langle a_2, b_2, p_2\rangle$ receive.
4. Execute procedure III:34 on $\langle X\rangle$ and let $\langle a_3, b_3, p_3\rangle$ receive.
5. Execute procedure III:79 on $\langle K\rangle$ and let $\langle a_4, b_4, c_4, d_4, p_4\rangle$ receive.
6. Let $a = a_3a_4$.
7. Let $b = a_2H^2 + a_3b_4$.
8. Let $c = \max(b_2, b_3, c_4)$.
9. Let $d = \max(b_1, d_4)$.
10. Let $p(x, n, k, m)$ be the following procedure:
    (a) Show that $\tau_m \leq a_1$ using procedure p_1.
    (b) Hence show that $\|\frac{k}{4}\tau_m i\|^2 = (\frac{k\tau_m}{4})^2$.
    (c) Hence using procedures p_2, p_3, p_4, show that $\exp_n(x + \frac{k}{4}\tau_m i)$
       i. $\equiv \exp_n(\frac{k}{4}\tau_m i)\exp_n(x)$ (err $\frac{a_2H^2}{n}$)
       ii. $\equiv i^k \exp_n(x)$ (err $a_3(\frac{a_4n}{m} + \frac{b_4}{n})$)

(d) **Hence show that** $\exp_n(x + \frac{k}{4}\tau_m i) \equiv i^k \exp_n(x) \text{ (err } \frac{a_2 H^2}{n} + a_3(\frac{a_4 n}{m} + \frac{b_4}{n})) \text{ (err } \frac{an}{m} + \frac{b}{n})$.

11. **Yield the tuple** $\langle a, b, c, d, p\rangle$.

Procedure III:83(3.89)

Objective

Choose a positive integer K. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(n, m, k)$, to show that $\exp_n(\frac{k}{K}\tau_m i)^K \equiv 1 \text{ (err } \frac{an}{m} + \frac{b}{n})$ when an integer k and positive integers n, m such that $0 \le k < K$, $n \ge c$, and $m > d$ are chosen.

Implementation

1. Execute procedure III:74 and let $\langle a_1, b_1, p_1\rangle$ receive.
2. Execute procedure III:38 on $\langle K a_1\rangle$ and let $\langle a_2, b_2, p_2\rangle$ receive.
3. Execute procedure III:79 on $\langle 4K\rangle$ and let $\langle a_3, b_3, c_3, d_3, p_3\rangle$ receive.
4. Let $a = a_3$.
5. Let $b = a_2 K + b_3$.
6. Let $c = \max(b_2, c_3)$.
7. Let $d = \max(b_1, d_3)$.
8. Let $p(n, m, k)$ be the following procedure:

(a) Show that $\tau_m \le a_1$ using procedure p_1.

(b) Hence show that $\|K\frac{k}{K}\tau_m i\| = \|k\tau_m\|^2 \le (K a_1)^2$.

(c) Now using procedures p_2, p_3, show that $\exp_n(\frac{k}{K}\tau_m i)^K$

i. $\equiv \exp_n(K\frac{k}{K}\tau_m i) \text{ (err } \frac{a_2 K}{n})$

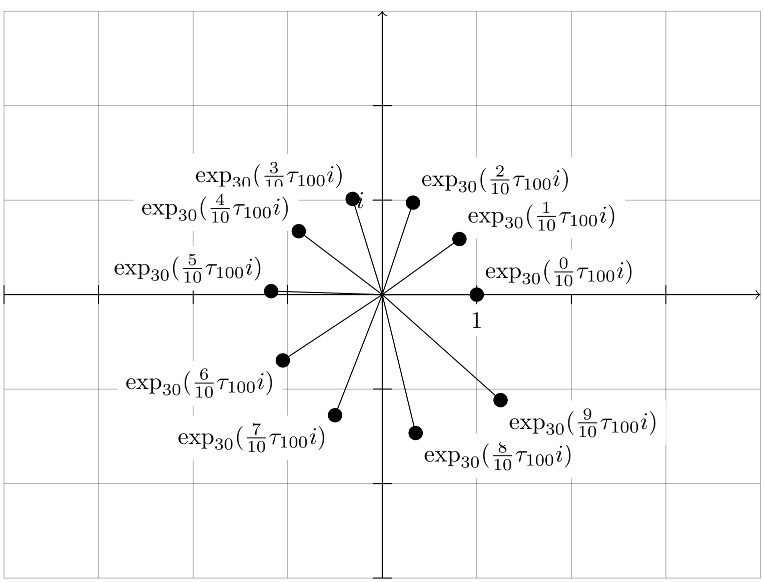
ii. $= \exp_n(\frac{4k}{4}\tau_m i)$

iii. $\equiv i^{4k} \text{ (err } \frac{a_3 n}{m} + \frac{b_3}{n})$

(d) **Hence show that** $\exp_n(\frac{k}{K}\tau_m i)^K \equiv i^{4k} \text{ (err } \frac{a_2 K}{n} + \frac{a_3 n}{m} + \frac{b_3}{n}) \text{ (err } \frac{an}{m} + \frac{b}{n})$.

9. **Yield the tuple** $\langle a, b, c, d, p\rangle$.

Figure III:1



A plot of the list of complex numbers $\exp_{30}(\frac{[0:11]}{10}\tau_{100} i)$. Notice that when measurements are done relative to the complex number 1, $\exp_{30}(\frac{1}{10}\tau_{100} i)$ is roughly $\frac{1}{10}^{\text{th}}$ of a revolution, and also that each complex number has an angle that is roughly an integral multiple of that of $\exp_{30}(\frac{1}{10}\tau_{100} i)$.

Procedure III:84(3.90)

Objective

Choose a two rationals M, N such that $0 < M$ and $N^2 < 12$. The objective of the following instructions is to construct rational numbers a, b such that $a > 0$, and a procedure, $p(x, n)$, to show that $\|\cos_n(x) - 1\|^2 \ge a^2$ when a rational number x and a positive integer n such that $M \le |x| \le N$ and $n > b$ are chosen.

Implementation

1. Let $a = \frac{M^2}{4}(1 - \frac{N^2}{12})$.
2. **Show that** $a > 0$**.**
3. Let $b = 4$.
4. Let $p(x, n)$ be the following procedure:
   (a) Using procedure III:41, show that $(\cos_n(x) - 1)^2$
      i. $= (\frac{1}{2}((1 + \frac{xi}{n})^n + (1 - \frac{xi}{n})^n) - 1)^2$
      ii. $= (\frac{1}{2}(\sum_r^{[0:n+1]} \frac{n^r}{r!}(\frac{x}{n})^r i^r + \sum_r^{[0:n+1]} \frac{n^r}{r!}(\frac{x}{n})^r(-i)^r) - 1)^2$
      iii. $= (\sum_r^{[0:\lfloor\frac{n}{2}\rfloor+1]} \frac{n^{2r}}{(2r)!}(\frac{x}{n})^{2r}(-1)^r - 1)^2$
      iv. $= (\sum_r^{[1:\lfloor\frac{n}{2}\rfloor+1]} \frac{n^{2r}}{(2r)!}(\frac{x}{n})^{2r}(-1)^r)^2$
      v. $= (\sum_r^{[1:\lfloor\frac{\lfloor\frac{n}{2}\rfloor}{2}\rfloor+1]}(-\frac{n^{4r-2}}{(4r-2)!}(\frac{x}{n})^{4r-2} + \frac{n^{4r}}{(4r)!}(\frac{x}{n})^{4r}) - \frac{n^{2\lfloor\frac{n}{2}\rfloor}}{(2\lfloor\frac{n}{2}\rfloor)!}(\frac{x}{n})^{2\lfloor\frac{n}{2}\rfloor}[\lfloor\frac{n}{2}\rfloor \bmod 2 = 1])^2$
      vi. $\geq (\sum_r^{[1:\lfloor\frac{\lfloor\frac{n}{2}\rfloor}{2}\rfloor+1]} \frac{n^{4r-2}}{(4r-2)!}(\frac{x}{n})^{4r-2}(-1 + \frac{(n-4r+2)^{\underline{2}}}{(4r)^{\underline{2}}}(\frac{x}{n})^2))^2$
      vii. $\geq (\sum_r^{[1:\lfloor\frac{\lfloor\frac{n}{2}\rfloor}{2}\rfloor+1]} \frac{n^{4r-2}}{(4r-2)!}(\frac{x}{n})^{4r-2}(-1 + \frac{1}{(4r)^{\underline{2}}}(x)^2))^2$
      viii. $\geq (\sum_r^{[1:\lfloor\frac{\lfloor\frac{n}{2}\rfloor}{2}\rfloor+1]} \frac{n^{4r-2}}{(4r-2)!}(\frac{x}{n})^{4r-2}(-1 + \frac{1}{12}x^2))^2$
      ix. $\geq (\sum_r^{[1:\lfloor\frac{\lfloor\frac{n}{2}\rfloor}{2}\rfloor+1]} \frac{n^{4r-2}}{(4r-2)!}(\frac{x}{n})^{4r-2}(-1 + \frac{N^2}{12}))^2$
      x. $\geq (\frac{n^2}{2}(\frac{x}{n})^2(-1 + \frac{N^2}{12}))^2$
      xi. $\geq (\frac{1}{4}x^2(-1 + \frac{N^2}{12}))^2$
      xii. $\geq (\frac{M^2}{4}(-1 + \frac{N^2}{12}))^2$
      xiii. $= a^2$
5. **Yield the tuple** $\langle a, b, p\rangle$**.**

Procedure III:85(3.60)

Objective

Choose a positive integer K. The objective of the following instructions is to construct rational numbers a, b, c such that $a > 0$, and a procedure, $p(n, m, k)$, to show that $\|\exp_n(\frac{k}{K}\tau_m i) - 1\|^2 \geq a^2$ when an integer k and positive integers n, m such that $0 < |k| \leq \frac{K}{2}$, $n > b$, and $m > c$ are chosen.

Implementation

1. Execute procedure III:74 and let $\langle a_1, c, p_1\rangle$ receive.
2. Show that $(\frac{a_1}{2})^2 < 12$.
3. Execute procedure III:73 and let $\langle a_2, p_2\rangle$ receive.
4. Show that $a_2 > 0$.
5. Execute procedure III:84 on $\langle \frac{a_2}{K}, \frac{a_1}{2}\rangle$ and let $\langle a, b, p_3\rangle$ receive.
6. **Show that** $a > 0$**.**
7. Let $p(n, m, k)$ be the following procedure:
   (a) Show that $\frac{1}{K} \leq \frac{|k|}{K} \leq \frac{1}{2}$ given that $1 \leq |k| \leq \frac{K}{2}$.
   (b) Hence show that $0 < \frac{a_2}{K} \leq \frac{1}{K}\tau_m \leq \frac{|k|}{K}\tau_m \leq \frac{1}{2}\tau_m \leq \frac{a_1}{2}$ using procedures p_1 and p_2.
   (c) Hence show that $(\cos_n(\frac{k}{K}\tau_m) - 1)^2 \geq a^2$ using procedure p_3.
   (d) Using procedure III:41, show that $\|\exp_n(\frac{k}{K}\tau_m i) - 1\|^2$
      i. $\geq \mathrm{re}(\exp_n(\frac{k}{K}\tau_m i) - 1)^2$
      ii. $= (\cos_n(\frac{k}{K}\tau_m) - 1)^2$
      iii. $\geq a^2$
8. **Yield the tuple** $\langle a, b, c, p\rangle$**.**

Procedure III:86(3.61)

Objective

Choose a positive integer K. The objective of the following instructions is to construct rational numbers a, b, c such that $a > 0$, and a procedure, $p(n, m, j, k)$, to show that $\|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2 \geq a^2$ when positive integers n, j, k, m such that $-K < j \leq k < K$, $0 < k - j \leq \frac{K}{2}$, $n \geq b$, and $m \geq c$ are chosen.

Implementation

1. Execute procedure III:74 and let $\langle a_1, b_1, p_1\rangle$ receive.
2. Execute procedure III:35 on $\langle a_1\rangle$ and let $\langle a_2, b_2, p_2\rangle$ receive.
3. Execute procedure III:85 on $\langle K\rangle$ and let $\langle a_3, b_3, c_3, p_3\rangle$ receive.
4. Execute procedure III:36 on $\langle a_1\rangle$ and let $\langle a_4, b_4, p_4\rangle$ receive.
5. Let $a = \frac{1}{2}a_2a_3$.
6. Let $b = \max(\frac{2a_4{a_1}^2}{a_2a_3}, b_3, b_4, b_2)$.
7. Let $c = \max(b_1, c_3)$.
8. Let $p(n, m, j, k)$ be the following procedure:

(a) Show that $\|\frac{j}{K}\|^2 < 1$

i. given that $-1 < \frac{j}{K} < 1$

ii. given that $-K < j < K$.

(b) Hence show that $\|\frac{j}{K}\tau_m i\|^2 = \|\frac{j}{K}\|^2\|\tau_m\|^2 \leq \|\tau_m\|^2 \leq {a_1}^2$ using procedure p_1.

(c) Hence show that $\|\exp_n(\frac{j}{K}\tau_m i)\|^2 \geq {a_2}^2 > 0$ using procedure p_2.

(d) Hence show that $\|\exp_n(\frac{k-j}{K}\tau_m i) - 1\|^2 \geq {a_3}^2 > 0$ using procedure p_3.

(e) Show that $\|\frac{k-j}{K}\tau_m i\|^2 \leq \|\frac{k-j}{K}\|^2\|\tau_m\|^2 \leq \|\tau_m\|^2 \leq {a_1}^2$ given that $0 < \frac{k-j}{K} \leq \frac{1}{2}$.

(f) Show that $n \geq b \geq \frac{2a_4{a_1}^2}{a_2a_3}$.

(g) Hence show that $\|\exp_n(\frac{k-j}{K}\tau_m i)\exp_n(\frac{j}{K}\tau_m i) - \exp_n(\frac{k-j}{K}\tau_m i + \frac{j}{K}\tau_m i)\|^2 \leq \frac{{a_4}^2\|\frac{k-j}{K}\tau_m i\|^2\|\frac{j}{K}\tau_m i\|^2}{n^2} \leq \frac{{a_4}^2{a_1}^4}{n^2} \leq (\frac{a_2a_3}{2})^2$ using procedure p_4.

(h) Hence using procedure III:19, show that $\|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2$

i. $= \|\exp_n(\frac{k-j}{K}\tau_m i + \frac{j}{K}\tau_m i) - \exp_n(\frac{k-j}{K}\tau_m i)\exp_n(\frac{j}{K}\tau_m i) + \exp_n(\frac{k-j}{K}\tau_m i)\exp_n(\frac{j}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2$

ii. $= \|\exp_n(\frac{j}{K}\tau_m i)(\exp_n(\frac{k-j}{K}\tau_m i) - 1) - (\exp_n(\frac{k-j}{K}\tau_m i + \frac{j}{K}\tau_m i) - \exp_n(\frac{k-j}{K}\tau_m i)\exp_n(\frac{j}{K}\tau_m i))\|^2$

iii. $\geq (a_2a_3 - \frac{a_2a_3}{2})^2$

iv. $\geq a^2$.

9. **Yield the tuple $\langle a, b, c, p\rangle$.**

Procedure III:87(3.62)

Objective

Choose a positive integer K. The objective of the following instructions is to construct rational numbers a, b, c such that $a > 0$, and a procedure, $p(n, m, j, k)$, to show that $\|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2 \geq a^2$ when positive integers n, j, k, m such that $0 \leq j \leq k < K$, $\frac{K}{2} \leq k - j < K$, $n \geq b$, and $\frac{m}{n} \geq c$ are chosen.

Implementation

1. Execute procedure III:86 on $\langle K\rangle$ and let $\langle a_1, b_1, c_1, p_1\rangle$ receive.
2. Execute procedure III:74 and let $\langle a_2, b_2, p_2\rangle$ receive.
3. Execute procedure III:82 on $\langle a_2, 4\rangle$ and let $\langle a_3, b_3, c_3, d_3, p_3\rangle$ receive.
4. Let $a = \frac{1}{2}a_1$.
5. Let $b = \max(\frac{4b_3}{a_1}, b_1, c_3)$.
6. Let $c = \max(\frac{4a_3}{a_1}, \frac{c_1}{b}, \frac{b_2}{b}, \frac{d_3}{b})$.
7. Let $p(n, m, j, k)$ be the following procedure:

(a) Show that $-\frac{K}{2} \leq k - K < j < \frac{K}{2}$.

(b) Also show that $0 < j - (k - K) \leq \frac{K}{2}$.

(c) Show that $m \geq cn \geq \frac{c_1}{b}b = c_1$.

(d) Hence show that $\|\exp_n(\frac{j}{K}\tau_m i) - \exp_n(\frac{k-K}{K}\tau_m i)\|^2 \geq {a_1}^2$ using procedure p_1.

(e) Show that $m \geq cn \geq \frac{b_2}{b}b = b_2$.

(f) Hence show that $\tau_m \leq a_2$ using procedure p_2.

(g) Hence show that $\|\frac{k}{K}\tau_m i\|^2 = \|\frac{k}{K}\|^2\|\tau_m\|^2 \leq \|\tau_m\|^2 \leq {a_2}^2$.

(h) Also show that $m \geq cn \geq \frac{d_3}{b}b = d_3$.

(i) Hence show that $\|i^{-4}\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{k}{K}\tau_m i - \frac{4}{4}\tau_m i)\|^2 \leq (\frac{a_3 n}{m} + \frac{b_3}{n})^2 \leq (\frac{a_1}{2})^2$ using procedure p_3.

(j) Now show that $\|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2$

i. $= \|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{k}{K}\tau_m i - \tau_m i) + \exp_n(\frac{k-K}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2$

ii. $\geq \frac{1}{2}\|\exp_n(\frac{k-K}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2 - \|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{k}{K}\tau_m i - \tau_m i)\|^2$

iii. $\geq \frac{1}{2}{a_1}^2 - (\frac{a_1}{2})^2$

iv. $\geq a^2$.

8. **Yield the tuple** $\langle a, b, c, p\rangle$**.**

Procedure III:88(3.63)

Objective

Choose a positive integer K. The objective of the following instructions is to construct rational numbers a, b, c such that $a > 0$, and a procedure, $p(n, m, j, k)$, to show that $\|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2 \geq a^2$ when positive integers n, j, k, m such that $0 \leq j \leq k < K$, $0 < k - j < K$, $n \geq b$, and $\frac{m}{n} \geq c$ are chosen.

Implementation

1. Execute procedure III:86 on $\langle K\rangle$ and let $\langle a_1, b_1, c_1, p_1\rangle$ receive.
2. Execute procedure III:87 on $\langle K\rangle$ and let $\langle a_2, b_2, c_2, p_2\rangle$ receive.
3. Let $a = \min(a_1, a_2)$.
4. **Show that** $a > 0$**.**
5. Let $b = \max(b_1, b_2)$.
6. Let $c = \max(\frac{c_1}{b}, c_2)$.
7. Let $p(n, m, j, k)$ be the following procedure:

(a) If $k - j \leq \frac{K}{2}$, then do the following:

i. Show that $m \geq cn \geq \frac{c_1}{b}b = c_1$.

ii. **Hence show that** $\|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2 \geq a_1 \geq a$ **using procedure** p_1**.**

(b) Otherwise if $k - j > \frac{K}{2}$, then do the following:

i. **Show that** $\|\exp_n(\frac{k}{K}\tau_m i) - \exp_n(\frac{j}{K}\tau_m i)\|^2 \geq a_2 \geq a$ **using procedure** p_2**.**

8. **Yield the tuple** $\langle a, b, c, p\rangle$**.**

Declaration III:20(3.34)

The phrase "complex polynomial" will be used to indicate that the declarations and procedures pertaining to polynomials are being used but with the provison that all uses of rational numbers therein are substituted with uses of complex numbers.

Procedure III:89(3.64)

Objective

Choose a positive integer K. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(n, m)$, to construct a list of complex numbers z and a list of complex polynomials q such that,

1. $z_k = \exp_n(\frac{K-k-1}{K}\tau_m i)$ for $k \in [0 : K]$
2. $q_K = \lambda^K - 1$
3. $q_{K-1} = \sum_r^{[0:K]} \lambda^r$
4. $q_{k+1} = (\lambda - z_k)q_k + \Lambda(q_{k+1}, z_k)$ for $k \in [0 : K]$
5. $(q_k)_{\deg(q_k)} = 1$ for $k \in [0 : K + 1]$
6. $\Lambda(q_k, z_j) \equiv 0$ (err $\frac{an}{m} + \frac{b}{n}$) for $j \in [0 : k]$, for $k \in [0 : K + 1]$

when two positive integers n, m such that $n > c$ and $\frac{m}{n} > d$ are chosen.

Implementation

1. Execute procedure III:83 on $\langle K\rangle$ and let $\langle a_1, b_1, c_1, d_1, p_1\rangle$ receive.
2. Execute procedure III:88 on $\langle K\rangle$ and let $\langle a_2, b_2, c_2, p_2\rangle$ receive.
3. Let $a = \max(1, \frac{2}{a_2})^K a_1$.
4. Let $b = \max(1, \frac{2}{a_2})^K b_1$.
5. Let $c = \max(c_1, b_2)$.
6. Let $d = \max(d_1, c_2)$.
7. Let $p(n, m)$ be the following procedure:

(a) **Let** $q_K = \lambda^K - 1$**.**

(b) For $k \in [K : 0]$, do the following:

i. **Let** $z_k = \exp_n(\frac{K-k-1}{K}\tau_m i)$**.**

ii. **Now show that** $\|\Lambda(q_K, z_k)\|^2 \leq (\frac{a_1 n}{m} + \frac{b_1}{n})^2$ **using procedure** p_1**.**

(c) For $k \in [K:0]$, do the following:

i. Let $q_k = q_{k+1} \operatorname{div}(\lambda - z_k)$.

ii. Let $r_k = q_{k+1} \bmod (\lambda - z_k)$.

iii. Show that $\deg(r_k) = 0$ given that $\deg(r_k) < \deg(\lambda - z_k) = 1$.

iv. **Show that** $1 = (q_{k+1})_{\deg(q_{k+1})} = ((\lambda - z_k)q_k + r_k)_{\deg(q_{k+1})} = (q_k)_{\deg(q_k)}$ **given that** $q_{k+1} = (\lambda - z_k)q_k + r_k$.

v. **Show that** $q_{k+1} = (\lambda - z_k)q_k + \Lambda(q_{k+1}, z_k)$ **given that** $\Lambda(q_{k+1}, z_k) = \Lambda(\lambda - z_k, z_k)\Lambda(q_k, z_k) + \Lambda(r_k, z_k) = (z_k - z_k)\Lambda(q_k, z_k) + r_k = r_k$.

vi. **Execute the subprocedure III:90:0 on** $\langle k, q_{k+1}, z\rangle$.

(d) Now using (cv), verify that $(\lambda - 1)\sum_r^{[0:K]} \lambda^r$

i. $= q_K$

ii. $= (\lambda - z_{K-1})q_{K-1} + \Lambda(q_K, z_{K-1})$

iii. $= (\lambda - 1)q_{K-1} + \Lambda(\lambda^K - 1, 1)$

iv. $= (\lambda - 1)q_{K-1}$.

(e) **Hence show that** $\sum_r^{[0:K]} \lambda^r = q_{K-1}$.

(f) **Yield the tuple** $\langle z, q\rangle$.

8. **Yield the tuple** $\langle a, b, c, d, p\rangle$.

Subprocedure III:90:0

Objective Choose a non-negative integer k, a complex polynomial q_{k+1}, and a list of complex numbers z such that $z_j = \exp_n(\frac{j}{K}\tau_m i)$ and $\Lambda(q_{k+1}, z_j) \equiv 0$ (err $(\frac{2}{a_2})^{K-(k+1)}(\frac{a_1 n}{m} + \frac{b_1}{n})$) for $j \in [k+1:0]$. Let $q_k = q_{k+1} \operatorname{div}(\lambda - z_k)$. The objective of the following instructions is to show that $\Lambda(q_k, z_j) \equiv 0$ (err $(\frac{2}{a_2})^{K-k}(\frac{a_1 n}{m} + \frac{b_1}{n})$) (err $\frac{an}{m} + \frac{b}{n}$) for $j \in [k:0]$.

Implementation

1. For $j \in [k:0]$, do the following:

(a) Show that $\Lambda(q_{k+1}, z_j) - \Lambda(q_{k+1}, z_k) = (z_j - z_k)\Lambda(q_k, z_j)$ given that $\Lambda(q_{k+1}, z_j) = \Lambda(\lambda - z_k, z_j)\Lambda(q_k, z_j) + \Lambda(q_{k+1}, z_k)$.

(b) Show that $\|z_j - z_k\|^2 \geq {a_2}^2$ using procedure $p_2(n, m, \min(j, k), \max(j, k))$.

(c) Hence show that ${a_2}^2\|\Lambda(q_k, z_j)\|^2$

i. $\leq \|z_j - z_k\|^2\|\Lambda(q_k, z_j)\|^2$

ii. $= \|(z_j - z_k)\Lambda(q_k, z_j)\|^2$

iii. $= \|\Lambda(q_{k+1}, z_j) - \Lambda(q_{k+1}, z_k)\|^2$

iv. $\leq ((\frac{2}{a_2})^{K-k-1}(\frac{a_1 n}{m} + \frac{b_1}{n}) + (\frac{2}{a_2})^{K-k-1}(\frac{a_1 n}{m} + \frac{b_1}{n}))^2$

v. $= (2(\frac{2}{a_2})^{K-k-1}(\frac{a_1 n}{m} + \frac{b_1}{n}))^2$

vi. $= {a_2}^2((\frac{2}{a_2})^{K-k}(\frac{a_1 n}{m} + \frac{b_1}{n}))^2$.

(d) **Hence show that** $\|\Lambda(q_k, z_j)\|^2 \leq ((\frac{2}{a_2})^{K-k}(\frac{a_1 n}{m} + \frac{b_1}{n}))^2 \leq (\frac{an}{m} + \frac{b}{n})^2$.

Procedure III:90(3.65)

Objective

Choose a rational number X and a positive integer K. The objective of the following instructions is to construct rational numbers a, b, c, d, and a procedure, $p(x, n, m)$, to show that $\sum_r^{[0:K]} x^r \equiv \prod_r^{[1:K]}(x - \exp_n(\frac{r}{K}\tau_m i))$ (err $\frac{an}{m} + \frac{b}{n}$) when a complex number x and positive integers n, m such that $n > c$, $\frac{m}{n} > d$, and $\|x\|^2 \leq X$ are chosen.

Implementation

1. Execute procedure III:89 on $\langle K\rangle$ and let $\langle a_1, b_1, c_1, d_1, p_1\rangle$ receive.

2. Execute procedure III:74 and let $\langle a_2, b_2, p_2\rangle$ receive.

3. Execute procedure III:34 on $\langle a_2\rangle$ and let $\langle a_3, b_3, p_3\rangle$ receive.

4. Let $l = \sum_k^{[0:K-1]} \prod_j^{[k+1:K-1]}(X + a_3)$.

5. Let $a = a_1 l$.

6. Let $b = b_1 l$.

7. Let $c = \max(c_1, b_3)$.

8. Let $d = \max(d_1, b_2)$.

9. Let $p(x, n, m)$ be the following procedure:

(a) Show that $\tau_m \leq a_2$ using procedure p_2.

(b) Execute procedure p_1 on $\langle n, m\rangle$ and let $\langle z, t\rangle$ receive.

(c) For $j \in [1:K]$, do the following:

i. Show that $\|\frac{j}{K}\tau_m i\|^2 = \|\frac{j}{K}\|^2\|\tau_m\|^2 \leq \|\tau_m\|^2 \leq a_2$.

ii. Hence show that $\|z_j\|^2 = \|\exp_n(\frac{j}{K}\tau_m i)\|^2 \leq a_3$ using procedure p_3.

(d) Hence show that $\|\sum_r^{[0:K]} x^r - \prod_r^{[1:K]}(x - z_r)\|^2$

i. $= \|\Lambda(\sum_r^{[0:K]} \lambda^r, x) - \prod_r^{[1:K]}(x - z_r)\|^2$

ii. $= \|\Lambda(t_{K-1}, x) - \prod_r^{[1:K]}(x - z_r)\|^2$

iii. $= \|\Lambda(\prod_j^{[0:K-1]}(\lambda - z'_j) + \sum_k^{[0:K-1]} \Lambda(t_{k+1}, z'_k) \prod_j^{[k+1:K-1]}(\lambda - z'_j), x) - \prod_r^{[1:K]}(x - z_r)\|^2$

iv. $= \|\prod_j^{[0:K-1]}(x - z'_j) + \sum_k^{[0:K-1]} \Lambda(t_{k+1}, z'_k) \prod_j^{[k+1:K-1]}(x - z'_j) - \prod_r^{[1:K]}(x - z_r)\|^2$

v. $= \|\sum_k^{[0:K-1]} \Lambda(t_{k+1}, z'_k) \prod_j^{[k+1:K-1]}(x - z'_j)\|^2$

vi. $\leq (\sum_k^{[0:K-1]}(\frac{a_1 n}{m} + \frac{b_1}{n}) \prod_j^{[k+1:K-1]}(X + a_3))^2$

vii. $= ((\frac{a_1 n}{m} + \frac{b_1}{n}) \sum_k^{[0:K-1]} \prod_j^{[k+1:K-1]}(X + a_3))^2$

viii. $= (\frac{an}{m} + \frac{b}{n})^2$.

10. **Yield the tuple** $\langle a, b, c, d, p\rangle$**.**

Procedure III:91(3.66)

Objective

Choose a rational number X and a positive integer K. The objective of the following instructions is to construct rational numbers $a, b, c, d,$ and a procedure, $p(x, n, m)$, to show that $x^K - 1 \equiv \prod_r^{[0:K]}(x - \exp_n(\frac{r}{K}\tau_m i))$ (err $\frac{an}{m} + \frac{b}{n}$) when a complex number x and positive integers n, m such that $n > c$, $\frac{m}{n} > d$, and $\|x\|^2 \leq X$ are chosen.

Implementation

1. Execute procedure III:90 on $\langle X, K\rangle$ and let $\langle a_1, b_1, c, d, p_1\rangle$ receive.
2. Let $a = (X + 1)a_1$.
3. Let $b = (X + 1)b_1$.
4. Let $p(x, n, m)$ be the following procedure:

(a) Show that $\|\sum_r^{[0:K]} x^r - \prod_r^{[1:K]}(x - \exp_n(\frac{r}{K}\tau_m i))\|^2 \leq (\frac{a_1 n}{m} + \frac{b_1}{n})^2$ using procedure p_1.

(b) Hence show that $\|x^K - 1 - \prod_r^{[0:K]}(x - \exp_n(\frac{r}{K}\tau_m i))\|^2$

i. $= \|(x - 1)\sum_r^{[0:K]} x^r - (x - 1)\prod_r^{[1:K]}(x - \exp_n(\frac{r}{K}\tau_m i))\|^2$

ii. $= \|x - 1\|^2 \|\sum_r^{[0:K]} x^r - \prod_r^{[1:K]}(x - \exp_n(\frac{r}{K}\tau_m i))\|^2$

iii. $\leq (X + 1)^2(\frac{a_1 n}{m} + \frac{b_1}{n})^2$

iv. $= (\frac{an}{m} + \frac{b}{n})^2$.

5. **Yield the tuple** $\langle a, b, c, d, p\rangle$**.**

Procedure III:92(3.67)

Objective

Choose a rational number X and a positive integer K. The objective of the following instructions is to construct rational numbers $a, b, c, d,$ and a procedure, $p(x, n, m)$, to show that $\exp_K(x) - 1 \equiv x\prod_r^{[1:K]}(1 - \frac{x}{K(\exp_n(\frac{r}{K}\tau_m i) - 1)})$ (err $\frac{an}{m} + \frac{b}{n}$) when a complex number x and positive integers n, m such that $n > c$, $\frac{m}{n} > d$, and $\|x\|^2 \leq X$ are chosen.

Implementation

1. Execute procedure III:91 on $\langle 1 + \frac{X}{K}, K\rangle$ and let $\langle a_1, b_1, c_1, d_1, p_1\rangle$ receive.
2. Execute procedure III:90 on $\langle 1, K\rangle$ and let $\langle a_2, b_2, c_2, d_2, p_2\rangle$ receive.
3. Execute procedure III:88 on $\langle K\rangle$ and let $\langle a_3, b_3, c_3, p_3\rangle$ receive.
4. Let $l = \frac{X}{K}(1 + \frac{X}{Ka_3})^{K-1}$.
5. Let $a = a_1 + la_2$.
6. Let $b = b_1 + lb_2$.
7. Let $c = \max(c_1, c_2, b_3)$.
8. Let $d = \max(d_1, d_2, c_3)$.
9. Let $p(x, n, m)$ be the following procedure:

(a) Show that $\|1 + \frac{x}{K}\|^2 \leq (1 + \frac{X}{K})^2$.

(b) Hence show that $\|(1 + \frac{x}{K})^K - 1 - \prod_r^{[0:K]}(1 + \frac{x}{K} - \exp_n(\frac{r}{K}\tau_m i))\|^2 \leq (\frac{a_1 n}{m} + \frac{b_1}{n})^2$ using procedure p_1.

(c) Hence show that $\|K - \prod_r^{[1:K]}(1 - \exp_n(\frac{r}{K}\tau_m i))\|^2 = \sum_r^{[0:K]} 1^r - \prod_r^{[1:K]}(1 -$

$\exp_n(\frac{r}{K}\tau_m i))\|^2 \leq (\frac{a_2 n}{m} + \frac{b_2}{n})^2$ using procedure p_2.

(d) For $j \in [1:K]$, do the following:

i. Show that $\|\exp_n(\frac{j}{K}\tau_m i) - 1\|^2 \geq a_3{}^2$ using procedure p_3.

ii. Let $z_j = K(\exp_n(\frac{j}{K}\tau_m i) - 1)$.

(e) Hence show that $\|\exp_K(x) - 1 - x\prod_r^{[1:K]}(1 - \frac{x}{z_r})\|^2$

i. $= \|\exp_K(x) - 1 - \prod_r^{[0:K]}(1 + \frac{x}{K} - \exp_n(\frac{r}{K}\tau_m i)) + \prod_r^{[0:K]}(1 + \frac{x}{K} - \exp_n(\frac{r}{K}\tau_m i)) - x\prod_r^{[1:K]}(1 - \frac{x}{z_r})\|^2$

ii. $= \|\exp_K(x) - 1 - \prod_r^{[0:K]}(1 + \frac{x}{K} - \exp_n(\frac{r}{K}\tau_m i)) + \frac{x}{K}\prod_r^{[1:K]}(1 + \frac{x}{K} - \exp_n(\frac{r}{K}\tau_m i)) - x\prod_r^{[1:K]}(1 - \frac{x}{z_r})\|^2$

iii. $= \|\exp_K(x) - 1 - \prod_r^{[0:K]}(1 + \frac{x}{K} - \exp_n(\frac{r}{K}\tau_m i)) + \frac{x}{K}\prod_r^{[1:K]}(1 - \exp_n(\frac{r}{K}\tau_m i))\prod_r^{[1:K]}(1 - \frac{x}{z_r}) - x\prod_r^{[1:K]}(1 - \frac{x}{z_r})\|^2$

iv. $= \|(\exp_K(x) - 1 - \prod_r^{[0:K]}(1 + \frac{x}{K} - \exp_n(\frac{r}{K}\tau_m i))) + \frac{x}{K}\prod_r^{[1:K]}(1 - \frac{x}{z_r})(\prod_r^{[1:K]}(1 - \exp_n(\frac{r}{K}\tau_m i)) - K)\|^2$

v. $\leq ((\frac{a_1 n}{m} + \frac{b_1}{n}) + \frac{X}{K}(\prod_r^{[1:K]}(1 + \frac{X}{K a_3}))(\frac{a_2 n}{m} + \frac{b_2}{n}))^2$

vi. $= ((\frac{a_1 n}{m} + \frac{b_1}{n}) + \frac{X}{K}(1 + \frac{X}{K a_3})^{K-1}(\frac{a_2 n}{m} + \frac{b_2}{n}))^2$

vii. $= (\frac{an}{m} + \frac{b}{n})^2$.

10. **Yield the tuple $\langle a, b, c, d, p \rangle$.**

Part IV

Differential Arithmetic

Chapter 13

Differential Arithmetic

Procedure IV:0(tue2008191129)

Objective

Choose the following:

1. A procedure $q_1(x, n)$ to show that $p_n(x) \equiv 0$ (err a_1) when a complex number x and a positive integer n such that $P(x)$ and $n > c_1$ are chosen.
2. A procedure $q_2(x, n)$ to show that $t_n(x) \equiv 0$ (err a_2)^2 when a complex number x and a positive integer n such that $R(x)$ and $n > c_2$ are chosen.

The objective of the following instructions is to construct the following:

1. Rational numbers a_3, b_3.
2. A procedure $q_3(x, n)$ to show that $p_n(x) + t_n(x) \equiv 0$ (err a_3) when a complex number x and a positive integer n such that $P(x)$, $R(x)$, and $n > b_3$ are chosen.

Implementation

1. Let $a_3 = a_1 + a_2$.
2. Let $b_3 = \max(c_1, c_2)$.
3. Let $q_3(x, n)$ be the following procedure:
   (a) Show that $p_n(x) \equiv 0$ (err a_1) using procedure q_1.
   (b) Show that $t_n(x) \equiv 0$ (err a_2) using procedure q_2.
   (c) Hence show that $p_n(x) + t_n(x) \equiv 0$ (err $a_1 + a_2$) (err a_3).
4. **Yield the tuple** $\langle a_3, b_3, q_3 \rangle$.

Procedure IV:1(tue2008191139)

Objective

Choose the following:

1. A procedure $q_1(x, n)$ to show that $p_n(x) \equiv 0$ (err a_1) when a complex number x and a positive integer n such that $P(x)$ and $n > c_1$ are chosen.
2. A procedure $q_2(x, n)$ to show that $t_n(x) \equiv 0$ (err a_2) when a complex number x and a positive integer n such that $R(x)$ and $n > c_2$ are chosen.

The objective of the following instructions is to construct the following:

1. Rational numbers a_3, b_3.
2. A procedure $q_3(x, n)$ to show that $p_n(x)t_n(x) \equiv 0$ (err a_3) when a complex number x and a positive integer n such that $P(x)$, $R(x)$, and $n > b_3$ are chosen.

Implementation

Implementation is analogous to that of procedure IV:0.

Declaration IV:0(tue2008190516)

The notation $\{x\}$, where x is a complex number, will be used as a shorthand for $|\mathrm{re}(x)| + |\mathrm{im}(x)|$.

Procedure IV:2(tue2008190655)

Objective

Choose a complex number a such that $\{a\} = 0$. The objective of the following instructions is to show that $a = 0$.

Implementation

1. Using declaration IV:0, show that $|\mathrm{re}(a)| + |\mathrm{im}(a)| = 0$.
2. Hence show that $\mathrm{re}(a) = 0$
   (a) given that $|\mathrm{re}(a)| = 0$
   (b) given that $0 \geq |\mathrm{re}(a)| \geq 0$
   (c) given that $|\mathrm{im}(a)| \geq 0$.
3. Also show that $\mathrm{im}(a) = 0$
   (a) given that $|\mathrm{im}(a)| = 0$
   (b) given that $0 \geq |\mathrm{im}(a)| \geq 0$
   (c) given that $|\mathrm{re}(a)| \geq 0$.
4. **Hence show that** $a = 0$**.**

Procedure IV:3(tue2008190520)

Objective

Choose a complex number a and a rational number b. The objective of the following instructions is to show that $\{ba\} = |b|\{a\}$.

Implementation

1. Using declaration IV:0, show that $\{ba\}$
   (a) $= |\mathrm{re}(ba)| + |\mathrm{im}(ba)|$
   (b) $= |b\,\mathrm{re}(a)| + |b\,\mathrm{im}(a)|$
   (c) $= |b|(|\mathrm{re}(a)| + |\mathrm{im}(a)|)$
   (d) $= |b|\{a\}$.

Procedure IV:4(tue2008190540)

Objective

Choose two complex numbers a, b. The objective of the following instructions is to show that $\{a + b\} \leq \{a\} + \{b\}$.

Implementation

1. Using declaration IV:0, show that $\{a + b\}$
   (a) $= |\mathrm{re}(a + b)| + |\mathrm{im}(a + b)|$
   (b) $= |\mathrm{re}(a) + \mathrm{re}(b)| + |\mathrm{im}(a) + \mathrm{im}(b)|$
   (c) $\leq |\mathrm{re}(a)| + |\mathrm{re}(b)| + |\mathrm{im}(a)| + |\mathrm{im}(b)|$
   (d) $= \{a\} + \{b\}$.

Procedure IV:5(tue2008190546)

Objective

Choose two complex numbers a, b. The objective of the following instructions is to show that $\{ab\} \leq \{a\}\{b\}$.

Implementation

1. Using procedure IV:4, show that $\{ab\}$
   (a) $= \{(\mathrm{re}(a) + \mathrm{im}(b)i)b\}$
   (b) $= \{\mathrm{re}(a)b + \mathrm{im}(a)bi\}$
   (c) $\leq \{\mathrm{re}(a)b\} + \{\mathrm{im}(a)b\}$
   (d) $= (|\mathrm{re}(a)| + |\mathrm{im}(a)|)\{b\}$
   (e) $= \{a\}\{b\}$.

Procedure IV:6(tue2008190632)

Objective

Choose a complex number a. The objective of the following instructions is to show that $\|a\|^2 \leq \{a\}^2$.

Implementation

1. Using procedure III:18, show that $\|a\|^2$
   (a) $= \|\mathrm{re}(a) + \mathrm{im}(a)i\|^2$
   (b) $\leq (|\mathrm{re}(a)| + |\mathrm{im}(a)|)^2$
   (c) $= \{a\}^2$.

Procedure IV:7(tue2008190639)

Objective

Choose a complex number a. The objective of the following instructions is to show that $\{a\}^2 \leq 2\|a\|^2$.

Implementation

1. Show that $2\|a\|^2 - \{a\}^2$
   (a) $= 2\operatorname{re}(a)^2 + 2\operatorname{im}(a)^2 - (|\operatorname{re}(a)| + |\operatorname{im}(a)|)^2$
   (b) $= 2\operatorname{re}(a)^2 + 2\operatorname{im}(a)^2 - \operatorname{re}(a)^2 - 2|\operatorname{re}(a)||\operatorname{im}(a)| - \operatorname{im}(a)^2$
   (c) $= \operatorname{re}(a)^2 - 2|\operatorname{re}(a)||\operatorname{im}(a)| + \operatorname{im}(a)^2$
   (d) $= (|\operatorname{re}(a)| - |\operatorname{im}(a)|)^2$
   (e) ≥ 0.
2. **Hence show that** $\{a\}^2 \leq 2\|a\|^2$.

Declaration IV:1(3.29)

The notation $\Delta^z_{x=y}\, f(x)$, where x, z are complex numbers such that $z \neq 0$ and $f[x]$ is a function of x, will be used as a shorthand for $\frac{f(y+z)-f(y)}{z}$.

Procedure IV:8(3.83)

Objective

Choose two functions $f[x], g[x]$ and two complex numbers y, z such that $z \neq 0$. The objective of the following instructions is to show that $\Delta^z_{x=y}(f(x) + g(x)) = \Delta^z_{x=y}\, f(x) + \Delta^z_{x=y}\, g(x)$.

Implementation

1. Show that $\Delta^z_{x=y}(f(x) + g(x))$
   (a) $= \frac{(f(y+z)+g(y+z))-(f(y)+g(y))}{z}$
   (b) $= \frac{f(y+z)-f(y)}{z} + \frac{g(y+z)-g(y)}{z}$
   (c) $= \Delta^z_{x=y}\, f(x) + \Delta^z_{x=y}\, g(x)$.

Procedure IV:9(3.84)

Objective

Choose a functions $f[x]$ and complex numbers a, y, z such that $z \neq 0$. The objective of the following instructions is to show that $\Delta^z_{x=y}(af(x)) = a\,\Delta^z_{x=y}\, f(x)$.

Implementation

1. Show that $\Delta^z_{x=y}(af(x))$
   (a) $= \frac{af(y+z)-af(y)}{z}$
   (b) $= a\frac{f(y+z)-f(y)}{z}$
   (c) $= a\,\Delta^z_{x=y}\, f(x)$.

Procedure IV:10(mon1908191506)

Objective

Choose the following:

1. A procedure $q_0(x, n)$ to show that $p'_n(x) \equiv 0$ (err a_0) when a complex number x and a positive integer n such that $P(x)$ and $n > b_0$ are chosen.
2. A procedure $q_1(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} p_n(y) \equiv p'_n(x)$ (err $\frac{a_1}{n} + b_1\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > b_0$, and $0 < \|\delta\|^2 < {c_1}^2$ are chosen.
3. A procedure $q_2(x, n)$ to show that $t'_n(x) \equiv 0$ (err a_2) when a complex number x and a positive integer n such that $R(x)$ and $n > b_2$ are chosen.
4. A procedure $q_3(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} t_n(y) \equiv t'_n(x)$ (err $\frac{a_3}{n} + b_3\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $R(x)$, $n > b_2$, and $0 < \|\delta\|^2 < {c_3}^2$ are chosen.

The objective of the following instructions is to construct the following:

1. Rational numbers a_4, b_4, a_5, b_5, c_5.
2. A procedure $q_4(x, n)$ to show that $p'_n(x) + t'_n(x) \equiv 0$ (err a_4) when a complex number x and a positive integer n such that $P(x)$, $R(x)$, and $n > b_4$ are chosen.
3. A procedure $q_5(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x}(p_n(y) + t_n(y)) \equiv p'_n(x) + t'_n(x)$ (err $\frac{a_5}{n} + b_5\{\delta\}$) when two complex numbers x, δ such that $P(x)$, $R(x)$, $n > b_4$, and $0 < \|\delta\|^2 < c_5$.

Implementation

1. Let $a_5 = a_1 + a_3$.
2. Let $b_5 = b_1 + b_3$.
3. Let $q_5(x, n, \delta)$ be the following procedure:
   (a) Show that $\Delta^{+\delta}_{y=x} p_n(y) \equiv p'_n(x)$ (err $\frac{a_1}{n} + b_1\{\delta\}$) using procedure q_1.
   (b) Show that $\Delta^{+\delta}_{y=x} t_n(y) \equiv t'_n(x)$ (err $\frac{a_3}{n} + b_3\{\delta\}$) using procedure q_3.

(c) Hence using procedure IV:8, show that $\Delta^{+\delta}_{y=x}(p_n(y) + t_n(y))$

i. $= \Delta^{+\delta}_{y=x} p_n(y) + \Delta^{+\delta}_{y=x} t_n(y)$

ii. $\equiv p'_n(x) + \Delta^{+\delta}_{y=x} t_n(y)$ (err $\frac{a_1}{n} + b_1\{\delta\}$)

iii. $\equiv p'_n(x) + t'_n(x)$ (err $\frac{a_3}{n} + b_3\{\delta\}$)

(d) **Hence show that** $\Delta^{+\delta}_{y=x}(p_n(y) + t_n(y)) \equiv p'_n(x) + t'_n(x)$ (err $\frac{a_5}{n} + b_5\{\delta\}$)**.**

4. Let $q_4(x, n)$ be the following procedure:

(a) Show that $p'_n(x) \equiv 0$ (err a_0) using procedure q_0.

(b) Show that $t'_n(x) \equiv 0$ (err a_2) using procedure q_2.

(c) Hence show that $p'_n(x) + t'_n(x) \equiv 0$ (err $a_0 + a_2$).

5. **Yield the tuple** $\langle a_4, b_4, a_5, b_5, c_5, q_4, q_5\rangle$**.**

Procedure IV:11(sat0308191134)

Objective

Choose the following:

1. A procedure $q_0(x, n)$ to show that $p'_n(x) \equiv 0$ (err a_0) when a complex number x and a positive integer n such that $P(x)$, and $n > b_0$ are chosen
2. A procedure $q_1(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} p_n(y) \equiv p'_n(x)$ (err $\frac{a_1}{n} + b_1\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > b_0$, and $0 < \|\delta\|^2 < {c_1}^2$ are chosen
3. A procedure $q_2(x, n)$ to show that $t'_n(x) \equiv 0$ (err a_2) when a complex number x and a positive integer n such that $R(x)$, and $n > b_2$ are chosen
4. A procedure $q_3(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} t_n(y) \equiv t'_n(x)$ (err $\frac{a_3}{n} + b_3\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $R(x)$, $n > b_2$, and $0 < \|\delta\|^2 < {c_3}^2$ are chosen
5. A procedure $q_4(x, n)$ to show that $P(t_n(x))$ when a complex number x and a positive integer n such that $R(x)$ and $n > b_2$ are chosen

The objective of the following instructions is to construct the following:

1. Rational numbers a_5, b_5, a_6, b_6, c_6.
2. A procedure $q_5(x, n)$ to show that $p'_n(t_n(x))t'_n(x) \equiv 0$ (err a_5) when a complex number x such that $R(x)$, and $n > b_5$ are chosen.
3. A procedure $q_6(x, n, \delta)$ to show that $\Delta^{x+\delta}_{y=x} p_n(t_n(y)) \equiv p'_n(t_n(x))t'_n(x)$ (err $\frac{a_6}{n} + b_6\{\delta\}$) when two complex numbers x, dx such that $R(x)$, $n > b_5$, and $0 < \|\delta\|^2 < {c_6}^2$ are chosen.

Implementation

1. Let $a_5 = a_0 a_2$.
2. Let $b_5 = \max(b_0, b_2)$.
3. Let $a_6 = a_1 a_3 + a_1 a_2 + a_0 a_3$.
4. Let $b_6 = a_1 b_3 + b_1 a_3 + 2 b_1 b_3 c_6 + b_1 a_2 + a_0 b_3$.
5. Let $c_6 = \min(c_3, \frac{c_1}{a_3 + 2 b_3 c_3 + a_2})$.
6. Let $q_5(x, n, \delta)$ be the following procedure:

(a) Show that $P(t_n(x))$ using procedure q_4.

(b) If $\Delta^{+\delta}_{y=x} t_n(y) = 0$, then do the following:

i. Show that $t_n(x + \delta) = t_n(x)$ given that $t_n(x + \delta) - t_n(x) = 0\delta = 0$.

ii. Hence using procedures q_0, q_3, show that $\Delta^{+\delta}_{y=x} p_n(t_n(y))$

A. $= \frac{p_n(t_n(x+\delta)) - p_n(t_n(x))}{\delta}$

B. $= \frac{p_n(t_n(x)) - p_n(t_n(x))}{\delta}$

C. $= 0$

D. $= \Delta^{+\delta}_{y=x} t_n(y) p'_n(t_n(x))$

E. $\equiv t'_n(x) p'_n(t_n(x))$ (err $a_0(\frac{a_3}{n} + b_3\{\delta\})$).

(c) Otherwise do the following:

i. Using procedures q_3, q_4, show that $\Delta^{+\delta}_{y=x} t_n(y)$

A. $\equiv t'_n(x)$ (err $\frac{a_3}{n} + b_3\{\delta\}$)

B. $\equiv 0$ (err a_2).

ii. Show that $\{\delta\} \le 2c_6 \le 2c_3$ given that $\{\delta\}^2 \le 2\|\delta\|^2 \le 4{c_6}^2$.

iii. Show that $t_n(x + \delta) - t_n(x)$

A. $= \Delta^{+\delta}_{y=x} t_n(y)\delta$

B. $\equiv 0\delta$ (err $(\frac{a_3}{n}+b_3\{\delta\}+a_2)c_6$) (err $(a_3+2b_3c_3+a_2)c_6$) (err c_1).

iv. Hence using procedures q_0, q_1, show that $\Delta_{z=t_n(x)}^{t_n(x+\delta)-t_n(x)} p_n(z)$

A. $\equiv p_n'(t_n(x))$ (err $\frac{a_1}{n}+b_1\{\delta\}$)

B. $\equiv 0$ (err a_0).

v. Hence show that $\Delta_{y=x}^{+\delta} p_n(t_n(y))$

A. $= \Delta_{z=t_n(x)}^{t_n(x+\delta)-t_n(x)} p_n(z) \cdot \Delta_{y=x}^{+\delta} t_n(y)$

B. $\equiv p_n'(t_n(x)) \Delta_{y=x}^{+\delta} t_n(y)$ (err $(\frac{a_1}{n}+b_1\{\delta\})(\frac{a_3}{n}+b_3\{\delta\}+a_2)$)

C. $\equiv p_n'(t_n(x)) t_n'(x)$ (err $a_0(\frac{a_3}{n}+b_3\{\delta\})$).

(d) **Hence show that** $\Delta_{y=x}^{+\delta} p_n(t_n(y)) \equiv p_n'(t_n(x)) t_n'(x)$ (err $\frac{a_6}{n}+b_6\{\delta\}$)**.**

7. Let $q_6(x,n)$ be the following procedure:

(a) Show that $P(t_n(x))$ using procedure q_4.

(b) Show that $p_n'(t_n(x)) \equiv 0$ (err a_0) using procedure q_0.

(c) Show that $t_n'(x) \equiv 0$ (err a_2) using procedure q_2.

(d) Hence show that $p_n'(t_n(x)) t_n'(x) \equiv 0$ (err $a_0 a_2$) (err a_5).

8. **Yield the tuple** $\langle a_5, b_5, a_6, b_6, c_6, q_5, q_6 \rangle$**.**

Procedure IV:12(tue2008191001)

Objective

Choose the following:

1. A complex number B
2. A procedure $q_1(x,n)$ to show that $p_n'(x) \equiv 0$ (err a_1) when a complex number x and a positive integer n such that $P(x)$ and $n > b_1$ are chosen.
3. A procedure $q_2(x,n,\delta)$ to show that $\Delta_{y=x}^{+\delta} p_n(y) \equiv p'(x)$ (err $\frac{a_2}{n}+b_2\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > b_1$, and $0 < \|\delta\|^2 \leq {c_2}^2$ are chosen.

The objective of the following instructions is to construct the following:

1. Rational numbers a_3, b_3, a_4, b_4, c_4.
2. A procedure $q_3(x,n)$ to show that $Bp_n'(x) \equiv 0$ (err a_3) when a complex number x and a positive integer n such that $P(x)$ and $n > b_3$ are chosen.
3. A procedure $q_4(x,n,\delta)$ to show that $\Delta_{y=x}^{+\delta}(Bp_n(y)) \equiv Bp_n'(x)$ (err $\frac{a_4}{n}+b_4\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > b_3$, and $0 < \|\delta\|^2 \leq {c_4}^2$ are chosen.

Implementation

1. Let $a_3 = \{B\}a_1$.
2. Let $b_3 = b_1$.
3. Let $a_4 = \{B\}a_2$.
4. Let $b_4 = \{B\}b_2$.
5. Let $c_4 = c_2$.
6. Let $q_3(x,n)$ be the following procedure:

(a) Show that $p_n'(x) \equiv 0$ (err a_1) using procedure q_1.

(b) Hence show that $Bp_n'(x) \equiv 0B$ (err $\{B\}a_1$) (err a_3).

7. Let $q_4(x,n,\delta)$ be the following procedure:

(a) Show that $\Delta_{y=x}^{+\delta} p_n(y) \equiv p'(x)$ (err $\frac{a_2}{n}+b_2\{\delta\}$) using procedure q_4.

(b) Hence show that $B\Delta_{y=x}^{+\delta} p_n(y) \equiv Bp'(x)$

i. (err $\{B\}(\frac{a_2}{n}+b_2\{\delta\})$)

ii. (err $\frac{a_4}{n}+b_4\{\delta\}$).

8. **Yield the tuple** $\langle a_3, b_3, a_4, b_4, c_4, q_3, q_4 \rangle$**.**

Procedure IV:13(mon1908191207)

Objective

Choose the following:

1. A procedure $q_0(x,n)$ to show that $p_n(x) \equiv 0$ (err a_0) when a complex number x and a positive integer n such that $P(x)$ and $n > b_0$ are chosen.
2. A procedure $q_1(x,n)$ to show that $p_n'(x) \equiv 0$ (err a_1) when a complex number x and a positive integer n such that $P(x)$ and $n > b_0$ are chosen.

3. A procedure $q_2(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} p_n(y) \equiv p'_n(x)$ (err $\frac{a_2}{n} + b_2\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > b_0$, and $0 < \|\delta\|^2 < c_2{}^2$ are chosen.
4. A procedure $q_3(x, n)$ to show that $t_n(x) \equiv 0$ (err a_3) when a complex number x and a positive integer n such that $R(x)$ and $n > b_3$ are chosen.
5. A procedure $q_4(x, n)$ to show that $t'_n(x) \equiv 0$ (err a_4) when a complex number x and a positive integer n such that $R(x)$ and $n > b_3$ are chosen.
6. A procedure $q_5(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} t_n(y) \equiv t'_n(x)$ (err $\frac{a_5}{n} + b_5\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $R(x)$, $n > b_3$, and $0 < \|\delta\|^2 < c_5{}^2$ are chosen.

The objective of the following instructions is to construct the following:

1. Rational numbers a_6, b_6, a_7, b_7, c_7.
2. A procedure $q_6(x, n)$ to show that $p_n(x)t'_n(x) + p'_n(x)t_n(x) \equiv 0$ (err a_6) when a complex number x and a positive integer n such that $P(x)$, $R(x)$, and $n > b_6$ are chosen.
3. A procedure $q_7(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x}(p_n(y)t_n(y)) \equiv p_n(x)t'_n(x) + p'_n(x)t_n(x)$ (err $\frac{a_7}{n} + b_7\{\delta\}$) when two complex numbers x, δ such that $P(x)$, $R(x)$, $n > b_6$, and $0 < \|\delta\|^2 < c_7{}^2$ are chosen.

Implementation

1. Let $a_6 = a_0a_4 + a_1a_3$.
2. Let $b_6 = \max(b_0, b_3)$.
3. Let $a_7 = 0$.
4. Let $b_7 = (a_5 + b_5c_7 + a_4)(a_2 + b_2c_7 + a_1)$.
5. Let $c_7 = \min(c_2, c_5)$.
6. Let $q_7(x, n, \delta)$ be the following procedure:
   (a) Show that $\{\delta\} \leq 2c_7$ given that $\{\delta\}^2 \leq 2\|\delta\|^2 \leq 4c_7{}^2$.
   (b) Hence using procedures q_2, q_1, show that $\Delta^{+\delta}_{y=x} p_n(y)$
      i. $\equiv p'_n(x)$ (err $\frac{a_2}{n} + b_2\{\delta\}$)
      ii. $\equiv 0$ (err a_1).
   (c) Hence using procedures q_5, q_4, show that $\Delta^{+\delta}_{y=x} t_n(y)$
      i. $\equiv t'_n(x)$ (err $\frac{a_5}{n} + b_5\{\delta\}$)
      ii. $\equiv 0$ (err a_4).
   (d) Show that $p_n(x) \equiv 0$ (err a_0) using procedure q_0.
   (e) Show that $t_n(x) \equiv 0$ (err a_6) using procedure q_3.
   (f) Hence show that $\Delta^{+\delta}_{y=x}(p_n(y)t_n(y))$
      i. $= p_n(x + \delta)\Delta^{+\delta}_{y=x} t_n(y) + t_n(x)\Delta^{+\delta}_{y=x} p_n(y)$
      ii. $= (p_n(x) + \delta\Delta^{+\delta}_{y=x} p_n(y))\Delta^{+\delta}_{y=x} t_n(y) + t_n(x)\Delta^{+\delta}_{y=x} p_n(y)$
      iii. $= p_n(x)\Delta^{+\delta}_{y=x} t_n(y) + \delta\Delta^{+\delta}_{y=x} p_n(y)\Delta^{+\delta}_{y=x} t_n(y) + t_n(x)\Delta^{+\delta}_{y=x} p_n(y)$
      iv. $\equiv p_n(x)\Delta^{+\delta}_{y=x} t_n(y) + 0\delta\Delta^{+\delta}_{y=x} p_n(y) + t_n(x)\Delta^{+\delta}_{y=x} p_n(y)$ (err $(\frac{a_5}{n} + b_5\{\delta\} + a_4)\{\delta\}(\frac{a_2}{n} + b_2\{\delta\} + a_1)$)
   (g) **Hence show that $\Delta^{+\delta}_{y=x}(p_n(y)t_n(y)) \equiv p_n(x)\Delta^{+\delta}_{y=x} t_n(y) + t_n(x)\Delta^{+\delta}_{y=x} p_n(y)$ (err $\frac{a_7}{n} + b_7\{\delta\}$).**
7. Let $q_6(x, n)$ be the following procedure:
   (a) Show that $p'_n(x) \equiv 0$ (err a_1) using procedure q_1.
   (b) Show that $t'_n(x) \equiv 0$ (err a_4) using procedure q_4.
   (c) Show that $p_n(x) \equiv 0$ (err a_0) using procedure q_0.
   (d) Show that $t_n(x) \equiv 0$ (err a_3) using procedure q_3.
   (e) **Hence show that $p_n(x)t'_n(x) + p'_n(x)t_n(x) \equiv 0$ (err $a_0a_4 + a_1a_3$) (err a_6).**
8. **Yield the tuple $\langle a_6, b_6, a_7, b_7, c_7, q_6, q_7\rangle$.**

Procedure IV:14(fri2308191803)

Objective

Choose the following:

1. A procedure $q_0(x, n)$ to show that $p'_n(x) \equiv q'_n(x)$ (err $\frac{a_0}{n}$) when a complex number x and

a positive integer n such that $P(x)$ and $n > b_0$ are chosen.

2. A procedure $q_1(x, n)$ to show that $p'_n(x) \equiv 0$ (err a_1) when a complex number x and a positive integer n such that $P(x)$ and $n > b_1$ are chosen.

3. A procedure $q_2(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} p_n(y) \equiv p'_n(x)$ (err $\frac{a_2}{n} + b_2\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > b_1$, and $0 < \|\delta\|^2 \leq {c_2}^2$ are chosen.

The objective of the following instructions is to construct the following:

1. Rational numbers a_3, b_3, a_4, b_4, c_4.

2. A procedure $q_3(x, n)$ to show that $q'_n(x) \equiv 0$ (err a_3) when a complex number x and a positive integer n such that $P(x)$ and $n > b_3$ are chosen.

3. A procedure $q_4(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} p_n(y) \equiv q'_n(x)$ (err $\frac{a_4}{n} + b_4\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > b_3$, and $0 < \|\delta\|^2 \leq {c_4}^2$ are chosen.

Implementation

1. Let $a_3 = a_0 + a_1$.
2. Let $b_3 = \max(b_0, b_1)$.
3. Let $a_4 = a_0 + a_2$.
4. Let $b_4 = b_2$.
5. Let $c_4 = c_2$.
6. Let $q_3(x, n)$ be the following procedure:
   (a) Show that $p'_n(x) \equiv q'_n(x)$ (err $\frac{a_0}{n}$) using procedure q_0.
   (b) Show that $p'_n(x) \equiv 0$ (err a_1) using procedure q_1.
   (c) **Hence show that** $q'_n(x) \equiv 0$ (err a_3)**.**
7. Let $q_4(x, n, \delta)$ be the following procedure:
   (a) Using procedures q_0, q_2, show that $\Delta^{+\delta}_{y=x} p_n(y)$
      i. $\equiv p'_n(x)$ (err $\frac{a_2}{n} + b_2\{\delta\}$)
      ii. $\equiv q'_n(x)$ (err $\frac{a_0}{n}$).
   (b) Hence show that $\Delta^{+\delta}_{y=x} p_n(y) \equiv q'_n(x)$
      i. (err $\frac{a_2}{n} + b_2\{\delta\} + \frac{a_0}{n}$)
      ii. (err $\frac{a_4}{n} + b_4\{\delta\}$).
8. **Yield the tuple** $\langle a_3, b_3, a_4, b_4, c_4, q_3, q_4 \rangle$**.**

Chapter 14

Common Derivatives

Procedure IV:15(tue2008191151)

Objective

Choose a complex number B and a rational number $D > 0$. The objective of the following instructions is to construct rational numbers a, b, c, d, a procedure $p(x, n)$ to show that $0 \equiv 0$ (err a) when a complex number x and a positive integer n such that $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} B \equiv 0$ (err $\frac{b}{n} + c\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Let $a = b = c = d = 0$.
2. Let $p(x, n)$ be the following procedure:
   (a) **Show that** $0 \equiv 0$ (err a)**.**
3. Let $q(x, n, \delta)$ be the following procedure:
   (a) **Show that** $\Delta^{+\delta}_{y=x} B \equiv 0$ (err $\frac{b}{n} + c\{\delta\}$)**.**
4. **Yield the tuple** $\langle a, b, c, d, p, q \rangle$**.**

Procedure IV:16(tue2008191209)

Objective

Choose a positive integer N and positive rational numbers X, D. The objective of the following instructions is to construct rational numbers a, b, c, d, a procedure $p(x, n)$ to show that $Nx^{N-1} \equiv 0$ (err a) when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} y^N \equiv Nx^{N-1}$ (err $\frac{b}{n} + c\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Let $a = NX^{N-1}$.
2. Let $b = d = 0$.
3. Let $c = \sum_r^{[0:N-1]} \binom{N}{r} X^r D^{N-r-2}$.
4. Let $p(x, n)$ be the following procedure:
   (a) **Show that** $Nx^{N-1} \equiv 0$ (err Nx^{N-1}) (err NX^{N-1}) (err a)**.**
5. Let $q(x, n, \delta)$ be the following procedure:
   (a) Show that $\Delta^{+\delta}_{y=x} y^N \equiv Nx^{N-1}$
      i. (err $\frac{(x+\delta)^N - x^N}{\delta} - Nx^{N-1}$)
      ii. (err $\frac{1}{\delta}(\sum_r^{[0:N+1]} \binom{N}{r} x^r \delta^{N-r} - x^N) - Nx^{N-1}$)
      iii. (err $\sum_r^{[0:N]} \binom{N}{r} x^r \delta^{N-r-1} - Nx^{N-1}$)
      iv. (err $\delta(\sum_r^{[0:N-1]} \binom{N}{r} x^r \delta^{N-r-2})$)
      v. (err $\frac{b}{n} + c\{\delta\}$).
6. **Yield the tuple** $\langle a, b, c, d, p, q \rangle$**.**

Procedure IV:17(tue2008191254)

Objective

Choose two rational numbers $X > D > 0$. The objective of the following instructions is to construct rational numbers a, b, c, d, a procedure $p(x, n)$ to show that $-\frac{1}{x^2} \equiv 0$ (err a) when a complex number x and a positive integer n such that $\|x\|^2 \geq X^2$ and $n > b$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x}\frac{1}{y} \equiv -\frac{1}{x^2}$ (err $\frac{c}{n}+d\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Let $a = \frac{1}{X^2}$.
2. Let $b = c = 0$.
3. Let $d = \frac{1}{X^2(X-D)}$.
4. Let $p(x, n)$ be the following procedure:
   (a) **Show that** $\frac{1}{x^2} \equiv 0$ (err $\frac{1}{x^2}$) (err $\frac{1}{X^2}$) (err a)**.**
5. Let $q(x, n, \delta)$ be the following procedure:
   (a) Show that $\Delta^{+\delta}_{y=x}\frac{1}{y} \equiv -\frac{1}{x^2}$
      i. (err $\frac{1}{\delta}(\frac{1}{x+\delta} - \frac{1}{x}) + \frac{1}{x^2}$)
      ii. (err $\frac{1}{\delta} \cdot \frac{-\delta}{x(x+\delta)} + \frac{1}{x^2}$)
      iii. (err $\frac{1}{x^2} - \frac{1}{x(x+\delta)}$)
      iv. (err $\frac{\delta}{x^2(x+\delta)}$)
      v. (err $\frac{\{\delta\}}{X^2(X-D)}$)
      vi. (err $\frac{c}{n} + d\{\delta\}$).
6. **Yield the tuple** $\langle a, b, c, d, p, q\rangle$**.**

Procedure IV:18(tue2008191341)

Objective

Choose a positive integer N and positive rational numbers $X < Y$. The objective of the following instructions is to construct positive rational numbers a, b, c, d, e, a procedure $p(x, n)$ to show that $-Nx^{-N-1} \equiv 0$ (err a) when a complex number x and a positive integer n such that $X^2 \leq \|x\|^2 \leq Y^2$ and $n > b$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x}y^{-N} \equiv -Nx^{-N-1}$ (err $\frac{c}{n} + d\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq e^2$ is chosen.

Implementation

1. Execute the following in post-order:
   (a) Execute procedure IV:11 on $\langle q_2, q_3, q_4, q_5, q_6\rangle$ and let $\langle a, b, c, d, e, q_0, q_1\rangle$ receive.
      i. Execute procedure IV:17 on $\langle X^N, \frac{X^N}{2}\rangle$ and let $\langle\cdots, q_2, q_3\rangle$ receive.
      ii. Execute procedure IV:16 on $\langle N, Y, Y\rangle$ and let $\langle\cdots, q_4, q_5\rangle$ receive.
      iii. Let $q_6(x, n)$ be the following procedure:
         A. Show that $\|x^N\|^2 = (\|x\|^2)^N \geq (X^2)^N = (X^N)^2$.
2. Let $p(x, n)$ be the following procedure:
   (a) **Show that** $-Nx^{-N-1} = -\frac{1}{(x^N)^2} \cdot Nx^{N-1} \equiv 0$ (err a) **using procedure** q_0**.**
3. Let $q(x, n, \delta)$ be the following procedure:
   (a) Using procedure q_1, show that $\Delta^{+\delta}_{y=x}y^{-N}$
      i. $= \frac{1}{\delta}(((x+\delta)^N)^{-1} - (x^N)^{-1})$
      ii. $\equiv -\frac{1}{(x^N)^2} \cdot Nx^{N-1}$ (err $\frac{c}{n} + d\{\delta\}$)
      iii. $= -Nx^{-N-1}$
   (b) **Hence show that** $\Delta^{+\delta}_{y=x}y^{-N} \equiv -Nx^{-N-1}$ (err $\frac{c}{n} + d\{\delta\}$)**.**
4. **Yield the tuple** $\langle a, b, c, d, e, p, q\rangle$**.**

Procedure IV:19(3.18)

Objective

Choose a rational number $D \geq 0$. The objective of the following instructions is to construct two rational numbers a, c and a procedure, $p(n, \delta)$, to show that $\Delta^{+\delta}_{x=0}\exp_n(x) \equiv 1$ (err $a\delta$) (err $a\{\delta\}$) when a complex number δ and a positive integer n such that $0 < \|\delta\|^2 \leq D^2$ and $n > c$ are chosen.

Implementation

1. Execute procedure III:34 on $\langle D\rangle$ and let $\langle a, c, q\rangle$ receive.
2. Let $p(\delta, n)$ be the following procedure:
   (a) Now using procedure II:27, and procedure q, show that $\exp_n(\delta) - 1 \equiv \delta$
      i. (err $\exp_n(\delta) - 1 - \delta$)
      ii. (err $(1 + \frac{\delta}{n})^n - 1 - \delta$)
      iii. (err $\frac{\delta}{n}\sum_r^{[0:n]}(1 + \frac{\delta}{n})^r - n\frac{\delta}{n}$)
      iv. (err $\frac{\delta}{n}\sum_r^{[0:n]}((1 + \frac{\delta}{n})^r - 1)$)
      v. (err $\frac{\delta}{n}\sum_r^{[0:n]}\frac{\delta}{n}\sum_k^{[0:r]}(1 + \frac{\delta}{n})^k$)
      vi. (err $\frac{\delta^2}{n^2}\sum_r^{[0:n]}\sum_k^{[0:r]}(1 + \frac{\delta}{n})^k$)

vii. (err $\frac{\delta^2}{n^2} \sum_r^{[0:n]} \sum_k^{[0:r]} a$)

viii. (err $\delta^2 a$).

(b) **Therefore show that** $\Delta_{x=0}^{+\delta} \exp_n(x) \equiv 1$ (err $a\delta$) (err $a\{\delta\}$).

3. **Yield the tuple** $\langle a, c, p \rangle$.

Procedure IV:20(3.19)

Objective

Choose two rational numbers $X \geq 0$, $D \geq 0$. The objective of the following instructions is to construct rational numbers l, a, b, d, a procedure $t(x, n)$ to show that $\exp_n(x) \equiv 0$ (err l) when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > d$ are chosen, and a procedure, $q(x, n, \delta)$, to show that $\Delta_{y=x}^{+\delta} \exp_n(y) \equiv \exp_n(x)$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Execute procedure III:36 on $\langle \max(X, D) \rangle$ and let $\langle e, f, u \rangle$ receive.
2. Execute procedure IV:19 on $\langle X \rangle$ and let $\langle h, j, r \rangle$ receive.
3. Execute procedure III:34 on $\langle X \rangle$ and let $\langle l, m, t \rangle$ receive.
4. Let $a = eX$.
5. Let $b = lh$.
6. Let $d = \max(f, j, m)$.
7. Let $p(x, n, \delta)$ be the following procedure:

(a) Using procedures u, r, t, show that $\Delta_{y=x}^{+\delta} \exp_n(y)$

i. $= \frac{\exp_n(x+\delta) - \exp_n(x)}{\delta}$

ii. $= \frac{\exp_n(x)\exp_n(\delta) - \exp_n(x)}{\delta}$

A. (err $\frac{ex\delta}{n\delta}$)

B. (err $\frac{eX}{n}$)

iii. $= \exp_n(x) \Delta_{y=0}^{\delta} \exp_n(y)$

iv. $\equiv \exp_n(x) \cdot 1$ (err $lh\{\delta\}$).

(b) **Hence show that** $\Delta_{y=x}^{+\delta} \exp_n(y) \equiv \exp_n(x)$ (err $\frac{ex}{n} + lh\{\delta\}$) (err $\frac{a}{n} + b\{\delta\}$).

8. **Yield the tuple** $\langle a, b, d, p \rangle$.

Procedure IV:21(3.27)

Objective

Choose non-negative rational numbers X, D. The objective of the following instructions is to construct rational numbers l, d, a, b, a procedure $q(x, n)$ to show that $\cos_n(x) \equiv 0$ (err l) when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > d$ are chosen, and a procedure $p(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} \sin_n(y) \equiv \cos_n(x)$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1) Execute the following in post-order:

a) Execute procedure IV:12 on $\langle \frac{1}{2i}, q_2, q_3 \rangle$ and let $\langle l, d, a, b, D, q_0, q_1 \rangle$ receive.

i) Execute procedure IV:10 on $\langle q_4, q_5, q_6, q_7 \rangle$ and let $\langle q_2, q_3 \rangle$ receive.

(1) Execute procedure IV:11 on $\langle q_8, q_9, q_{10}, q_{11}, q_{12} \rangle$ and let $\langle q_4, q_5 \rangle$ receive.

(a) Execute procedure IV:20 on $\langle X, D \rangle$ and let $\langle q_8, q_9 \rangle$ receive.

(b) Execute procedure IV:12 on $\langle i, q_{13}, q_{14} \rangle$ and let $\langle q_{10}, q_{11} \rangle$ receive.

(i) Execute procedure IV:16 on $\langle 1, X, D \rangle$ and let $\langle q_{13}, q_{14} \rangle$ receive.

(c) Let $q_{12}(x, n)$ be the following procedure:

(i) Show that $\|ix\|^2 = \|x\|^2 \leq X^2$.

(2) Execute procedure IV:12 on $\langle -1, q_{15}, q_{16} \rangle$ and let $\langle q_6, q_7 \rangle$.

(a) Execute procedure IV:11 on $\langle q_{17}, q_{18}, q_{19}, q_{20}, q_{21} \rangle$ and let $\langle q_{15}, q_{16} \rangle$ receive.

(i) Execute procedure IV:20 on $\langle X, D \rangle$ and let $\langle q_{17}, q_{18} \rangle$ receive.

(ii) Execute procedure IV:12 on $\langle -i, q_{22}, q_{23} \rangle$ and let $\langle q_{19}, q_{20} \rangle$ receive.

(1) Execute procedure IV:16 on $\langle 1, X, D \rangle$ and let $\langle q_{22}, q_{23} \rangle$ receive.

(iii) Let $q_{21}(x, n)$ be the following procedure:

(1) Show that $\|-ix\|^2 = \|x\|^2 \leq X^2$.

2) Let $p(x, n)$ be the following procedure:

   1. Using procedure q_0, show that $\cos_n(x)$

   (a) $= \frac{1}{2}(\exp_n(ix) + \exp_n(-ix))$

   (b) $= \frac{1}{2i}(\exp_n(ix^1) \cdot i \cdot 1x^0 + (-1)\exp_n(-ix^1) \cdot (-i) \cdot 1 \cdot x^0)$

   (c) $\equiv 0$ (err l).

3) Let $q(x, n, \delta)$ be the following procedure:

   1. Using procedure q_1, show that $\Delta_{y=x}^{+\delta} \sin_n(y)$

   (a) $= \Delta_{y=x}^{+\delta}(\frac{\exp_n(ix)-\exp_n(-ix)}{2i})$

   (b) $= \Delta_{y=x}^{+\delta}(\frac{1}{2i}(\exp_n(ix^1)+(-1)\exp_n((-i)x^1)))$

   (c) $\equiv \frac{1}{2i}(\exp_n(ix^1) \cdot i \cdot 1x^0 + (-1)\exp_n(-ix^1) \cdot (-i) \cdot 1 \cdot x^0)$ (err $\frac{a}{n} + b\{\delta\}$)

   (d) $= \frac{\exp_n(ix)+\exp_n(-ix)}{2}$

   (e) $= \cos_n(x)$.

   2. **Hence show that** $\Delta_{y=x}^{+\delta} \sin_n(y) \equiv \cos_n(x)$ (err $\frac{a}{n} + b\{\delta\}$)**.**

4) **Yield the tuple** $\langle l, d, a, b, D, p, q\rangle$**.**

Procedure IV:22(3.28)

Objective

Choose non-negative rational numbers X, D. The objective of the following instructions is to construct rational numbers l, d, a, b, a procedure $q(x, n)$ to show that $-\sin_n(x) \equiv 0$ (err l) when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > d$ are chosen, and a procedure $p(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} \cos_n(y) \equiv -\sin_n(x)$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

Implementation is analogous to that of procedure IV:21.

Procedure IV:23(wed2108191034)

Objective

Choose non-negative rational numbers X, D such that $X + D < 1$. The objective of the following instructions is to construct rational numbers l, d, a, b, a procedure $p(x, n)$ to show that $(1 + x)_{n-1}^{-1} \equiv 0$ (err l) when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} \ln_n(1+y) \equiv (1+x)_{n-1}^{-1}$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Execute procedure III:55 on $\langle 1, X\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Let $l = a_1$.
3. Let $d = 1$.
4. Let $a = 0$.
5. Let $b = \frac{1}{D^2((X+D)^{-1}-1)}$.
6. Let $p(x, n)$ be the following procedure:

   (a) Using procedure p_1, show that $(1 + x)_{n-1}^{-1}$

   i. $= ((1 + x)_{n-1}^{-1})^1$

   ii. $\equiv 0$ (err a_1).

7. Let $q(x, n, \delta)$ be the following procedure:

   (a) Using procedure II:28, show that $\Delta_{y=x}^{+\delta} \ln_n(1 + y) \equiv (1 + x)_{n-1}^{-1}$

   i. (err $\Delta_{y=x}^{+\delta} \ln_n(1 + y) - (1 + x)_{n-1}^{-1}$)

   ii. (err $\frac{1}{\delta}(\sum_r^{[1:n]} \frac{(-1)^{r-1}}{r}(x + \delta)^r - \sum_r^{[1:n]} \frac{(-1)^{r-1}}{r} x^r) - \sum_r^{[0:n-1]} \binom{-1}{r} x^r$)

   iii. (err $\frac{1}{\delta} \sum_r^{[1:n]} \frac{(-1)^{r-1}}{r}(\sum_k^{[0:r+1]} \binom{r}{k} x^k \delta^{r-k} - x^r) - \sum_r^{[0:n-1]}(-1)^r x^r$)

   iv. (err $\sum_r^{[1:n]} \frac{(-1)^{r-1}}{r} \sum_k^{[0:r]} \binom{r}{k} x^k \delta^{r-1-k} - \sum_r^{[0:n-1]}(-1)^r x^r$)

   v. (err $\sum_r^{[1:n]} \frac{(-1)^{r-1}}{r}(\sum_k^{[0:r]} \binom{r}{k} x^k \delta^{r-1-k} - r x^{r-1})$)

   vi. (err $\delta(\sum_r^{[1:n]} \frac{(-1)^{r-1}}{r} \sum_k^{[0:r-1]} \binom{r}{k} x^k \delta^{r-2-k})$)

   vii. (err $\delta(\sum_r^{[1:n]} \sum_k^{[0:r-1]} \binom{r}{k} X^k D^{r-2-k})$)

   viii. (err $\delta(\frac{1}{D^2} \sum_r^{[1:n]} \sum_k^{[0:r-1]} \binom{r}{k} X^k D^{r-k})$)

   ix. (err $\delta(\frac{1}{D^2} \sum_r^{[1:n]}(X + D)^r)$)

   x. (err $\delta(\frac{1}{D^2((X+D)^{-1}-1)})$)

xi. (err $\frac{a}{n} + b\{\delta\}$).

8. **Yield the tuple $\langle l, d, a, b, p, q\rangle$.**

Procedure IV:24(wed2108191140)

Objective

Choose non-negative rational numbers X, D such that $X + D < 1$. The objective of the following instructions is to construct rational numbers l, d, a, b, a procedure $p(x, n)$ to show that $\frac{1}{1+x} \equiv 0$ (err l) when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x} \ln_n(1+y) \equiv \frac{1}{1+x}$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Execute procedure III:53 on $\langle X, 1\rangle$ and let $\langle a_1, b_1, p_1\rangle$ receive.
2. Execute procedure IV:23 on $\langle X, D\rangle$ and let $\langle a_2, b_2, c_2, b, p_2, q_2\rangle$ receive.
3. Let $l = \frac{1}{1-X}$.
4. Let $d = \max(1, b_2)$.
5. Let $a = 2a_1 l + c_2$.
6. Let $p(x, n)$ be the following procedure:
   (a) Show that $|\mathrm{re}(x)| \leq X$ given that $\mathrm{re}(x)^2 \leq \|x\|^2 \leq X^2$.
   (b) Hence show that $\|1 + x\|^2$
      i. $\geq \mathrm{re}(1 + x)^2$
      ii. $= (1 + \mathrm{re}(x))^2$
      iii. $\leq (1 - X)^2$.
   (c) Hence show that $\frac{1}{1+x} \equiv 0$ (err $\frac{1}{1+x}$) (err $\frac{1}{1-X}$) (err l).
7. Let $q(x, n, \delta)$ be the following procedure:
   (a) Show that $\|\frac{1}{1+x}\|^2 \leq l^2$ using procedure p.
   (b) Show that $\|(n-1)(-x)^{n-1}\|^2 \leq ({a_1 b_1}^{n-1})^2 \leq {a_1}^2$ using procedure p_1.
   (c) Hence show that $\|(-x)^{n-1}\|^2 \leq (\frac{a_1}{n-1})^2 \leq (\frac{2a_1}{n})^2$.
   (d) Now using procedure q_2, show that $\Delta^{+\delta}_{y=x} \ln_n(1 + y)$
      i. $\equiv (1 + x)^{-1}_{n-1}$ (err $\frac{c_2}{n} + b\{\delta\}$)
      ii. $= \frac{1-(-x)^{n-1}}{1-(-x)}$
      iii. $\equiv \frac{1}{1+x}$ (err $\frac{(-x)^{n-1}}{1+x}$) (err $\frac{2a_1 l}{n}$).
   (e) **Hence show that** $\Delta^{+\delta}_{y=x} \ln_n(1 + y) \equiv \frac{1}{1+x}$ (err $\frac{c_2}{n} + b\{\delta\} + \frac{2a_1 l}{n}$) (err $\frac{a}{n} + b\{\delta\}$).
8. **Yield the tuple $\langle l, d, a, b, p, q\rangle$.**

Procedure IV:25(sun0812191401)

Objective

Choose a rational number X such that $0 < X \leq 1$. The objective of the following instructions is to construct a rational number f such that $0 \leq f < 1$, and a procedure $p(x)$ to show that $\mathrm{re}(\frac{x-1}{x+1}) \geq -f$ and $\|\frac{x-1}{x+1}\|^2 \leq 1$ when a complex number x such that $\mathrm{re}(x) \geq 0$ and $\|x\|^2 \geq X^2$ is chosen.

Implementation

1. Let $f = \frac{1-X^2}{1+X^2}$.
2. Verify that $0 \leq f < 1$.
3. Let $p(x)$ be the following procedure:
   (a) Show that $\|\frac{x-1}{x+1}\|^2 \leq 1$
      i. given that $\|x - 1\|^2 \leq \|x + 1\|^2$
      ii. given that $(\mathrm{re}(x) - 1)^2 \leq (\mathrm{re}(x) + 1)^2$
      iii. given that $0 \leq \mathrm{re}(x)$.
   (b) Show that $\mathrm{re}(\frac{x-1}{x+1})$
      i. $= \mathrm{re}(\frac{(x-1)((x+1)^-)}{(x+1)((x+1)^-)})$
      ii. $= \mathrm{re}(\frac{\|x\|^2+x-(x)^- -1}{\|x\|^2+x+(x)^- +1})$
      iii. $= \frac{\|x\|^2-1}{\|x\|^2+2\,\mathrm{re}(x)+1}$
      iv. $\geq \frac{X^2-1}{\|x\|^2+2\,\mathrm{re}(x)+1}$
      v. $\geq \frac{X^2-1}{X^2+1} = -f$.

Declaration IV:2(wed2108191408)

The notation $\ln_n(x)$, where x is a complex number, will be used as a shorthand for $\ln_n(1+\frac{x-1}{x+1}) - \ln_n(1-\frac{x-1}{x+1})$ when $\mathrm{re}(x) \geq 0$, $\ln_n(\frac{x}{i}) + \frac{\tau_n}{4} i$ when $\mathrm{im}(x) \geq 0$, and $\ln_n(xi) - \frac{\tau_n}{4} i$ if otherwise.

Procedure IV:26(thu2208191250)

Objective

Choose a rational number X such that $1 \geq X > 0$. The objective of the following instructions is to construct a positive rational number a, and a procedure $p(x, k)$ to show that $\|\ln_k(x)\|^2 \leq a^2$ when a positive integer k and a complex number x such that $\|x\|^2 \geq X^2$ and $\mathrm{re}(x) \geq 0$ are chosen.

Implementation

1. Execute procedure IV:25 on $\langle X \rangle$ and let $\langle a_1, p_1 \rangle$ receive.
2. Verify that $0 < a_1 < 1$.
3. Execute procedure III:70 on $\langle a_1 \rangle$ and let $\langle a_2, p_2 \rangle$ receive.
4. Let $a = 2a_2$.
5. Let $p(x, k)$ be the following procedure:
   (a) Show that $\|\frac{x-1}{x+1}\|^2 \leq {a_1}^2$ using procedure p_1.
   (b) Show that $\|\ln_k(1 + \frac{x-1}{x+1})\|^2 \leq {a_2}^2$ using procedure p_2.
   (c) Show that $\|\ln_k(1 - \frac{x-1}{x+1})\|^2 \leq {a_2}^2$ using procedure p_2.
   (d) Hence show that $\|\ln_k(x)\|^2$
      i. $= \|\ln_k(1 + \frac{x-1}{x+1}) - \ln_k(1 - \frac{x-1}{x+1})\|^2$
      ii. $\leq a^2$.
6. **Yield the tuple** $\langle a, p \rangle$**.**

Procedure IV:27(sun0812191440)

Objective

Choose a rational number X such that $0 < X \leq 1$. The objective of the following instructions is to construct positive rational numbers a, b, and a procedure $p(x, k)$ to show that $\|\ln_k(x)\|^2 \leq a^2$ when a positive integer k and a complex number x such that $\|x\|^2 \geq X^2$ and $k > b$ are chosen.

Implementation

1. Execute procedure IV:26 on $\langle X \rangle$ and let $\langle a_1, p_1 \rangle$ receive.
2. Execute procedure III:74 and let $\langle a_2, b_2, p_2 \rangle$ receive.
3. Verify that $a_2 > 0$.
4. Let $a = a_1 + \frac{a_2}{4}$.
5. Let $p(x, k)$ be the following procedure:
   (a) Show that $\frac{1}{4}\tau_k \leq \frac{a_2}{4}$ using procedure p_2.
   (b) If $\mathrm{re}(x) \geq 0$, then do the following:
      i. **Show that** $\|\ln_k(x)\|^2 \leq {a_1}^2 \leq a^2$ **using procedure** p_1**.**
   (c) Otherwise if $\mathrm{im}(x) \geq 0$, then do the following:
      i. Show that $\|\frac{x}{i}\|^2 = \|x\|^2 \geq X^2$.
      ii. Show that $\mathrm{re}(\frac{x}{i}) = \mathrm{re}(\mathrm{im}(x) - \mathrm{re}(x)i) = \mathrm{im}(x) \geq 0$.
      iii. Hence show that $\|\ln_k(\frac{x}{i})\|^2 \leq {a_1}^2$ using procedure p_1.
      iv. **Hence show that** $\|\ln_k(x)\|^2 = \|\ln_k(\frac{x}{i}) + \frac{\tau_k}{4}i\|^2 \leq (a_1 + \frac{a_2}{4})^2 = a^2$**.**
   (d) Otherwise do the following:
      i. Show that $\|xi\|^2 = \|x\|^2 \geq X^2$.
      ii. Show that $\mathrm{re}(xi) = \mathrm{re}(-\mathrm{im}(x) + \mathrm{re}(x)i) = -\mathrm{im}(x) > 0$.
      iii. Hence show that $\|\ln_k(xi)\|^2 \leq {a_1}^2$ using procedure p_1.
      iv. **Hence show that** $\|\ln_k(x)\|^2 = \|\ln_k(xi) - \frac{\tau_k}{4}i\|^2 \leq (a_1 + \frac{a_2}{4})^2 = a^2$**.**
6. **Yield the tuple** $\langle a, b, p \rangle$**.**

Procedure IV:28(wed2108191401)

Objective

Choose a rational number X such that $1 \geq X > 0$. The objective of the following instructions is to construct positive rational numbers a, c, d, e and a procedure $p(x, n, k)$ to show that $\exp_n(\ln_k(x)) \equiv x$ (err $\frac{an}{k} + \frac{c}{n}$) when a complex number x and integers k, n such that $\mathrm{re}(x) \geq 0$, $\|x\|^2 \geq X^2$, $n > e$, and $k > d$ are chosen.

Implementation

1. Execute procedure IV:25 on $\langle X \rangle$ and let $\langle f, p_0 \rangle$ receive.
2. Execute procedure III:70 on $\langle f \rangle$ and let $\langle a_1, p_1 \rangle$ receive.

3. Execute procedure III:37 on $\langle a_1 \rangle$ and let $\langle a_2, b_2, p_2 \rangle$ receive.
4. Execute procedure III:35 on $\langle a_1 \rangle$ and let $\langle a_3, b_3, p_3 \rangle$ receive.
5. Execute procedure III:71 on $\langle f \rangle$ and let $\langle a_4, c_4, d, e_4, p_4 \rangle$ receive.
6. Let $a = \frac{a_4}{a_3} + \frac{a_4(1+f)}{a_3(1-f)}$.
7. Let $c = a_2 + \frac{c_4}{a_3} + \frac{c_4(1+f)}{a_3(1-f)}$.
8. Let $e = \max(b_2, b_3, e_4)$.
9. Let $p(x, n, k)$ be the following procedure:
   (a) Show that $\mathrm{re}(\frac{x-1}{x+1})^2 \leq \|\frac{x-1}{x+1}\|^2 \leq f^2$ using procedure p_0.
   (b) Hence show that $|\mathrm{re}(\frac{x-1}{x+1})| \leq f$.
   (c) Show that $\|\ln_k(1 + \frac{x-1}{x+1})\|^2 \leq {a_1}^2$ using procedure p_1.
   (d) Show that $\|\ln_k(1 - \frac{x-1}{x+1})\|^2 \leq {a_1}^2$ using procedure p_1.
   (e) Hence using procedures p_0, p_2, p_3, p_4, show that $\exp_n(\ln_k(x))$
      i. $= \exp_n(\ln_k(1 + \frac{x-1}{x+1}) - \ln_k(1 - \frac{x-1}{x+1}))$
      ii. $\equiv \frac{\exp_n(\ln_k(1+\frac{x-1}{x+1}))}{\exp_n(\ln_k(1-\frac{x-1}{x+1}))}$ (err $\frac{a_2}{n}$)
      iii. $\equiv \frac{1+\frac{x-1}{x+1}}{\exp_n(\ln_k(1-\frac{x-1}{x+1}))}$ (err $\frac{1}{a_3}(\frac{a_4 n}{k} + \frac{c_4}{n})$)
      iv. $\equiv \frac{1+\frac{x-1}{x+1}}{1-\frac{x-1}{x+1}}$ (err $(\frac{1+f}{a_3(1-f)})(\frac{a_4 n}{k} + \frac{c_4}{n})$)
      v. $= x$.
   (f) Hence show that $\exp_n(\ln_k(x)) \equiv x$
      i. (err $\frac{a_2}{n} + \frac{1}{a_3}(\frac{a_4 n}{k} + \frac{c_4}{n}) + (\frac{1+f}{a_3(1-f)})(\frac{a_4 n}{k} + \frac{c_4}{n})$)
      ii. (err $\frac{an}{k} + \frac{c}{n}$).
10. **Yield the tuple** $\langle a, c, d, e, p \rangle$.

Procedure IV:29(sun0812191512)

Objective

Choose a rational number X such that $0 < X \leq 1$. The objective of the following instructions is to construct positive rational numbers a, c, d, e and a procedure $p(x, n, k)$ to show that $\exp_n(\ln_k(x)) \equiv x$ (err $\frac{an}{k} + \frac{c}{n}$) when a complex number x and integers k, n such that $\|x\|^2 \geq X^2$, $n > e$, and $k > d$ are chosen.

Implementation

1. Execute procedure IV:28 on $\langle X \rangle$ and let $\langle a_1, b_1, c_1, d_1, p_1 \rangle$ receive.
2. Execute procedure IV:27 on $\langle X \rangle$ and let $\langle a_2, b_2, p_2 \rangle$ receive.
3. Execute procedure III:82 on $\langle a_2, 1 \rangle$ and let $\langle a_3, b_3, c_3, d_3, p_3 \rangle$ receive.
4. Let $a = a_2 + a_3$.
5. Let $c = b_1 + b_3$.
6. Let $d = \max(c_1, b_2, d_3)$.
7. Let $e = \max(c_3, d_1)$.
8. Let $p(x, n, k)$ be the following procedure:
   (a) If $\mathrm{re}(x) \geq 0$, then do the following:
      i. **Show that** $\exp_n(\ln_k(x)) \equiv x$ (err $\frac{a_2 n}{k} + \frac{b_1}{n}$) (err $\frac{an}{k} + \frac{c}{n}$) **using procedure** p_1**.**
   (b) Otherwise if $\mathrm{im}(x) \geq 0$, then do the following:
      i. Show that $\|\frac{x}{i}\|^2 = \|x\|^2 \geq X^2$.
      ii. Show that $\mathrm{re}(\frac{x}{i}) = \mathrm{re}(\mathrm{im}(x) - \mathrm{re}(x)i) = \mathrm{im}(x) \geq 0$.
      iii. Hence show that $\exp_n(\ln_k(\frac{x}{i})) \equiv \frac{x}{i}$ (err $\frac{a_2 n}{k} + \frac{b_1}{n}$) using procedure p_1.
      iv. Hence show that $\|\ln_k(\frac{x}{i})\|^2 \leq {a_2}^2$ using procedure p_2.
      v. Hence using procedure p_3, show that $\exp_n(\ln_k(x))$
         A. $= \exp_n(\ln_k(\frac{x}{i}) + \frac{\tau_k}{4} i)$
         B. $\equiv i^1 \exp_n(\ln_k(\frac{x}{i}))$ (err $\frac{a_3 n}{k} + \frac{b_3}{n}$)
         C. $\equiv i \cdot \frac{x}{i}$ (err $\frac{a_2 n}{k} + \frac{b_1}{n}$)
         D. $= x$.
      vi. **Hence show that** $\exp_n(\ln_k(x)) \equiv x$ (err $\frac{an}{k} + \frac{c}{n}$)**.**
   (c) Otherwise do the following:
      i. Show that $\|xi\|^2 = \|x\|^2 \geq X^2$.

ii. Show that $\mathrm{re}(xi) = \mathrm{re}(-\mathrm{im}(x) + \mathrm{re}(x)i) = -\mathrm{im}(x) > 0$.

iii. Hence show that $\exp_n(\ln_k(xi)) \equiv xi$ (err $\frac{a_2 n}{k} + \frac{b_1}{n}$) using procedure p_1.

iv. Hence show that $\|\ln_k(xi)\|^2 \leq {a_2}^2$ using procedure p_2.

v. Hence using procedure p_3, show that $\exp_n(\ln_k(x))$

A. $= \exp_n(\ln_k(xi) - \frac{\tau_k}{4} i)$

B. $\equiv i^{-1} \exp_n(\ln_k(xi))$ (err $\frac{a_3 n}{k} + \frac{b_3}{n}$)

C. $\equiv i^{-1} xi$ (err $\frac{a_2 n}{k} + \frac{b_1}{n}$)

D. $= x$.

vi. **Hence show that** $\exp_n(\ln_k(x)) \equiv x$ (err $\frac{an}{k} + \frac{c}{n}$)**.**

9. **Yield the tuple** $\langle a, c, d, e, p \rangle$**.**

Procedure IV:30(wed2108191324)

Objective

Choose two rational numbers X, ϵ such that $0 < \epsilon < 1$ and $X \geq 0$. The objective of the following instructions is to construct a rational number f such that $0 < f < 1$, and a procedure $p(x)$ to show that $\|\frac{x-1}{x+1}\|^2 \leq f^2$ when a complex number x such that $\mathrm{re}(x) \geq \epsilon$ and $\|x\|^2 \leq X^2$ is chosen.

Implementation

1. Let $f = 1 - \frac{2\epsilon}{X^2+1+2\epsilon}$.

2. Show that $0 < f < 1$.

3. Let $p(x)$ be the following procedure:

(a) Show that $X^2 + 1 + 2\epsilon \leq \frac{4\epsilon}{1-f^2}$

i. given that $\frac{4\epsilon}{X^2+1+2\epsilon} \geq 1 - f^2$

ii. given that $f^2 = 1 - \frac{4\epsilon}{X^2+1+2\epsilon} + (\frac{2\epsilon}{X^2+1+2\epsilon})^2 \geq 1 - \frac{4\epsilon}{X^2+1+2\epsilon}$.

(b) Hence show that $\|x\|^2$

i. $\leq X^2$

ii. $\leq \frac{4\epsilon}{1-f^2} - (1 + 2\epsilon)$

iii. $= \frac{4\epsilon - 1 + f^2 - 2\epsilon + 2\epsilon f^2}{1-f^2}$

iv. $= \frac{f^2 - 1 + 2\epsilon(1+f^2)}{1-f^2}$

v. $\leq \frac{f^2 - 1 + 2\,\mathrm{re}(x)(1+f^2)}{1-f^2}$.

(c) **Hence show that** $\|\frac{x-1}{x+1}\|^2 \leq f^2$

i. given that $(\mathrm{re}(x) - 1)^2 + \mathrm{im}(x)^2 \leq f^2((\mathrm{re}(x)+1)^2 + \mathrm{im}(x)^2)$

ii. given that $(1 - f^2)(\mathrm{re}(x)^2 + \mathrm{im}(x)^2) \leq f^2 - 1 + 2\,\mathrm{re}(x)(1 + f^2)$.

4. **Yield the tuple** $\langle f, p \rangle$**.**

Procedure IV:31(wed2108191603)

Objective

Choose two rational numbers X, ϵ such that $0 < \epsilon < 1$ and $X \geq 0$. The objective of the following instructions is to construct rational numbers c, d, a, b, e, a procedure $p(x, n)$ to show that $\|\frac{1}{x}\|^2 \leq c^2$ when a complex number x and a positive integer n such that $\mathrm{re}(x) \geq \epsilon$, $\|x\|^2 \leq X^2$, and $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} \ln_n(y) \equiv \frac{1}{x}$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq e^2$ is chosen.

Implementation

1) Execute the following in post-order:

a) Execute procedure IV:10 on $\langle q_3, q_4, q_5, q_6 \rangle$ and let $\langle c, d, a, b, e, q_1, q_2 \rangle$ receive.

i) Execute procedure IV:11 on $\langle q_7, q_8, q_9, q_{10}, q_{11} \rangle$ and let $\langle q_3, q_4 \rangle$ receive.

(1) Execute procedure IV:24 on $\langle e_1, \frac{1-e_1}{2} \rangle$ and let $\langle q_7, q_8 \rangle$ receive.

(a) Execute procedure IV:30 on $\langle X, \epsilon \rangle$ and let $\langle e_1, q_{12} \rangle$ receive.

(2) Execute procedure IV:10 on $\langle q_{13}, q_{14}, q_{15}, q_{16} \rangle$ and let $\langle q_9, q_{10} \rangle$ receive.

(a) Execute procedure IV:15 on $\langle 1, 1 \rangle$ and let $\langle q_{13}, q_{14} \rangle$ receive.

(b) Execute procedure IV:12 on $\langle -2, q_{17}, q_{18} \rangle$ and let $\langle q_{15}, q_{16} \rangle$ receive.

(i) Execute procedure IV:11 on $\langle q_{19}, q_{20}, q_{21}, q_{22}, q_{23} \rangle$ and let $\langle q_{17}, q_{18} \rangle$ receive.

(1) Execute procedure IV:18 on $\langle 1, 1 + \epsilon, X + 1 \rangle$ and let $\langle q_{19}, q_{20} \rangle$ receive.

(2) Execute procedure IV:10 on $\langle q_{24}, q_{25}, q_{26}, q_{27}\rangle$ and let $\langle q_{21}, q_{22}\rangle$ receive.

(a) Execute procedure IV:15 on $\langle 1, 1\rangle$ and let $\langle q_{24}, q_{25}\rangle$ receive.

(b) Execute procedure IV:16 on $\langle 1, X, 1\rangle$ and let $\langle q_{26}, q_{27}\rangle$ receive.

(3) Let $q_{24}(x, n)$ be the following procedure:

(a) Show that $(1+\epsilon)^2 \leq (1+\mathrm{re}(x))^2 = \mathrm{re}(x+1)^2 \leq \|x+1\|^2 \leq (X+1)^2$.

(3) Let $q_{11}(x, n)$ be the following procedure:

(a) Show that $\|1 - 2(x+1)^{-1}\|^2 = \|\frac{x-1}{x+1}\|^2 \leq {e_1}^2$ using procedure q_{12}.

ii) Execute procedure IV:12 on $\langle -1, q_{28}, q_{29}\rangle$ and let $\langle q_5, q_6\rangle$ receive.

(1) Execute procedure IV:11 on $\langle q_{30}, q_{31}, q_{32}, q_{33}, q_{34}\rangle$ and let $\langle q_{28}, q_{29}\rangle$ receive.

(a) Execute procedure IV:24 on $\langle e_1, \frac{1-e_1}{2}\rangle$ and let $\langle q_{30}, q_{31}\rangle$ receive.

(b) Execute procedure IV:12 on $\langle -1, q_9, q_{10}\rangle$ and let $\langle q_{32}, q_{33}\rangle$ receive.

(c) Let $q_{34}(x, n)$ be the following procedure:

(i) Show that $\|-(1+(-2)(x+1)^{-1})\|^2 = \|\frac{x-1}{x+1}\|^2 \leq {e_1}^2$ using procedure q_{12}.

2) Let $p(x, n)$ be the following procedure:

a) **Show that** $\frac{1}{x} \equiv 0$ (err $\frac{1}{x}$) (err $\frac{1}{\mathrm{re}(x)}$) (err $\frac{1}{\epsilon}$) (err c)**.**

3) Let $q(x, n, \delta)$ be the following procedure:

a) Using procedure q_2, show that $\Delta^{+\delta}_{y=x} \ln_n(y)$

1. $= \Delta^{+\delta}_{y=x}(\ln_n(1+\frac{y-1}{y+1}) - \ln_n(1-\frac{y-1}{y+1}))$

2. $= \Delta^{+\delta}_{y=x}(\ln_n(1+(1+(-2)(y+1)^{-1})) + (-1)\ln_n(1+(-1)(1+(-2)(y+1)^{-1})))$

3. $\equiv ((1+(1+(-2)(x+1)^{-1}))^{-1}(0+(-2)(-1)(x+1)^{-2}(1+0)+(-1)((1+(-1)(1+(-2)(x+1)^{-1}))^{-1}\cdot(0+(-1)(0+(-2)(-1)(x+1)^{-2}(1+0)))))$ (err $\frac{a}{n} + b\{\delta\}$)

4. $= \frac{1}{x}$

b) **Hence show that** $\Delta^{+\delta}_{y=x} \ln_n(y) \equiv \frac{1}{x}$ (err $\frac{a}{n} + b\{\delta\}$)**.**

4) **Yield the tuple** $\langle c, d, a, b, e, p, q\rangle$**.**

Procedure IV:32(thu2208191330)

Objective

Choose a complex number A and non-negative rational numbers X, D such that $X + D < 1$. The objective of the following instructions is to construct rational numbers l, d, a, b, a procedure $p(x, n)$ to show that $\|A(1+x)^{A-1}_{n-1}\|^2 \leq l^2$ when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta^{+\delta}_{y=x}(1+y)^A_n \equiv A(1+x)^{A-1}_{n-1}$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Execute procedure III:52 on $\langle\{A+1\}, X+D\rangle$ and let $\langle a_1, b_1, p_1\rangle$ receive.

2. Execute procedure III:55 on $\langle\{A-1\}, X\rangle$ and let $\langle a_2, p_2\rangle$ receive.

3. Let $l = \{A\}a_2$.

4. Let $d = 1$.

5. Let $a = 0$.

6. Let $b = \frac{a_1 b_1}{D^2(1-b_1)}$.

7. Let $p(x, n)$ be the following procedure:

(a) Using procedure p_2, show that $A(1+x)^{A-1}_{n-1} \equiv 0$

i. (err $A(1+x)^{A-1}_{n-1}$)

ii. (err $\{A\}a_2$)

iii. (err l).

8. Let $q(x, n, \delta)$ be the following procedure:

(a) For $r \in [1:n]$, do the following:

i. Show that $\|A+1\|^2 \leq \{A+1\}^2$.

ii. Hence show that $\|\binom{A}{r}(X+D)^r\|^2 \leq (a_1 {b_1}^r)^2$ using procedure p_1.

iii. Hence show that $\|\binom{A}{r}\sum^{[0:r-1]}_k \binom{r}{k} x^k \delta^{r-2-k}\|^2$

A. $\leq \|\binom{A}{r}\|^2(\sum^{[0:r-1]}_k \binom{r}{k} X^k D^{r-2-k})^2$

B. $= \|\binom{A}{r}\|^2(\frac{1}{D^2}\sum_k^{[0:r-1]}\binom{r}{k}X^kD^{r-k})^2$

C. $\leq \|\frac{1}{D^2}\binom{A}{r}(X+D)^r\|^2$

D. $\leq (\frac{a_1{b_1}^r}{D^2})^2$.

(b) Now show that $\Delta_{y=x}^{+\delta}(1+y)_n^A \equiv A(1+x)_{n-1}^{A-1}$

i. (err $\frac{1}{\delta}((1+x+\delta)_n^A-(1+x)_n^A)-A(1+x)_{n-1}^{A-1}$)

ii. (err $\frac{1}{\delta}(\sum_r^{[0:n]}\binom{A}{r}(x+\delta)^r-\sum_r^{[0:n]}\binom{A}{r}x^r)-A\sum_r^{[0:n-1]}\binom{A-1}{r}x^r$)

iii. (err $\frac{1}{\delta}(\sum_r^{[0:n]}\binom{A}{r}(\sum_k^{[0:r+1]}\binom{r}{k}x^k\delta^{r-k}-x^r))-A\sum_r^{[0:n-1]}\binom{A-1}{r}x^r$)

iv. (err $\sum_r^{[0:n]}\binom{A}{r}\sum_k^{[0:r]}\binom{r}{k}x^k\delta^{r-1-k}-\sum_r^{[0:n-1]}(r+1)\binom{A}{r+1}x^r$)

v. (err $\sum_r^{[1:n]}\binom{A}{r}\sum_k^{[0:r]}\binom{r}{k}x^k\delta^{r-1-k}-\sum_r^{[1:n]}r\binom{A}{r}x^{r-1}$)

vi. (err $\delta(\sum_r^{[1:n]}\binom{A}{r}\sum_k^{[0:r-1]}\binom{r}{k}x^k\delta^{r-2-k})$)

vii. (err $\delta(\sum_r^{[1:n]}\frac{a_1{b_1}^r}{D^2})$)

viii. (err $\delta(\frac{a_1b_1}{D^2(1-b_1)})$)

ix. (err $\frac{a}{n}+b\{\delta\}$).

9. **Yield the tuple $\langle l,d,a,b,p,q\rangle$.**

Procedure IV:33(thu2208191432)

Objective

Choose a complex number A and non-negative rational numbers X, D such that $X+D<1$. The objective of the following instructions is to construct rational numbers l,d,a,b, a procedure $p(x,n)$ to show that $\|A(1+x)_n^{A-1}\|^2 \leq l^2$ when a complex number x and a positive integer n such that $\|x\|^2 \leq X^2$ and $n>d$ are chosen, and a procedure $q(x,n,\delta)$ to show that $\Delta_{y=x}^{+\delta}(1+y)_n^A \equiv A(1+x)_n^{A-1}$ (err $\frac{a}{n}+b\{\delta\}$) when in addition a complex number δ such that $0<\|\delta\|^2 \leq D^2$ is chosen.

Implementation

1. Execute procedure III:52 on $\langle\{A\},X\rangle$ and let $\langle a_1,b_1,p_1\rangle$ receive.
2. Execute procedure III:55 on $\langle\{A-1\},X\rangle$ and let $\langle a_2,p_2\rangle$ receive.
3. Execute procedure III:53 on $\langle b_1,1\rangle$ and let $\langle a_3,b_3,p_3\rangle$ receive.
4. Execute procedure IV:32 on $\langle X,D\rangle$ and let $\langle a_4,b_4,c_4,d_4,p_4,q_4\rangle$ receive.
5. Let $l=\{a\}a_2$.
6. Let $d=\max(1,b_4)$.
7. Let $a=c_4+2\{A\}a_1a_3$.
8. Let $b=d_4$.
9. Let $p(x,n)$ be the following procedure:
   (a) Using procedure p_2, show that $A(1+x)_n^{A-1}\equiv 0$
      i. (err $A(1+x)_n^{A-1}$)
      ii. (err $\{A\}a_2$)
      iii. (err l).
10. Let $q(x,n,\delta)$ be the following procedure:
   (a) Show that $\|\binom{A-1}{n-1}x^{n-1}\|^2 \leq (a_1{b_1}^{n-1})^2$ using procedure p_1.
   (b) Show that $\|(n-1){b_1}^{n-1}\|^2 \leq (a_3{b_3}^{n-1})^2 \leq {a_3}^2$ using procedure p_3.
   (c) Hence show that $\|{b_1}^{n-1}\|^2 \leq (\frac{a_3}{n-1})^2 \leq (\frac{2a_3}{n})^2$.
   (d) Now using procedure q_4, show that $\Delta_{y=x}^{+\delta}(1+y)_n^A$
      i. $\equiv A(1+x)_{n-1}^{A-1}$ (err $\frac{c_4}{n}+d_4\{\delta\}$)
      ii. $\equiv A(1+x)_n^{A-1}$
         A. (err $A\binom{A-1}{n-1}x^{n-1}$)
         B. (err $\{A\}a_1{b_1}^{n-1}$)
         C. (err $\frac{2\{A\}a_1a_3}{n}$).
   (e) Hence show that $\Delta_{y=x}^{+\delta}(1+y)_n^A \equiv A(1+x)_n^{A-1}$
      i. (err $\frac{c_4}{n}+d_4\{\delta\}+\frac{2\{A\}a_1a_3}{n}$)
      ii. (err $\frac{a}{n}+b\{\delta\}$).
11. **Yield the tuple $\langle l,d,a,b,p,q\rangle$.**

Declaration IV:3(thu2208191619)

The notation x_n^a, where x,a are complex numbers and n is a positive integer, will be used as a shorthand for $(1+\frac{x-1}{x+1})_n^a(1-\frac{x-1}{x+1})_n^{-a}$.

Procedure IV:34(sat2408190819)

Objective

Choose three non-negative rational numbers A, X, ϵ such that $0 < \epsilon < 1$. The objective of the following instructions is to construct positive rational numbers B, C, D, and a procedure $p(x, a, n)$ to show that $x_n^a \equiv x^a$ (err BC^n) when a complex number x, and integers a, n such that $\|x\|^2 \le X^2$, $\|a\|^2 \le A^2$, $\text{re}(x) \ge \epsilon$, and $n > D$ are chosen.

Implementation

1. Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Show that $0 < a_1 < 1$.
3. Execute procedure III:57 on $\langle A, a_1\rangle$ and let $\langle a_2, b_2, c_2, p_2\rangle$ receive.
4. Execute procedure III:55 on $\langle A, a_1\rangle$ and let $\langle a_3, p_3\rangle$ receive.
5. Let $B = a_3 a_2$.
6. Let $C = b_2$.
7. Let $D = \max(c_2, A)$.
8. Let $p(x, a, n)$ be the following procedure:
   (a) Show that $\|\frac{x-1}{x+1}\|^2 \le {a_1}^2$ using procedure p_1.
   (b) If $a \ge 0$, then do the following:
      i. Using procedure III:49 and procedures p_2, p_3, show that x_n^a
         A. $= (1 + \frac{x-1}{x+1})_n^a (1 - \frac{x-1}{x+1})_n^{0-a}$
         B. $\equiv (1 + \frac{x-1}{x+1})_n^a \frac{(1-\frac{x-1}{x+1})_n^0}{(1-\frac{x-1}{x+1})_n^a}$ (err $a_3 a_2 {b_2}^n$)
         C. $= \frac{(1+\frac{x-1}{x+1})^a}{(1-\frac{x-1}{x+1})^a}$
         D. $= x^a$
   (c) Otherwise do the following:
      i. Using procedure III:49 and procedures p_2, p_3, show that x_n^a
         A. $= (1 + \frac{x-1}{x+1})_n^{0-(-a)} (1 - \frac{x-1}{x+1})_n^{-a}$
         B. $\equiv \frac{(1+\frac{x-1}{x+1})_n^0}{(1+\frac{x-1}{x+1})_n^{-a}} (1 - \frac{x-1}{x+1})_n^{-a}$ (err $a_3 a_2 {b_2}^n$)
         C. $= \frac{(1-\frac{x-1}{x+1})_n^{-a}}{(1+\frac{x-1}{x+1})_n^{-a}}$
         D. $= (\frac{1}{x})^{-a}$
         E. $= x^a$.
   (d) **Hence show that** $x_n^a \equiv x^a$ (err $a_3 a_2 {b_2}^n$) (err BC^n)**.**
9. **Yield the tuple** $\langle B, C, D, p\rangle$**.**

Procedure IV:35(sat2408191109)

Objective

Choose three non-negative rational numbers A, X, ϵ such that $0 < \epsilon < 1$. The objective of the following instructions is to construct positive rational numbers B, C, and a procedure $p(x, a, b, n)$ to show that $x_n^{a+b} \equiv x_n^a x_n^b$ (err BC^n) when complex numbers x, a, b, and a positive integer n such that $\|x\|^2 \le X^2$, $\|a\|^2 \le A^2$, $\|b\|^2 \le A^2$, and $\text{re}(x) \ge \epsilon$ are chosen.

Implementation

1. Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Execute procedure III:54 on $\langle A, a_1\rangle$ and let $\langle a_2, b_2, p_2\rangle$ receive.
3. Execute procedure III:55 on $\langle 2A, a_1\rangle$ and let $\langle a_3, p_3\rangle$ receive.
4. Let $B = a_2 a_3 (1 + a_3)$.
5. Let $C = b_2$.
6. Let $p(x, a, b, n)$ be the following procedure:
   (a) Using procedures p_1, p_2, p_3, show that x_n^{a+b}
      i. $= (1 + \frac{x-1}{x+1})_n^{a+b} (1 - \frac{x-1}{x+1})_n^{-(a+b)}$
      ii. $\equiv (1 + \frac{x-1}{x+1})_n^a (1 + \frac{x-1}{x+1})_n^b (1 - \frac{x-1}{x+1})_n^{(-a)+(-b)}$ (err $a_2 {b_2}^n a_3$)
      iii. $\equiv (1 + \frac{x-1}{x+1})_n^a (1 + \frac{x-1}{x+1})_n^b (1 - \frac{x-1}{x+1})_n^{-a} (1 - \frac{x-1}{x+1})_n^{-b}$ (err ${a_3}^2 a_2 {b_2}^n$)
      iv. $= x_n^a x_n^b$.
   (b) **Hence show that** $x_n^{a+b} \equiv x_n^a x_n^b$ (err BC^n)**.**
7. **Yield the tuple** $\langle B, C, p\rangle$**.**

Procedure IV:36(sat2408191137)

Objective

Choose three non-negative rational numbers A, X, ϵ such that $0 < \epsilon < 1$. The objective of the following instructions is to construct a positive rational number D, and a procedure $p(x, n, a, k)$ to show that $(x_n^a)^k \equiv 0$ (err D) when complex numbers x, a, k, and a positive integer n such that $\|x\|^2 \leq X^2$, $\|ka\|^2 \leq A^2$, and $\mathrm{re}(x) \geq \epsilon$ are chosen.

Implementation

1. Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Execute procedure III:55 on $\langle A, a_1\rangle$ and let $\langle a_2, p_2\rangle$ receive.
3. Let $D = {a_2}^2$.
4. Let $p(x, n, a, k)$ be the following procedure:
   (a) Using procedures p_1, p_2, show that $(x_n^a)^k$
      i. $= ((1 + \frac{x-1}{x+1})_n^a (1 - \frac{x-1}{x+1})_n^{-a})^k$
      ii. $= ((1 + \frac{x-1}{x+1})_n^a)^k ((1 - \frac{x-1}{x+1})_n^{-a})^k$
      iii. $\equiv 0((1 - \frac{x-1}{x+1})_n^{-a})^k$ (err ${a_2}^2$)
      iv. $= 0$.
   (b) **Hence show that** $(x_n^a)^k \equiv 0$ (err D)**.**
5. **Yield the tuple** $\langle D, p\rangle$**.**

Procedure IV:37(thu2908190744)

Objective

Choose three non-negative rational numbers A, X, ϵ such that $0 < \epsilon < 1$. The objective of the following instructions is to construct a positive rational number D, and a procedure $p(x, n, a)$ to show that $\|x_n^a\|^2 \geq D^2$ when complex numbers x, a, and a positive integer n such that $\|x\|^2 \leq X^2$, $\|a\|^2 \leq A^2$, and $\mathrm{re}(x) \geq \epsilon$ are chosen.

Implementation

1. Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Execute procedure III:56 on $\langle A, a_1\rangle$ and let $\langle a_2, b_2, p_2\rangle$ receive.
3. Let $D = {a_2}^2$.
4. Let $p(x, n, a)$ be the following procedure:
   (a) Show that $\|\frac{x-1}{x+1}\|^2 \leq {a_1}^2$ using procedure p_1.
   (b) Show that $\|(1 + \frac{x-1}{x+1})_n^a\|^2 \geq {a_2}^2$ using procedure p_2.
   (c) Show that $\|(1 - \frac{x-1}{x+1})_n^{-a}\|^2 \geq {a_2}^2$ using procedure p_2.
   (d) Hence using declaration IV:3, show that $\|x_n^a\|^2$
      i. $= \|(1 + \frac{x-1}{x+1})_n^a\|^2 \|(1 - \frac{x-1}{x+1})_n^{-a}\|^2$
      ii. $\geq {a_2}^2 {a_2}^2$
      iii. $= D^2$.
5. **Yield the tuple** $\langle D, p\rangle$**.**

Procedure IV:38(thu2908190802)

Objective

Choose three non-negative rational numbers A, X, ϵ such that $0 < \epsilon < 1$. The objective of the following instructions is to construct positive rational numbers B, C, D, and a procedure $p(x, a, b, n)$ to show that $x_n^{a-b} \equiv \frac{x_n^a}{x_n^b}$ (err BC^n) when complex numbers x, a, b, and a positive integer n such that $\|x\|^2 \leq X^2$, $\|a\|^2 \leq A^2$, $\|b\|^2 \leq A^2$, $\mathrm{re}(x) \geq \epsilon$, and $n > D$ are chosen.

Implementation

1. Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Execute procedure III:57 on $\langle A, a_1\rangle$ and let $\langle a_2, b_2, c_2, p_2\rangle$ receive.
3. Execute procedure III:56 on $\langle A, a_1\rangle$ and let $\langle a_3, b_3, p_3\rangle$ receive.
4. Execute procedure III:55 on $\langle 2A, a_1\rangle$ and let $\langle a_4, p_4\rangle$ receive.
5. Let $B = a_2 a_4 (1 + \frac{1}{a_3})$.
6. Let $C = b_2$.
7. Let $D = \max(c_2, b_3)$.
8. Let $p(x, a, b, n)$ be the following procedure:
   (a) Using procedures p_1, p_2, p_3, p_4, show that x_n^{a-b}
      i. $= (1 + \frac{x-1}{x+1})_n^{a-b} (1 - \frac{x-1}{x+1})_n^{(-a)-(-b)}$

ii. $\equiv (1+\frac{x-1}{x+1})_n^{a-b}\frac{(1-\frac{x-1}{x+1})_n^{-a}}{(1-\frac{x-1}{x+1})_n^{-b}}$ (err $a_4a_2{b_2}^n$)

iii. $\equiv \frac{(1+\frac{x-1}{x+1})_n^a}{(1+\frac{x-1}{x+1})_n^b}\frac{(1-\frac{x-1}{x+1})_n^{-a}}{(1-\frac{x-1}{x+1})_n^{-b}}$ (err $a_2{b_2}^n\frac{a_4}{a_3}$)

iv. $= \frac{x_n^a}{x_n^b}$.

(b) **Hence show that** $x_n^{a-b} \equiv \frac{x_n^a}{x_n^b}$ (err $a_4a_2{b_2}^n + a_2{b_2}^n\frac{a_4}{a_3}$) (err BC^n)**.**

9. **Yield the tuple** $\langle B, C, D, p\rangle$**.**

Procedure IV:39(sat2408191538)

Objective

Choose three non-negative rational numbers A, X, ϵ such that $0 < \epsilon < 1$. The objective of the following instructions is to construct a positive rational number B, C, and a procedure $p(x, n, a, k)$ to show that $(x_n^a)^k \equiv x_n^{ak}$ (err BC^n) when complex numbers x, a, k, and a positive integer n such that $\|x\|^2 \le X^2$, $\|ka\|^2 \le A^2$, and $\mathrm{re}(x) \ge \epsilon$ are chosen.

Implementation

1. Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle a_1, p_1\rangle$ receive.
2. Execute procedure III:58 on $\langle A, a_1\rangle$ and let $\langle a_2, b_2, p_2\rangle$ receive.
3. Execute procedure III:55 on $\langle A, a_1\rangle$ and let $\langle a_3, p_3\rangle$ receive.
4. Let $B = 2a_2a_3$.
5. Let $C = b_2$.
6. Let $p(x, n, a, k)$ be the following procedure:

(a) Using procedures p_1, p_2, p_3, show that $(x_n^a)^k$

i. $= ((1+\frac{x-1}{x+1})_n^a(1-\frac{x-1}{x+1})_n^{-a})^k$

ii. $= ((1+\frac{x-1}{x+1})_n^a)^k((1-\frac{x-1}{x+1})_n^{-a})^k$

iii. $\equiv (1+\frac{x-1}{x+1})_n^{ak}((1-\frac{x-1}{x+1})_n^{-a})^k$ (err $a_2{b_2}^na_3$)

iv. $\equiv ((1+\frac{x-1}{x+1})_n^{ak})^1(1-\frac{x-1}{x+1})_n^{-ak}$ (err $a_3a_2{b_2}^n$)

v. $= x_n^{ak}$.

(b) **Hence show that** $(x_n^a)^k \equiv x_n^{ak}$ (err BC^n)**.**

7. **Yield the tuple** $\langle B, C, p\rangle$**.**

Procedure IV:40(thu2208191610)

Objective

Choose a complex number f and two rational numbers X, ϵ such that $0 < \epsilon < 1$ and $X \ge 0$. Let $g(f, x, n)$ be a shorthand for $[2f(1+\frac{x-1}{x+1})_n^f \cdot (1-\frac{x-1}{x+1})_n^{-f-1}(x+1)^{-2}] + [2f(1+\frac{x-1}{x+1})_n^{f-1} \cdot (1-\frac{x-1}{x+1})_n^{-f}(x+1)^{-2}]$. The objective of the following instructions is to construct rational numbers c, d, a, b, e, a procedure $p(x, n)$ to show that $\|g(f, x, n)\|^2 \le c^2$ when a complex number x and a positive integer n such that $\mathrm{re}(x) \ge \epsilon$, $\|x\|^2$, and $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} x_n^f \equiv g(f, x, n)$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \le e^2$ is chosen.

Implementation

1) Execute the following in post-order:

a) Execute procedure IV:13 on $\langle q_7, q_3, q_4, q_8, q_5, q_6\rangle$ and let $\langle c, d, a, b, e, p, q\rangle$ receive.

i) Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle e_1, q_9\rangle$ receive.

ii) Execute procedure III:55 on $\langle \{f\}, e_1\rangle$ and let $\langle e_2, q_{10}\rangle$ receive.

iii) Let $q_7(x, n)$ be the following procedure:

(1) Show that $\|\frac{x-1}{x+1}\|^2 \le {e_1}^2$ using procedure q_9.

(2) Using procedure q_{10}, show that $\|(1+(1+(-2)(x+1)^{-1}))_n^f\|^2$

(a) $= \|(1+\frac{x-1}{x+1})_n^f\|^2$

(b) $\le {e_2}^2$.

iv) Let $q_8(x, n)$ be the following procedure:

(1) Show that $\|\frac{x-1}{x+1}\|^2 \le {e_1}^2$ using procedure q_9.

(2) Using procedure q_{10}, show that $\|(1-(1+(-2)(x+1)^{-1}))_n^{-f}\|^2$

(a) $= \|(1-\frac{x-1}{x+1})_n^{-f}\|^2$

(b) $\le {e_2}^2$.

v) Execute procedure IV:11 on $\langle q_{11}, q_{12}, q_{13}, q_{14}, q_{15}\rangle$ and let $\langle q_3, q_4\rangle$ receive.

(1) Execute procedure IV:33 on $\langle f, e_1, \frac{1-e_1}{2}\rangle$ and let $\langle q_{11}, q_{12}\rangle$ receive.

(2) Execute procedure IV:10 on $\langle q_{16}, q_{17}, q_{18}, q_{19}\rangle$ and let $\langle q_{13}, q_{14}\rangle$ receive.

(a) Execute procedure IV:15 on $\langle 1, 1\rangle$ and let $\langle q_{16}, q_{17}\rangle$ receive.

(b) Execute procedure IV:12 on $\langle -2, q_{20}, q_{21}\rangle$ and let $\langle q_{18}, q_{19}\rangle$ receive.

(i) Execute procedure IV:11 on $\langle q_{22}, q_{23}, q_{24}, q_{25}, q_{26}\rangle$ and let $\langle q_{20}, q_{21}\rangle$ receive.

(1) Execute procedure IV:18 on $\langle 1, 1+\epsilon, 1+X\rangle$ and let $\langle q_{22}, q_{23}\rangle$ receive.

(2) Execute procedure IV:10 on $\langle q_{27}, q_{28}, q_{29}, q_{30}\rangle$ and let $\langle q_{24}, q_{25}\rangle$ receive.

(a) Execute procedure IV:15 on $\langle 1, 1\rangle$ and let $\langle q_{27}, q_{28}\rangle$ receive.

(b) Execute procedure IV:16 on $\langle 1, X, 1\rangle$ and let $\langle q_{29}, q_{30}\rangle$ receive.

(3) Let $q_{26}(x, n)$ be the following procedure:

(a) Show that $(1+\epsilon)^2$

(i) $\le (1+\mathrm{re}(x))^2$

(ii) $\le \mathrm{re}(x+1)^2$

(iii) $\le \|x+1\|^2$

(iv) $\le (X+1)^2$.

(3) Let $q_{15}(x, n)$ be the following procedure:

(a) **Hence show that** $\|1+(-2)(x+1)^{-1}\|^2 = \|\frac{x-1}{x+1}\|^2 \le {e_1}^2$ **using procedure** q_9**.**

vi) Execute procedure IV:11 on $\langle q_{31}, q_{32}, q_{33}, q_{34}, q_{35}\rangle$ and let $\langle q_5, q_6\rangle$ receive.

(1) Execute procedure IV:33 on $\langle -f, e_1, \frac{1-e_1}{2}\rangle$ and let $\langle q_{31}, q_{32}\rangle$ receive.

(2) Execute procedure IV:12 on $\langle -1, q_{13}, q_{14}\rangle$ and let $\langle q_{33}, q_{34}\rangle$ receive.

(3) Let $q_{35}(x, n)$ be the following procedure:

(a) **Hence show that** $\|-(1+(-2)(x+1)^{-1})\|^2 = \|\frac{x-1}{x+1}\|^2 \le {e_1}^2$ **using procedure** q_9**.**

Procedure IV:41(thu2208191859)

Objective

Choose a complex number f and two rational numbers X, ϵ such that $0 < \epsilon < 1$ and $X \ge 0$. The objective of the following instructions is to construct rational numbers c, d, a, b, e, a procedure $p(x, n)$ to show that $\|fx_n^{f-1}\|^2 \le c^2$ when a complex number x and a positive integer n such that $\mathrm{re}(x) \ge \epsilon$, $\|x\|^2 \le X^2$, and $n > d$ are chosen, and a procedure $q(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} x_n^f \equiv fx_n^{f-1}$ (err $\frac{a}{n} + b\{\delta\}$) when in addition a complex number δ such that $0 < \|\delta\|^2 \le e^2$ is chosen.

Implementation

1) Execute procedure IV:30 on $\langle X, \epsilon\rangle$ and let $\langle a_1, p_1\rangle$ receive.

2) Execute procedure III:54 on $\langle \{f\}+1, a_1\rangle$ and let $\langle a_2, b_2, p_2\rangle$ receive.

3) Execute procedure III:55 on $\langle \{f\}+1, a_1\rangle$ and let $\langle a_3, p_3\rangle$ receive.

4) Execute procedure III:53 on $\langle b_2, 1\rangle$ and let $\langle a_4, b_4, p_4\rangle$ receive.

5) Execute procedure IV:40 on $\langle f, X, \epsilon\rangle$ and let $\langle p_5, p_6\rangle$ receive.

6) Let t be subprocedure IV:42:0.

7) **Execute procedure IV:14 on** $\langle t, p_5, p_6\rangle$ **and let** $\langle c, d, a, b, e, p, q\rangle$ **receive.**

Subprocedure IV:42:0

Objective Choose a complex number f and two rational numbers X, ϵ such that $0 < \epsilon < 1$ and $X \ge 0$. Let $g(f, x, n)$ be a shorthand for $[2f(1+\frac{x-1}{x+1})_n^f \cdot (1-\frac{x-1}{x+1})_n^{-f-1}(x+1)^{-2}] + [2f(1+\frac{x-1}{x+1})_n^{f-1} \cdot (1-\frac{x-1}{x+1})_n^{-f}(x+1)^{-2}]$. The objective of the following instructions is to construct a rational number h, and a procedure $t(x, n)$ to show that $g(f, x, n) \equiv fx_n^{f-1}$ (err $\frac{h}{n}$) when a complex number x and a positive integer n such that $\mathrm{re}(x) \ge \epsilon$, $\|x\|^2 \le X^2$, and $n > d$ are chosen.

Implementation

1. Let $h = \{f\}a_2a_3a_4((\frac{2}{1+\epsilon})^2 + 1)$.
2. Let $t(x, n)$ be the following procedure:

(a) Show that $\|\frac{1}{(x+1)^2}\|^2$

i. $= \frac{1}{\|1+x\|^4}$

ii. $= \frac{1}{(\mathrm{re}(1+x)^2+\mathrm{im}(x)^2)^2}$

iii. $\leq (\frac{1}{1+\epsilon})^4$.

(b) Using procedures p_1,p_2,p_3,p_4, show that $[2f(1+\frac{x-1}{x+1})_n^f \cdot (1-\frac{x-1}{x+1})_n^{-f-1}(x+1)^{-2}] + [2f(1+\frac{x-1}{x+1})_n^{f-1} \cdot (1-\frac{x-1}{x+1})_n^{-f}(x+1)^{-2}]$

i. $\equiv [2f(1+\frac{x-1}{x+1})_n^{f-1}(1+\frac{x-1}{x+1})_n^1 \cdot (1-\frac{x-1}{x+1})_n^{-f-1}(x+1)^{-2}] + [2f(1+\frac{x-1}{x+1})_n^{f-1} \cdot (1-\frac{x-1}{x+1})_n^{-f}(x+1)^{-2}]$

A. (err $2\{f\}a_2{b_2}^n a_3(\frac{1}{1+\epsilon})^2$)

B. (err $\frac{2\{f\}a_2a_3a_4}{n}(\frac{1}{1+\epsilon})^2$)

ii. $\equiv [2f(1+\frac{x-1}{x+1})_n^{f-1}(1+\frac{x-1}{x+1})_n^1 \cdot (1-\frac{x-1}{x+1})_n^{-f-1}(x+1)^{-2}] + [2f(1+\frac{x-1}{x+1})_n^{f-1} \cdot (1-\frac{x-1}{x+1})_n^{-f-1}(1-\frac{x-1}{x+1})_n^1(x+1)^{-2}]$

A. (err $2\{f\}a_3a_2{b_2}^n(\frac{1}{1+\epsilon})^2$)

B. (err $\frac{2\{f\}a_3a_2a_4}{n}(\frac{1}{1+\epsilon})^2$)

iii. $= 2f(1+\frac{x-1}{x+1})_n^{f-1}(1-\frac{x-1}{x+1})_n^{-f-1}[(1+\frac{x-1}{x+1})^1 \cdot (x+1)^{-2} + (1-\frac{x-1}{x+1})^1(x+1)^{-2}]$

iv. $= 4f(1+\frac{x-1}{x+1})_n^{f-1}(1-\frac{x-1}{x+1})_n^{-f-1}[(x+1)^{-2}]$

v. $= f(1+\frac{x-1}{x+1})_n^{f-1}(1-\frac{x-1}{x+1})_n^{-f-1}(1-\frac{x-1}{x+1})_n^2$

vi. $\equiv f(1+\frac{x-1}{x+1})_n^{f-1}(1-\frac{x-1}{x+1})_n^{-(f-1)}$

A. (err $\{f\}a_3a_2{b_2}^n$)

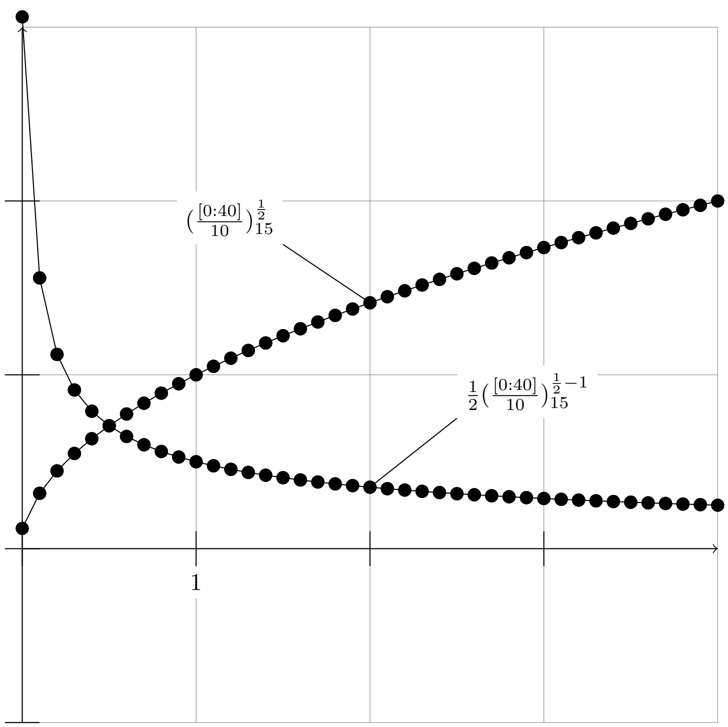
B. (err $\frac{\{f\}a_3a_2a_4}{n}$)

vii. $= fx_n^{f-1}$

(c) **Hence show that** $[2f(1+\frac{x-1}{x+1})_n^f \cdot (1-\frac{x-1}{x+1})_n^{-f-1}(x+1)^{-2}] + [2f(1+\frac{x-1}{x+1})_n^{f-1} \cdot (1-\frac{x-1}{x+1})_n^{-f}(x+1)^{-2}] \equiv fx_n^{f-1}$ (err $\frac{h}{n}$)**.**

3. **Yield the tuple $\langle h, t\rangle$.**

Figure IV:0



A plot of the lists of complex numbers $(\frac{[0:40]}{10})_{15}^{\frac{1}{2}}$ and $\frac{1}{2}(\frac{[0:40]}{10})_{15}^{\frac{1}{2}-1}$. Note that the steepness of $(\frac{[0:40]}{10})_{15}^{\frac{1}{2}}$ is approximately given by the y-coordinates of $\frac{1}{2}(\frac{[0:40]}{10})_{15}^{\frac{1}{2}-1}$. That is, where the graph of $(\frac{[0:40]}{10})_{15}^{\frac{1}{2}}$ is rapidly increasing, the graph of $\frac{1}{2}(\frac{[0:40]}{10})_{15}^{\frac{1}{2}-1}$ has a relatively large positive value, and where the graph of $(\frac{[0:40]}{10})_{15}^{\frac{1}{2}}$ flattens out, the graph of $\frac{1}{2}(\frac{[0:40]}{10})_{15}^{\frac{1}{2}-1}$ has a relatively small positive value.

Chapter 15

Integral Arithmetic

Declaration IV:4(3.30)

The notation $\int_r^R f(r, \delta_r)$, where:

1. $f(r, \delta_r)$ is a procedure to construct a complex number when complex numbers r, δ_r such that $P(r, \delta_r)$ are chosen
2. R is a non-empty list of complex numbers such that $P(R_t, R_{t+1} - R_t)$ for $t \in [0 : |R| - 1]$

will be used as a shorthand for $\sum_t^{[0:|R|-1]} f(R_t, R_{t+1} - R_t)$.

Procedure IV:42(3.86)

Objective

Choose the following:

1. A procedure $f(r, \delta)$ to construct a complex number when complex numbers r, δ_r such that $P(r, \delta_r)$ are chosen.
2. A procedure $g(r, \delta)$ to construct a complex number when complex numbers r, δ_r such that $Q(r, \delta_r)$ are chosen.
3. A non-empty list of complex numbers R such that $P(R_t, R_{t+1} - R_t)$ and $Q(R_t, R_{t+1} - R_t)$ for $t \in [0 : |R| - 1]$.

The objective of the following instructions is to show that $\int_r^R (f(r, \delta_r) + g(r, \delta_r)) = \int_r^R f(r, \delta_r) + \int_r^R g(r, \delta_r)$.

Implementation

1. Show that $\int_r^R (f(r, \delta_r) + g(r, \delta_r))$
   (a) $= \sum_t^{[0:|R|-1]} (f(R_t, R_{t+1} - R_t) + g(R_t, R_{t+1} - R_t))$
   (b) $= \sum_t^{[0:|R|-1]} f(R_t, R_{t+1} - R_t) + \sum_t^{[0:|R|-1]} g(R_t, R_{t+1} - R_t)$
   (c) $= \int_r^R f(r, \delta_r) + \int_r^R g(r, \delta_r)$

Procedure IV:43(3.87)

Objective

Choose the following:

1. A complex number a.
2. A procedure $f(r, \delta)$ to construct a complex number when complex numbers r, δ_r such that $P(r, \delta_r)$ are chosen.
3. A non-empty list of complex numbers R such that $P(R_t, R_{t+1} - R_t)$ for $t \in [0 : |R| - 1]$.

The objective of the following instructions is to show that $\int_r^R af(r, \delta_r) = a \int_r^R f(r, \delta_r)$.

Implementation

1. Show that $\int_r^R af(r, \delta_r)$
   (a) $= \sum_t^{[0:|R|-1]} af(R_t, R_{t+1} - R_t)$
   (b) $= a \sum_t^{[0:|R|-1]} f(R_t, R_{t+1} - R_t)$
   (c) $= a \int_r^R f(r, \delta_r)$

Procedure IV:44(3.88)

Objective

Choose the following:

1. A procedure $f(r)$ to construct a complex number when a complex number r such that $P(r)$ is chosen.
2. A non-empty list of complex numbers R such that $P(R_t)$ for $t \in [0 : |R| - 1]$.
3. A non-empty list of complex numbers S such that $P(S_t)$ for $t \in [0 : |R| - 1]$ and $R_{|R|-1} = S_0$.

The objective of the following instructions is to show that $\int_r^{R \frown S} f(r)\delta_r = \int_r^R f(r)\delta_r + \int_r^S f(r)\delta_r$.

Implementation

1. Let $T = R \frown S$.
2. Show that $\int_r^T f(r)\delta_r$

(a) $= \sum_t^{[0:|T|-1]} f(T_t)(T_{t+1} - T_t)$

(b) $= \sum_t^{[0:|R|-1]} f(T_t)(T_{t+1} - T_t) + \sum_t^{[|R|-1:|R|]} f(T_t)(T_{t+1} - T_t) + \sum_t^{[|R|:|T|-1]} f(T_t)(T_{t+1} - T_t)$

(c) $= \sum_t^{[0:|R|-1]} f(R_t)(R_{t+1} - R_t) + f(T_{|R|-1})(T_{|R|} - T_{|R|-1}) + \sum_t^{[|R|:|T|-1]} f(S_{t-|R|}) \cdot (S_{t+1-|R|} - S_{t-|R|})$

(d) $= \sum_t^{[0:|R|-1]} f(R_t)(R_{t+1} - R_t) + f(T_{|R|-1})(S_0 - R_{|R|-1}) + \sum_t^{[0:|S|-1]} f(S_t)(S_{t+1} - S_t)$

(e) $= \int_r^R f(r)\delta_r + \int_r^S f(r)\delta_r$.

Procedure IV:45(3.34)

Objective

Choose the following:

1. A procedure $f(r)$ to construct a complex number when a complex number r such that $P(r)$ is chosen.
2. A non-empty list of complex numbers R such that $P(R_t)$ for $t \in [0 : |R| - 1]$.

The objective of the following instructions is to show that $\int_r^R \delta_r \, \Delta_{z=r}^{+\delta_r} f(z) = f(R_{|R|-1}) - f(R_0)$.

Implementation

1. Show that $\int_r^R \delta_r \, \Delta_{z=r}^{\delta_r} f(z)$

(a) $= \int_r^R \delta_r (\frac{f(r+\delta_r) - f(r)}{\delta_r})$

(b) $= \int_r^R (f(r + \delta_r) - f(r))$

(c) $= \sum_k^{[0:|R|-1]} (f(R_{k+1}) - f(R_k))$

(d) $= f(R_{|R|-1}) - f(R_0)$.

Declaration IV:5(3.31)

The notation ΔX, where X is a list, will be used as a shorthand for $\langle X_1 - X_0, X_2 - X_1, \cdots, X_{|X|-1} - X_{|X|-2}\rangle$.

Procedure IV:46(fri3008190328)

Objective

Choose the following:

1. A non-negative rational number A.
2. A procedure $q_1(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} f_n(y) \equiv f'_n(x)$ (err $\frac{a_1}{n} + b_1\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > c_1$, and $0 < \|\delta\|^2 < {d_1}^2$ are chosen.

The objective of the following instructions is to construct the following:

1. Non-negative rational numbers a, b, c, d.
2. A procedure $p(R, n)$ to show that $\int_r^R f'_n(r)\delta_r \equiv f_n(R_{|R|-1}) - f_n(R_0)$ (err $\frac{a}{n} + b \max(\{\Delta R\})$) when an integer n and a non-empty list of complex numbers R such that $P(R_t)$ and $0 < \|R_{t+1} - R_t\|^2 < d^2$ for $t \in [0 : |R| - 1]$, $\int_r^R \{\delta_r\} \leq A$, and $n > c$ are chosen.

Implementation

1. Let $a = a_1 A$.
2. Let $b = b_1 A$.
3. Let $c = c_1$.
4. Let $d = d_1$.
5. Let $p(R, n)$ be the following procedure:

(a) Using procedure q_1, show that $\int_r^R f'_n(r)\delta_r$

i. $= \sum_k^{[0:|R|-1]} f'_n(R_k)(R_{k+1} - R_k)$

ii. $\equiv \sum_k^{0:|R|-1} \Delta_{y=R_k}^{R_{k+1}-R_k} f_n(y)(R_{k+1} - R_k)$

A. (err $\sum_k^{0:|R|-1}(\frac{a_1}{n} + b_1\{R_{k+1} - R_k\})\{R_{k+1} - R_k\})$

B. (err $(\frac{a_1}{n}+b_1 \max(\{\Delta R\})) \sum_k^{0:|R|-1}\{R_{k+1}-R_k\})$

C. (err $(\frac{a_1}{n} + b_1 \max(\{\Delta R\})) \int_r^R \{\delta_r\})$

D. (err $(\frac{a_1}{n} + b_1 \max(\{\Delta R\}))A)$

E. (err $\frac{a}{n} + b \max(\{\Delta R\}))$

iii. $= \sum_k^{0:|R|-1} \frac{f_n(R_k+(R_{k+1}-R_k))-f_n(R_k)}{R_{k+1}-R_k} \cdot (R_{k+1} - R_k)$

iv. $= \sum_k^{0:|R|-1}(f_n(R_{k+1}) - f_n(R_k))$

v. $= f_n(R_{|R|-1}) - f_n(R_0)$.

(b) **Therefore show that** $\int_r^R f'_n(r)\delta_r \equiv f_n(R_{|R|-1}) - f_n(R_0)$ (err $\frac{a}{n} + b \max(\{\Delta R\})$)**.**

6. **Yield the tuple** $\langle a, b, c, d, p\rangle$**.**

Procedure IV:47(fri3008190457)

Objective

Choose the following:

1. A non-negative rational number A.
2. A procedure $q_1(x, n, \delta)$ to show that $\Delta_{y=x}^{+\delta} g_n(y) \equiv g'_n(x)$ (err $\frac{a_1}{n} + b_1\{\delta\}$) when two complex numbers x, δ and a positive integer n such that $P(x)$, $n > c_1$, and $0 < \|\delta\|^2 < {d_1}^2$ are chosen.
3. A procedure $q_2(x, n)$ to show that $f_n(x) \equiv 0$ (err a_2) when a complex number x and a positive integer n such that $Q(x)$ and $n > b_2$ are chosen.
4. A procedure $q_3(x, n)$ to show that $Q(g_n(x))$ when a complex number x and a positive integer n such that $P(x)$ and $n > c_1$ are chosen

The objective of the following instructions is to construct the following:

1. Non-negative rational numbers a, b, c, d.
2. A procedure $p(R, n)$ to show that $\int_r^{g(R)} f_n(r)\delta_r \equiv \int_r^R f_n(g_n(r))g'_n(r)\delta_r$ (err $\frac{a}{n} + b \max(\{\Delta R\})$) when an integer n and a non-empty list of complex numbers R such that $P(R_t)$ and $0 < \|R_{t+1} - R_t\|^2 < d^2$ for $t \in [0 : |R| - 1]$, $\int_r^R \{\delta_r\} \le A$, and $n > c$ are chosen.

Implementation

1. Let $a = a_1a_2A$.
2. Let $b = b_1a_2A$.
3. Let $c = \max(c_1, b_2)$.
4. Let $d = d_1$.
5. Let $p(R, n)$ be the following procedure:

(a) Using procedures q_1, q_2, q_3, show that $\int_r^{g_n(R)} f_n(r)\delta_r$

i. $= \sum_k^{[0:|R|-1]} f_n(g_n(R_k))(g_n(R_{k+1}) - g_n(R_k))$

ii. $= \sum_k^{[0:|R|-1]} f_n(g_n(R_k))\Delta_{y=R_k}^{R_{k+1}-R_k} g_n(y)(R_{k+1}-R_k)$

iii. $\equiv \sum_k^{[0:|R|-1]} f_n(g_n(R_k))g'_n(R_k)(R_{k+1} - R_k)$

A. (err $\sum_k^{[0:|R|-1]} a_2(\frac{a_1}{n} + b_1\{R_{k+1} - R_k\})\{R_{k+1} - R_k\})$

B. (err $a_2(\frac{a_1}{n}+b_1 \max(\{\Delta R\})) \sum_k^{[0:|R|-1]}\{R_{k+1}-R_k\})$

C. (err $a_2(\frac{a_1}{n} + b_1 \max(\{\Delta R\})) \int_r^R \{\delta_r\})$

D. (err $a_2(\frac{a_1}{n} + b_1 \max(\{\Delta R\}))A)$

E. (err $\frac{a}{n} + b \max(\{\Delta R\}))$

iv. $= \int_r^R f_n(g_n(r))g'_n(r)\delta_r$.

(b) **Hence show that** $\int_r^{g_n(R)} f_n(r)\delta_r \equiv \int_r^R f_n(g_n(r))g'_n(r)\delta_r$ (err $\frac{a}{n} + b \max(\{\Delta R\})$)**.**

6. **Yield the tuple** $\langle a, b, c, d, p\rangle$**.**

Procedure IV:48(fri3008190709)

Objective

Choose three rational numbers A, X, ϵ such that $0 < \epsilon < 1$ and $X \ge 0$. The objective of the following instructions is to construct the following:

1. Non-negative rational numbers a, b, c, d.

2. A procedure $p(R, n)$ to show that $\int_r^R \frac{\delta_r}{r} \equiv \ln_n(R_{|R|-1})$ (err $\frac{a}{n} + b \max(\{\Delta R\})$) when an integer n and a non-empty list of complex numbers R such that $\mathrm{re}(R_t) \geq \epsilon$, $\|R_t\|^2 \leq X^2$ and $0 < \|R_{t+1} - R_t\|^2 < d^2$ for $t \in [0 : |R|-1]$, $R_0 = 1$, $\int_r^R \{\delta_r\} \leq A$, and $n > c$ are chosen.

Implementation

1. Execute procedure IV:31 on $\langle X, \epsilon \rangle$ and let $\langle \cdots, q \rangle$ receive.
2. Hence execute procedure IV:46 on $\langle A, q \rangle$ and let $\langle a, b, c, d, t \rangle$ receive.
3. Let $p(R, n)$ be the following procedure:
   (a) Using procedure t, show that $\int_r^R \frac{\delta_r}{r}$
      i. $\equiv \ln_n(R_{|R|-1}) - \ln_n(R_0)$ (err $\frac{a}{n} + b \max(\{\Delta R\})$)
      ii. $= \ln_n(R_{|R|-1}) - \ln_n(1)$
      iii. $= \ln_n(R_{|R|-1})$.
   (b) **Hence show that** $\int_r^R \frac{\delta_r}{r} \equiv \ln_n(R_{|R|-1})$ (err $\frac{a}{n} + b \max(\{\Delta R\})$)**.**
4. **Yield the tuple** $\langle a, b, c, d, p \rangle$**.**

Part V

Matrix Arithmetic

Chapter 16

Matrix Arithmetic

Declaration V:0(4.28)

The phrase "matrix" will be used as a shorthand for a list of equally lengthed lists of polynomials. In particular, the phrase "$m \times n$ matrix" will be used as a shorthand for a length-m list of length-n lists of polynomials.

Declaration V:1(4.29)

The notation $A_{I,J}$, where A is a matrix and I, J are lists of indicies, will be used as a shorthand for $\langle (A_j)_J \text{ for } j \in I \rangle$.

Declaration V:2(4.30)

The phrase "$A = B$", where A, B are $m \times n$ matrices, will be used as a shorthand for "$A_{i,j} = B_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$".

Procedure V:0(4.73)

Objective

Choose an $m \times n$ matrix A. The objective of the following instructions is to show that $A = A$.

Implementation

1. Verify that $A_{i,j} = A_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
2. **Hence verify that $A = A$.**

Procedure V:1(4.74)

Objective

Choose two $m \times n$ matrices A, B such that $A = B$. The objective of the following instructions is to show that $B = A$.

Implementation

1. Verify that $A_{i,j} = B_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
2. Hence verify that $B_{i,j} = A_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
3. **Hence verify that $B = A$.**

Procedure V:2(4.75)

Objective

Choose three $m \times n$ matrices A, B, C such that $A = B$ and $B = C$. The objective of the following instructions is to show that $A = C$.

Implementation

1. Verify that $A_{i,j} = B_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
2. Verify that $B_{i,j} = C_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
3. Hence verify that $A_{i,j} = C_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
4. **Hence verify that $A = C$.**

Declaration V:3(4.31)

The notation $A + B$, where A, B are $m \times n$ matrices, will be used as a shorthand for the list $\langle\langle A_{i,j} + B_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$.

Procedure V:3(4.76)

Objective

Choose four $m \times n$ matrices A, B, C, D such that $A = C$ and $B = D$. The objective of the following instructions is to show that $A + B = C + D$.

Implementation

1. Verify that $A_{i,j} = C_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
2. Verify that $B_{i,j} = D_{i,j}$ for $j \in [0 : n]$, for $i \in [0 : m]$.
3. Hence verify that $A + B$

(a) $= \langle\langle A_{i,j} + B_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(b) $= \langle\langle C_{i,j} + D_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(c) $= C + D$.

Procedure V:4(4.77)

Objective

Choose three $m \times n$ matrices A, B, C. The objective of the following instructions is to show that $(A + B) + C = A + (B + C)$.

Implementation

1. Verify that $(A + B) + C$

(a) $= \langle\langle (A + B)_{i,j} + C_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(b) $= \langle\langle (A_{i,j} + B_{i,j}) + C_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(c) $= \langle\langle A_{i,j} + (B_{i,j} + C_{i,j})$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(d) $= \langle\langle A_{i,j} + (B + C)_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(e) $= A + (B + C)$.

Procedure V:5(4.78)

Objective

Choose two $m \times n$ matrices A, B. The objective of the following instructions is to show that $A + B = B + A$.

Implementation

1. $A + B$

(a) $= \langle\langle A_{i,j} + B_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(b) $= \langle\langle B_{i,j} + A_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(c) $= B + A$.

Declaration V:4(4.32)

The notation $0_{m \times n}$ will contextually be used as a shorthand for the list $\langle\langle 0$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$ where the natural numbers m, n are determined by the context.

Procedure V:6(4.79)

Objective

Choose an $m \times n$ matrix A. The objective of the following instructions is to show that $0 + A = A$.

Implementation

1. Verify that $0 + A$

(a) $= 0_{m \times n} + A$

(b) $= \langle\langle 0_{i,j} + A_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(c) $= \langle\langle 0 + A_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(d) $= \langle\langle A_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$

(e) $= A$.

Declaration V:5(4.33)

The notation $-A$, where A is an $m \times n$ matrix, will be used as a shorthand for the list $\langle\langle -A_{i,j}$ for $j \in [0 : n]\rangle$ for $i \in [0 : m]\rangle$.

Procedure V:7(4.80)

Objective

Choose two $m \times n$ matrices A, B such that $A = B$. The objective of the following instructions is to show that $-A = -B$.

Implementation

1. Verify that $A_{i,j} = B_{i,j}$ for $j \in [0:n]$, for $i \in [0:m]$.
2. Hence verify that $-A$

   (a) $= \langle\langle -A_{i,j}$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$

   (b) $= \langle\langle -B_{i,j}$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$

   (c) $= -B$.

Procedure V:8(4.81)

Objective

Choose a $m \times n$ matrix A. The objective of the following instructions is to show that $-A + A = 0$.

Implementation

1. Verify that $-A + A$

   (a) $\langle\langle(-A)_{i,j} + A_{i,j}$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$

   (b) $\langle\langle -(A_{i,j}) + A_{i,j}$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$

   (c) $\langle\langle 0$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$

   (d) $= 0$.

Declaration V:6(4.34)

The notation AB, where A is an $m \times n$ matrix and B is an $n \times k$ matrix, will be used as a shorthand for the list $\langle\langle \sum_r^{[0:n]} A_{i,r}B_{r,j}$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$.

Procedure V:9(4.82)

Objective

Choose two $m \times n$ matrices A, C and two $n \times k$ matrices B, D such that $A = C$ and $B = D$. The objective of the following instructions is to show that $AB = CD$.

Implementation

1. Verify that $A_{i,j} = C_{i,j}$ for $j \in [0:n]$, for $i \in [0:m]$.
2. Verify that $B_{i,j} = D_{i,j}$ for $j \in [0:k]$, for $i \in [0:n]$.
3. Hence verify that AB

   (a) $= \langle\langle \sum_r^{[0:n]} A_{i,r}B_{r,j}$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$

   (b) $= \langle\langle \sum_r^{[0:n]} C_{i,r}D_{r,j}$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$

   (c) $= CD$.

Procedure V:10(4.02)

Objective

Choose an $m \times n$ matrix, A, an $n \times p$ matrix, B, and a $p \times q$ matrix, C. The objective of the following instructions is to show that $(AB)C = A(BC)$.

Implementation

1. Verify that $(AB)C$

   (a) $= \langle\langle \sum_r^{[0:p]} (AB)_{i,r}C_{r,j}$ for $j \in [0:q]\rangle$ for $i \in [0:m]\rangle$

   (b) $= \langle\langle \sum_r^{[0:p]} (\sum_l^{[0:n]} A_{i,l}B_{l,r})C_{r,j}$ for $j \in [0:q]\rangle$ for $i \in [0:m]\rangle$

   (c) $= \langle\langle \sum_r^{[0:p]} \sum_l^{[0:n]} A_{i,l}B_{l,r}C_{r,j}$ for $j \in [0:q]\rangle$ for $i \in [0:m]\rangle$

   (d) $= \langle\langle \sum_l^{[0:n]} \sum_r^{[0:p]} A_{i,l}B_{l,r}C_{r,j}$ for $j \in [0:q]\rangle$ for $i \in [0:m]\rangle$

   (e) $= \langle\langle \sum_l^{[0:n]} A_{i,l} \sum_r^{[0:p]} B_{l,r}C_{r,j}$ for $j \in [0:q]\rangle$ for $i \in [0:m]\rangle$

   (f) $= \langle\langle \sum_l^{[0:n]} A_{i,l}(BC)_{l,j}$ for $j \in [0:q]\rangle$ for $i \in [0:m]\rangle$

   (g) $= A(BC)$.

Declaration V:7(4.35)

The notation $a_{m\times m}$, where $a \neq 0$ is a polynomial, will contextually be used as a shorthand for the list $\langle\langle a[i=j]$ for $j \in [0:m]\rangle$ for $i \in [0:m]\rangle$.

Procedure V:11(4.84)

Objective

Choose an $m \times n$ matrix, A. The objective of the following instructions is to show that $1A = A$.

Implementation

1. Verify that $1A$
   (a) $= 1_m A$
   (b) $= \langle\langle \sum_r^{[0:m]} 1_{i,r} A_{r,j}$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$
   (c) $= \langle\langle \sum_r^{[0:m]} [i=r] A_{r,j}$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$
   (d) $= \langle\langle A_{i,j}$ for $j \in [0:n]\rangle$ for $i \in [0:m]\rangle$
   (e) $= A$.

Procedure V:12(4.85)

Objective

Choose an $m \times n$ matrix A, and two $n \times k$ matrices B, C. The objective of the following instructions is to show that $A(B+C) = AB + AC$.

Implementation

1. $A(B+C)$
   (a) $= \langle\langle \sum_r^{[0:n]} A_{i,r}(B+C)_{r,j}$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$
   (b) $= \langle\langle \sum_r^{[0:n]} A_{i,r}(B_{r,j} + C_{r,j})$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$
   (c) $= \langle\langle \sum_r^{[0:n]} (A_{i,r}B_{r,j} + A_{i,r}C_{r,j})$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$
   (d) $= \langle\langle \sum_r^{[0:n]} A_{i,r}B_{r,j} + \sum_r^{[0:n]} A_{i,r}C_{r,j}$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$
   (e) $= \langle\langle \sum_r^{[0:n]} A_{i,r}B_{r,j}$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle + \langle\langle \sum_r^{[0:n]} \sum_r^{[0:n]} A_{i,r}C_{r,j}$ for $j \in [0:k]\rangle$ for $i \in [0:m]\rangle$
   (f) $= AB + AC$.

Declaration V:8(4.36)

The phrase "row i of A" and the notation $A_{i,*}$, where A is an $m \times n$ matrix and $0 \le i < m$, will be used as a shorthand for $A_{i,[0:n]}$.

Declaration V:9(4.37)

The phrase "column i of A" and the notation $A_{*,i}$, where A is an $m \times n$ matrix and $0 \le i < n$, will be used as a shorthand for $A_{[0:m],i}$.

Procedure V:13(4.00)

Objective

Choose an $m \times 2$ matrix, A. Let $\deg(0) = \infty$. Let $k = \min(\deg(A_{0,0}), \deg(A_{0,1}))$ and $q = \deg(A_{0,0})$. The objective of the following instructions is to make $A_{0,1} = 0$, $\deg(A_{0,0}) \le k$, and either leave $A_{*,0}$ unchanged or make $\deg(A_{0,0}) < q$ by a sequence of operations whereby, in each step a polynomial times either of the columns is added to the other.

Implementation

1. Let A be our working matrix.
2. While $A_{0,1} \ne 0$, do the following:
   (a) If $\deg(A_{0,0}) \le \deg(A_{0,1})$, then:
      i. Subtract $\frac{(A_{0,1})_{\deg(A_{0,1})}}{(A_{0,0})_{\deg(A_{0,0})}} \lambda^{\deg(A_{0,1}) - \deg(A_{0,0})}$ times $A_{0,0}$ from $A_{0,1}$.
      ii. Now verify that either $A_{0,1}$'s degree has decreased or $A_{0,1} = 0$.
   (b) Otherwise, do the following:
      i. Let $p = \frac{(A_{0,0})_{\deg(A_{0,0})}}{(A_{0,1})_{\deg(A_{0,1})}} \lambda^{\deg(A_{0,0}) - \deg(A_{0,1})}$.
      ii. If $A_{0,0} = pA_{0,1}$, then do the following:
         A. Add $1 - p$ times $A_{0,1}$ to $A_{0,0}$.
         B. Verify that now $A_{0,0} = A_{0,1}$.
      iii. Otherwise, do the following:
         A. Verify that $A_{0,0} \ne pA_{0,1}$.
         B. Add $-p$ times $A_{0,1}$ to $A_{0,0}$.
      iv. Therefore verify that $A_{0,0} \ne 0$.
      v. Also verify that $A_{0,0}$'s degree has decreased.
3. **Verify that $A_{0,1} = 0$.**
4. Verify that the changes to $A_{0,0}$, if any, have decreased its degree.
5. If both operations are well-defined, then do the following:
   (a) Verify that all changes to $A_{0,1}$ but the last have decreased its degree.
   (b) Verify that $\deg(A_{0,0}) \le$ the degree of the penultimate value of $A_{0,1}$.

6. **Therefore verify that** $\deg(A_{0,0}) \leq k$**.**
7. If $A_{*,0}$ was changed, then do the following:
   (a) Verify that $A_{0,0}$ was also changed.
   (b) **Therefore verify that** $\deg(A_{0,0}) < q$**.**
8. **Yield the tuple** $\langle A \rangle$**.**

Declaration V:10(4.01)

The phrase "matrix diagonal" will be used as a shorthand for matrix positions such that the row index equals the column index.

Declaration V:11(4.02)

The phrase "diagonal matrix" will be used to refer to matrices with 0s in all off-diagonal positions.

Procedure V:14(4.01)

Objective

Choose a $m \times n$ matrix, A. The objective of the following instructions is to transform A into an $m \times n$ diagonal matrix by a sequence of operations whereby either a polynomial times any of the columns is added to a different column, or a polynomial times any of the rows is added to a different row.

Implementation

1. If $m = 0$ or $n = 0$, then do the following:
   (a) **Verify that** A **is an** $m \times n$ **diagonal matrix.**
   (b) **Yield the tuple** $\langle A \rangle$**.**
2. Otherwise do the following:
3. Verify that $m > 0$ and $n > 0$.
4. Let A be our working matrix.
5. Now do the following:
   (a) While $A_{0,[1:n]} \neq 0$, do the following:
      i. Select the $m \times 2$ matrix whose top-right entry coincides with the last non-zero entry of the first row
      ii. Apply procedure V:13 on this submatrix.
      iii. Verify that the top-left and top-right entries of the submatrix are now non-zero and zero respectively.
      iv. If $A_{*,0}$ was modified by (5aii), then do the following:
         A. Verify that $\deg(A_{0,0})$ decreased.
         B. Go back to (5).
   (b) Now do the same operations as in (a), but this time with the operations themselves reflected across the matrix's diagonal.
6. Verify that $A_{0,[1:n]} = 0$.
7. Also verify that $A_{[1:m],0} = 0$.
8. Apply procedure V:14 on the submatrix $A_{[1:m],[1:n]}$.
9. Verify that (8)'s execution leaves the first row and column unchanged.
10. Also verify that $A_{[1:m],[1:n]}$ is now a $(m-1) \times (n-1)$ diagonal matrix.
11. **Therefore verify that** A **is now an** $m \times n$ **diagonal matrix.**
12. **Yield the tuple** $\langle A \rangle$**.**

Declaration V:12(4.04)

The phrase "tilt matrix" will be used to refer to square matrices with only 1s on the diagonal, a single polynomial off the diagonal, and 0s everywhere else.

Procedure V:15(4.03)

Objective

Choose a procedure, A, and two non-negative integers m, n. The objective of the following instructions is, once A has been executed, to construct a list of $m \times m$ tilts, M, and a list of $n \times n$ tilts, N such that $M_{|M|-1-i}$ equals 1_m after applying the i^{th} row operation carried out by A also on it, and N_i equals 1_n after applying the i^{th} row operation carried out by A also on it.

Implementation

1. Make an empty list, N.
2. Augment procedure A so that each time a polynomial x times a column i is added onto column j, an $n \times n$ matrix that only has 1s on its diagonal, and such that the only non-zero

entry off its diagonal is x at position (i, j), is appended onto N.

3. Make an empty list, M.
4. Also augment procedure A so that each time a polynomial x times a row i is added onto row j, an $n \times n$ matrix that only has 1s on its diagonal, and such that the only non-zero entry off its diagonal is x at position (j, i), is prepended onto M.
5. Now run procedure A.
6. **Yield the tuple** $\langle M, N \rangle$**.**

Procedure V:16(4.04)

Objective

Choose a $m \times n$ matrix, A. The objective of the following instructions is to show that $1_m A = A = A 1_n$.

Implementation

1. For $0 \leq r < m$, do the following:
   (a) For $0 \leq t < n$, do the following:
      i. Verify that $(1_m A)_{r,t} = \sum_u^{[0:m]} (1_m)_{r,u} A_{u,t} = (1_m)_{r,r} A_{r,t} = 1 * A_{r,t} = A_{r,t}$.
2. **Therefore verify that** $1_m A = A$**.**
3. For $0 \leq r < m$, do the following:
   (a) For $0 \leq t < n$, do the following:
      i. Verify that $(A 1_n)_{r,t} = \sum_u^{[0:m]} A_{r,u} (1_n)_{u,t} = A_{r,t} (1_n)_{t,t} = A_{r,t} * 1 = A_{r,t}$.
4. **Therefore verify that** $A 1_n = A$**.**

Declaration V:13(4.05)

The notation A^{-1}, where A is a list of $m \times m$ tilts, will be used to refer to the result yielded by executing the following instructions:

1. Let A^{-1} be $\langle \rangle$.
2. For i in $[0 : |A|]$, do the following:
   (a) Let (j, k) be the position of the off diagonal entry of A_i.
   (b) Let B equal A_i but with entry (j, k) negated.
   (c) Now prepend B onto A^{-1}.
3. **Yield** $\langle A^{-1} \rangle$**.**

Procedure V:17(4.05)

Objective

Choose a list of $m \times m$ tilts, A. The objective of the following instructions is to show that $A_* {A^{-1}}_* = 1_m$.

Implementation

1. Verify that $|A| = |A^{-1}|$.
2. For i in $[0 : |A|]$, do the following:
   (a) Let (j, k) be the position of the off diagonal entry of A_i.
   (b) Let $B = {A^{-1}}_{|A|-1-i}$.
   (c) For r in $[0 : m]$ and $r \neq j$, do the following:
      i. For t in $[0 : m]$, do the following:
         A. Verify that $(A_i B)_{r,t} = \sum_u^{[0:m]} (A_i)_{r,u} B_{u,t} = (A_i)_{r,r} B_{r,t} = 1 * B_{r,t} = [r = t]$.
   (d) For t in $[0 : m]$ and $t \neq k$, do the following:
      i. Verify that $(A_i B)_{j,t} = \sum_u^{[0:m]} (A_i)_{j,u} B_{u,t} = (A_i)_{j,t} B_{t,t} = (A_i)_{j,t} * 1 = [j = t]$.
   (e) Verify that $(A_i B)_{j,k} = \sum_u^{[0:m]} (A_i)_{j,u} B_{u,k} = (A_i)_{j,j} B_{j,k} + (A_i)_{j,k} B_{k,k} = 1 * B_{j,k} + (A_i)_{j,k} * 1 = B_{j,k} + (A_i)_{j,k} = 0$.
   (f) Therefore verify that $A_i B = 1_m$.
3. Therefore using procedure V:10 and procedure V:16, verify that $A_* {A^{-1}}_*$
   (a) $= A_0 \cdots A_{|A|-2} A_{|A|-1} {A^{-1}}_0 {A^{-1}}_1 \cdots {A^{-1}}_{|A|-1}$
   (b) $= A_0 \cdots A_{|A|-3} A_{|A|-2} 1_m {A^{-1}}_1 {A^{-1}}_2 \cdots {A^{-1}}_{|A|-1}$
   (c) $= A_0 \cdots A_{|A|-3} A_{|A|-2} {A^{-1}}_1 {A^{-1}}_2 \cdots {A^{-1}}_{|A|-1}$
   (d) $\vdots$
   (e) $= A_0 1_m {A^{-1}}_{|A|-1}$
   (f) $= A_0 {A^{-1}}_{|A|-1}$
   (g) $= 1_m$.

Procedure V:18(4.06)

Objective

Choose a list of $m \times m$ tilts, A. The objective of the following instructions is to show that $(A^{-1})^{-1} = A$ and ${A^{-1}}_* A_* = 1_m$.

Implementation

1. **Verify that $(A^{-1})^{-1} = A$.**
2. **Therefore using procedure V:17, verify that $A^{-1}{}_*A_* = A^{-1}{}_*(A^{-1})^{-1}{}_* = 1_m$.**

Procedure V:19(4.07)

Objective

Choose a 2×2 diagonal matrix, A. The objective of the following instructions is to construct polynomials u, v and transform A into a 2×2 diagonal matrix, A', such that $A'_{1,1} = uA'_{0,0}$ and $A_{0,0} = vA'_{0,0}$ by a sequence of operations whereby either a polynomial times any of the columns is added to a different column, or a polynomial times any of the rows is added to a different row.

Implementation

1. Add row 1 to row 0.
2. Now verify that $A_{0,1} = A_{1,1}$.
3. Set $A' = A$ and let A' be our working matrix.
4. Let $\langle M, N\rangle$ receive the results of executing procedure V:15 on the pair $\langle 2, 2\rangle$ and the following procedure:
   (a) Execute procedure V:13 on A'.
5. Using (4), verify that M is empty.
6. Using (4) and (5), verify that $AN_* = M_*AN_* = A'$.
7. Using (6), verify that $A = A1_n = AN_*N^{-1}{}_* = A'N^{-1}{}_*$.
8. Using (4), verify that $A'_{0,1} = 0$.
9. **Using (4) and (7), verify that $A_{0,0} = A'_{0,0}N^{-1}{}_{*0,0} + A'_{0,1}N^{-1}{}_{*1,0} = A'_{0,0}N^{-1}{}_{*0,0}$.**
10. Using (4) and (7), verify that $A_{1,1} = A_{0,1} = A'_{0,0}N^{-1}{}_{*0,1} + A'_{0,1}N^{-1}{}_{*1,1} = A'_{0,0}N^{-1}{}_{*0,1}$.
11. Using (2), verify that $A_{1,0} = 0$.
12. Using (6) and (11), verify that $A'_{1,0} = A_{1,0}N_{*0,0} + A_{1,1}N_{*1,0} = A_{1,1}N_{*1,0} = A'_{0,0}N^{-1}{}_{*0,1}N_{*1,0}$.
13. **Using (6) and (11), verify that $A'_{1,1} = A_{1,0}N_{*0,1} + A_{1,1}N_{*1,1} = A_{1,1}N_{*1,1} = A'_{0,0}N^{-1}{}_{*0,1}N_{*1,1}$.**
14. Subtract $N^{-1}{}_{*0,1}N_{*1,0}$ times row 0 from row 1.
15. Now using (14) and (12), verify that $A'_{1,0} = 0$.
16. **Therefore verify that A' is a 2×2 diagonal matrix.**
17. **Let $A = A'$.**
18. **Yield $\langle N^{-1}{}_{*0,1}N_{*1,1}, N^{-1}{}_{*0,0}\rangle$.**

Procedure V:20(4.08)

Objective

Choose a $m\times n$ matrix, A such that $\min(m, n) > 0$. The objective of the following instructions is to define a list of polynomials u and transform A into an $m\times n$ diagonal matrix such that $A_{k,k} = u_kA_{0,0}$ for k in $[0 : \min(m, n)]$ by a sequence of operations whereby either a polynomial times any of the columns is added to a different column, or a polynomial times any of the rows is added to a different row.

Implementation

1. Let $u = \langle 1\rangle$.
2. Execute procedure V:14 on A.
3. Verify that A is an $m\times n$ diagonal matrix.
4. For j in $[1 : \min(m, n)]$, do the following:
   (a) Using (h), verify that $A_{k,k} = u_kA_{0,0}$ for k in $[0 : j]$.
   (b) Set $A' = A$.
   (c) Execute procedure V:19 on $A'_{\langle 0,j\rangle,\langle 0,j\rangle}$ and let $\langle u_j, v\rangle$ receive.
   (d) Using (c), verify that A and A' are the same modulo positions $\langle 0, 0\rangle$ and $\langle j, j\rangle$.
   (e) Therefore verify that A' is an $m\times n$ diagonal matrix.
   (f) Also, using (c), verify that $A'_{j,j} = u_jA'_{0,0}$.
   (g) Also, for k in $[1 : j]$, do the following:
      i. Using (a), (c), and (d), verify that $A'_{k,k} = A_{k,k} = u_kA_{0,0} = u_kA'_{0,0}v$.
      ii. Set $u_k = u_kv$.
      iii. Hence verify that $A'_{k,k} = u_kA'_{0,0}$.

(h) Therefore verify that $A_{k,k} = u_k A_{0,0}$ for k in $[0 : j + 1]$.

(i) Now let $A = A'$.

5. **Hence using (4h), verify that** $A_{k,k} = u_k A_{0,0}$ **for** k **in** $[0 : \min(m, n)]$**.**
6. **Also, using (4e), verify that** A **is an** $m \times n$ **diagonal matrix.**
7. **Yield** $\langle u \rangle$**.**

Procedure V:21(4.09)

Objective

Choose a $m \times n$ matrix, A, and a $n \times k$ matrix, B. Choose integers $0 \le a < m$, $0 \le b < n$, and $0 \le c < k$. The objective of the following instructions is to show that

1. $(AB)_{[0:a],[0:c]} = A_{[0:a],[0:b]} B_{[0:b],[0:c]} + A_{[0:a],[b:n]} B_{[b:n],[0:c]}$
2. $(AB)_{[0:a],[c:k]} = A_{[0:a],[0:b]} B_{[0:b],[c:k]} + A_{[0:a],[b:n]} B_{[b:n],[c:k]}$
3. $(AB)_{[a:m],[0:c]} = A_{[a:m],[0:b]} B_{[0:b],[0:c]} + A_{[a:m],[b:n]} B_{[b:n],[0:c]}$
4. $(AB)_{[a:m],[c:k]} = A_{[a:m],[0:b]} B_{[0:b],[c:k]} + A_{[a:m],[b:n]} B_{[b:n],[c:k]}$.

Implementation

1. For each $0 \le i < a$, do the following:

(a) For each $0 \le j < c$, do the following:

i. Verify that $(AB)_{i,j} = \sum_p^{[0:n]} A_{i,p} B_{p,j} = \sum_p^{[0:b]} A_{i,p} B_{p,j} + \sum_p^{[b:n]} A_{i,p} B_{p,j} = \sum_p^{[0:b]} (A_{[0:a],[0:b]})_{i,p} (B_{[0:b],[0:c]})_{p,j} + \sum_p^{[0:n-b]} (A_{[0:a],[b:n]})_{i,p} (B_{[b:n],[0:c]})_{p,j} = (A_{[0:a],[0:b]} B_{[0:b],[0:c]})_{i,j} + (A_{[0:a],[b:n]} B_{[b:n],[0:c]})_{i,j}$.

2. **Therefore verify that** $(AB)_{[0:a],[0:c]} = A_{[0:a],[0:b]} B_{[0:b],[0:c]} + A_{[0:a],[b:n]} B_{[b:n],[0:c]}$**.**
3. **Using computations analogous to (1) and (2), show items (2), (3), and (4) of the objective.**

Declaration V:14(4.06)

The phrase "number of rows of A" and the notation rows(A), where A is an $m \times n$ matrix, will be used as a shorthand for m.

Declaration V:15(4.07)

The phrase "number of columns of A" and the notation cols(A), where A is an $m \times n$ matrix, will be used as a shorthand for n.

Declaration V:16(4.08)

The notation diag(C), where C is a list of rational square matrices, will be used to refer to the result yielded by executing the following instructions:

1. Let E be a 0×0 matrices.
2. Now for i in $[0 : |C|]$:

(a) Add cols(C_i) columns filled with zeros to the right end of E.

(b) Add rows(C_i) rows filled with zeros to the bottom end of E.

(c) Set the bottom-right corner of E equal to C_i.

3. **Yield the tuple** $\langle E \rangle$**.**

Procedure V:22(4.10)

Objective

Choose a $m \times n$ matrix, A. Let $A_{-1,-1} = 1$. The objective of the following instructions is to construct the list of polynomials v and transform A into an $m \times n$ diagonal matrix such that $A_{k,k} = v_k A_{k-1,k-1}$ for k in $[0 : \min(m, n)]$ by a sequence of operations whereby either a polynomial times any of the columns is added to a different column, or a polynomial times any of the rows is added to a different row.

Implementation

1. If $\min(m, n) = 0$, then do the following:

(a) **Verify that** A **is an** $m \times n$ **diagonal matrix.**

(b) **Yield** $\langle\rangle$**.**

2. Otherwise do the following:

(a) Apply procedure V:20 on A, and let $\langle u \rangle$ receive.

(b) Verify that A is an $m \times n$ diagonal matrix.

(c) Verify that $A_{k,k} = u_k A_{0,0}$ for k in $[0 : \min(m, n)]$.

(d) Let B, C be an $(m-1) \times (n-1)$ diagonal matrix with $u_{1:|u|}$ on the diagonal.

(e) Let $\langle M, N \rangle$ receive the results of executing procedure V:15 on the pair $\langle m-1, n-1 \rangle$ and the following procedure:

  i. Execute procedure V:22 on C and let $\langle w \rangle$ receive.

(f) Therefore verify that C is an $(m-1) \times (n-1)$ diagonal matrix.

(g) Also verify that $C = M_* B N_*$.

(h) Let $C_{-1,-1} = 1$.

(i) Now using (ei), verify that $C_{k,k} = w_k C_{k-1,k-1}$ for k in $[0 : \min(m, n) - 1]$.

(j) Therefore using (c), verify that $A_{0,0}C = M_*(A_{0,0}B)N_* = M_* A_{[1:m],[1:n]} N_*$.

(k) Premultiply A by $\operatorname{diag}(1, M_k)$ for k in $[|M| : 0]$.

(l) Postmultiply A by $\operatorname{diag}(1, N_k)$ for k in $[0 : |N|]$.

(m) Now verify that $A_{[1:m],[1:n]} = A_{0,0}C$.

(n) Now let $u = \langle A_{0,0} \rangle ^\frown w$.

(o) **Therefore verify that** $A_{k,k} = u_k A_{k-1,k-1}$ **for** k **in** $[0 : \min(m, n)]$**.**

(p) **Yield the tuple** $\langle u \rangle$**.**

Chapter 17

Compound Matrices

Declaration V:17(4.09)

The notation $\det(A)$, where A is a $m \times m$ matrix, will be used to refer to the result yielded by executing the following instructions:

1. If $m = 0$, then do the following:
   (a) **Yield the tuple $\langle 1 \rangle$.**
2. Otherwise, do the following:
   (a) Let $h_r = A_{[0:r]\frown[r+1,m],[1:m]}$ for r in $[0 : m]$.
   (b) **Yield the tuple $\langle \sum_r^{[0:m]} (-1)^r A_{r,0} \det(h_r) \rangle$.**

Procedure V:23(4.11)

Objective

Choose a polynomial p. Choose two $1 \times m$ matrices, B and C. Choose an integer $0 \leq i < m$. Choose a $m \times m$ matrix, A, such that its i^{th} row is $B + pC$. Let A' be A but with the i^{th} row replaced by B and let A'' be A but with the i^{th} row replaced by C. The objective of the following instructions is to show that $\det(A) = \det(A') + p \det(A'')$.

Implementation

1. If $m = 1$, then do the following:
   (a) Verify that $i = 0$.
   (b) **Therefore verify that** $\det(A) = A_{0,0} = B_{0,0} + pC_{0,0} = \det(A') + p \det(A'')$**.**
2. Otherwise, do the following:
   (a) For r in $[0 : i]$, do the following:
      i. Verify that $(A_{[0:r]\frown[r+1:m],[1:m]})_{i-1,*} = B + pC$.
      ii. Verify that $A'_{[0:r]\frown[r+1:m],[1:m]}$ is $A_{[0:r]\frown[r+1:m],[1:m]}$ with row $i - 1$ replaced by B.
      iii. Verify that $A''_{[0:r]\frown[r+1:m],[1:m]}$ is $A_{[0:r]\frown[r+1:m],[1:m]}$ with row $i - 1$ replaced by C.
      iv. Execute procedure V:23 on $\langle p, B, C, i - 1, A_{[0:r]\frown[r+1:m],[1:m]} \rangle$.
      v. Therefore verify that $\det(A_{[0:r]\frown[r+1:m],[1:m]}) = \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \det(A''_{[0:r]\frown[r+1:m],[1:m]})$.
   (b) For r in $[i + 1 : m]$, do the following:
      i. Verify that $(A_{[0:r]\frown[r+1:m],[1:m]})_{i,*} = B + pC$.
      ii. Verify that $A'_{[0:r]\frown[r+1:m],[1:m]}$ is $A_{[0:r]\frown[r+1:m],[1:m]}$ with row i replaced by B.
      iii. Verify that $A''_{[0:r]\frown[r+1:m],[1:m]}$ is $A_{[0:r]\frown[r+1:m],[1:m]}$ with row i replaced by C.
      iv. Execute procedure V:23 on $\langle p, B, C, i, A_{[0:r]\frown[r+1:m],[1:m]} \rangle$.
      v. Therefore verify that $\det(A_{[0:r]\frown[r+1:m],[1:m]}) = \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \det(A''_{[0:r]\frown[r+1:m],[1:m]})$.
   (c) Therefore using (av) and (bv), verify that $\det(A)$
      i. $= \sum_r^{[0:m]} (-1)^r A_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]})$

ii. $= \sum_r^{[0:i]} (-1)^r A_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]}) + (-1)^i A_{i,0} \det(A_{[0:i]\frown[i+1:m],[1:m]}) + \sum_r^{[i+1:m]} (-1)^r A_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]})$

iii. $= \sum_r^{[0:i]} (-1)^r A_{r,0} (\det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \det(A''_{[0:r]\frown[r+1:m],[1:m]})) + (-1)^i (A'_{i,0} + pA''_{i,0}) \det(A_{[0:i]\frown[i+1:m],[1:m]}) + \sum_r^{[i+1:m]} (-1)^r A_{r,0} (\det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \det(A''_{[0:r]\frown[r+1:m],[1:m]}))$

iv. $= \sum_r^{[0:i]} (-1)^r A_{r,0} \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + (-1)^i A'_{i,0} \det(A_{[0:i]\frown[i+1:m],[1:m]}) + \sum_r^{[i+1:m]} (-1)^r A_{r,0} \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + \sum_r^{[0:i]} (-1)^r A_{r,0} p \det(A''_{[0:r]\frown[r+1:m],[1:m]}) + (-1)^i p A''_{i,0} \det(A_{[0:i]\frown[i+1:m],[1:m]}) + \sum_r^{[i+1:m]} (-1)^r A_{r,0} p \det(A''_{[0:r]\frown[r+1:m],[1:m]})$

v. $= \sum_r^{[0:m]} (-1)^r A'_{r,0} \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \sum_r^{[0:m]} (-1)^r A''_{r,0} \det(A''_{[0:r]\frown[r+1:m],[1:m]})$

vi. $= \det(A') + p \det(A'')$.

Procedure V:24(4.12)

Objective

Choose a polynomial p. Choose two $m \times 1$ matrices, B and C. Choose an integer $0 \le i < m$. Choose a $m \times m$ matrix, A, such that its i^{th} column is $B + pC$. Let A' be A but with the i^{th} column replaced by B and let A'' be A but with the i^{th} column replaced by C. The objective of the following instructions is to show that $\det(A) = \det(A') + p \det(A'')$.

Implementation

1. If $i = 0$, then verify that $\det(A)$

(a) $= \sum_r^{[0:m]} (-1)^r A_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]})$

(b) $= \sum_r^{[0:m]} (-1)^r (B+pC)_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]})$

(c) $= \sum_r^{[0:m]} (-1)^r (B)_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]}) + \sum_r^{[0:m]} (-1)^r (pC)_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]})$

(d) $= \sum_r^{[0:m]} (-1)^r (B)_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]}) + p \sum_r^{[0:m]} (-1)^r (C)_{r,0} \det(A_{[0:r]\frown[r+1:m],[1:m]})$

(e) $= \sum_r^{[0:m]} (-1)^r (A')_{r,0} \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \sum_r^{[0:m]} (-1)^r (A'')_{r,0} \det(A''_{[0:r]\frown[r+1:m],[1:m]})$

(f) $= \det(A') + p \det(A'')$

2. Otherwise, do the following:

(a) For r in $[0 : m]$, do the following:

i. Execute procedure V:24 on $\langle p, B_{[0:r]\frown[r+1:m],0}, C_{[0:r]\frown[r+1:m],0}, i - 1, A_{[0:r]\frown[r+1:m],[1:m]} \rangle$.

ii. Therefore verify that $\det(A_{[0:r]\frown[r+1:m],[1:m]}) = \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \det(A''_{[0:r]\frown[r+1:m],[1:m]})$.

(b) Therefore using (a), verify that $\det(A)$

i. $= \sum_r^{[0:m]} (-1)^r A_{r,0} \cdot \det(A_{[0:r]\frown[r+1:m],[1:m]})$

ii. $= \sum_r^{[0:m]} (-1)^r A_{r,0} (\det(A'_{[0:r]\frown[r+1:m],[1:m]}) + p \det(A''_{[0:r]\frown[r+1:m],[1:m]}))$

iii. $= \sum_r^{[0:m]} (-1)^r A'_{r,0} \det(A'_{[0:r]\frown[r+1:m],[1:m]}) + \sum_r^{[0:m]} (-1)^r A''_{r,0} p \det(A''_{[0:r]\frown[r+1:m],[1:m]})$

iv. $= \det(A') + p \det(A'')$.

Procedure V:25(4.13)

Objective

Choose a $m \times m$ matrix, A. Choose an integer $0 < i < m$. Let A' be A with rows $i - 1$ and i swapped. The objective of the following instructions is to show that $\det(A') = -\det(A)$.

Implementation

1. If $m = 2$, then do the following:

(a) Verify that $i = 1$.

(b) Therefore verify that $\det(A') = A'_{0,0} A'_{1,1} - A'_{1,0} A'_{0,1} = A_{1,0} A_{0,1} - A_{0,0} A_{1,1} = -\det(A)$.

2. Otherwise do the following:

(a) For r in $[0 : i - 1]$, do the following:

i. Verify that $A_{[0:r]\frown[r+1:m],[1:m]}$ is the same as $A'_{[0:r]\frown[r+1:m],[1:m]}$ but with rows $i - 2$ and $i - 1$ swapped.

ii. Execute procedure V:25 on $\langle A_{[0:r]\frown[r+1:m],[1:m]}, i - 1 \rangle$.

iii. Hence verify that $\det(A'_{[0:r]\frown[r+1:m],[1:m]}) = -\det(A_{[0:r]\frown[r+1:m],[1:m]})$.

(b) For r in $[i + 1 : m]$, do the following:

i. Verify that $A_{[0:r]\frown[r+1:m],[1:m]}$ is the same as $A'_{[0:r]\frown[r+1:m],[1:m]}$ but with rows $i-1$ and i swapped.

ii. Execute procedure V:25 on $\langle A_{[0:r]\frown[r+1:m],[1:m]}, i\rangle$.

iii. Hence verify that $\det(A'_{[0:r]\frown[r+1:m],[1:m]}) = -\det(A_{[0:r]\frown[r+1:m],[1:m]})$.

(c) Verify that $\det(A)$

i. $= \sum_r^{[0:m]}(-1)^r A_{r,0}\det(A_{[0:r]\frown[r+1:m],[1:m]})$

ii. $= \sum_r^{[0:i-1]}(-1)^r A_{r,0}\det(A_{[0:r]\frown[r+1:m],[1:m]}) + (-1)^{i-1}A_{i-1,0}\det(A_{[0:i-1]\frown[i:m],[1:m]}) + (-1)^i A_{i,0}\det(A_{[0:i]\frown[i+1:m],[1:m]}) + \sum_r^{[i+1:m]}(-1)^r A_{r,0}\det(A_{[0:r]\frown[r+1:m],[1:m]})$

iii. $= -\sum_r^{[0:i-1]}(-1)^r A'_{r,0}\det(A'_{[0:r]\frown[r+1:m],[1:m]}) - (-1)^i A'_{i,0}\det(A'_{[0:i]\frown[i+1:m],[1:m]}) - (-1)^{i-1}A'_{i-1,0}\det(A'_{[0:i-1]\frown[i:m],[1:m]}) - \sum_r^{[i+1:m]}(-1)^r A'_{r,0}\det(A'_{[0:r]\frown[r+1:m],[1:m]})$

iv. $= -\sum_r^{[0:m]}(-1)^r A'_{r,0}\det(A'_{[0:r]\frown[r+1:m],[1:m]})$

v. $= -\det(A')$.

Procedure V:26(4.14)

Objective

Choose a $m \times m$ matrix, A. Choose an integer $0 < i < m$. Let A' be A with columns $i-1$ and i swapped. The objective of the following instructions is to show that $\det(A') = -\det(A)$.

Implementation

1. If $i = 1$, then verify that $\det(A)$

(a) $= \sum_r^{[0:m]}(-1)^r A_{r,0}\det(A_{[0:r]\frown[r+1:m],[1:m]})$

(b) $= \sum_r^{[0:m]}(-1)^r A_{r,0}\sum_t^{[r+1:m]}(-1)^{t-1}A_{t,1} * \det(A_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m]}) + \sum_t^{[0:m]}(-1)^t A_{t,0}\sum_r^{[0:t]}(-1)^r A_{r,1} * \det(A_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m+1]})$

(c) $= \sum_t^{[0:m]}(-1)^{t-1}A_{t,1}\sum_r^{[0:t]}(-1)^r A_{r,0} * \det(A_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m+1]}) + \sum_r^{[0:m]}(-1)^r A_{r,1}\sum_t^{[r+1:m]}(-1)^t A_{t,0} * \det(A_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m+1]})$

(d) $= \sum_t^{[0:m]}(-1)^{t-1}A'_{t,0}\sum_r^{[0:t]}(-1)^r A'_{r,1} * \det(A'_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m+1]}) + \sum_r^{[0:m]}(-1)^r A'_{r,0}\sum_t^{[r+1:m]}(-1)^t A'_{t,1} * \det(A'_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m]})$

(e) $= -(\sum_r^{[0:m]}(-1)^r A'_{r,0}\sum_t^{[r+1:m]}(-1)^{t-1}A'_{t,1} * \det(A'_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m]}) + \sum_t^{[0:m]}(-1)^t A'_{t,0}\sum_r^{[0:t]}(-1)^r A'_{r,1} * \det(A'_{[0:r]\frown[r+1:t]\frown[t+1:m],[2:m]}))$

(f) $= -\det(A')$.

2. Otherwise do the following:

(a) Verify that $i > 1$.

(b) For r in $[0 : m]$, do the following:

i. Execute procedure V:26 on $\langle i-1, A_{[0:r]\frown[r+1:m],[1:m]}\rangle$.

ii. Therefore verify that $\det(A_{[0:r]\frown[r+1:m],[1:m]}) = -\det(A'_{[0:r]\frown[r+1:m],[1:m]})$.

(c) Therefore using (bii), verify that $\det(A) = \sum_r^{[0:m]}(-1)^r A_{r,0}\cdot\det(A_{[0:r]\frown[r+1:m],[1:m]}) = \sum_r^{[0:m]}(-1)^r A'_{r,0}\cdot(-\det(A'_{[0:r]\frown[r+1:m],[1:m]})) = -\det(A')$.

Procedure V:27(4.15)

Objective

Choose integers $0 < i < m$. Choose a $m \times m$ matrix, A, such that columns $i-1$ and i are the same. The objective of the following instructions is to show that $\det(A) = 0$.

Implementation

1. Let A' be A with columns $i-1$ and i swapped.
2. Execute procedure V:26 on $\langle A, i\rangle$.
3. Also, verify that $A' = A$.
4. Therefore verify that $\det(A) = \det(A') = -\det(A)$.
5. **Therefore verify that $\det(A) = 0$.**

Procedure V:28(4.16)

Objective

Choose integers $0 < i < m$. Choose a $m \times m$ matrix, A, such that rows $i-1$ and i are the same. The objective of the following instructions is to show that $\det(A) = 0$.

Implementation

Instructions are analogous to those of procedure V:27.

Procedure V:29(4.17)

Objective

Choose integers $0 \leq i < m$. Choose an integer $-i \leq j < m - i$. Choose a $m \times m$ matrix, A. Let A' be A but with column i moved j places. The objective of the following instructions is to show that $\det(A') = (-1)^j \det(A)$.

Implementation

1. Let $B = \langle A \rangle$.
2. For k in $[i : i + j]$, do the following:
   (a) Let $B_{|B|}$ be the result of swapping columns k and $k + 1$ of $B_{|B|-1}$.
   (b) Using procedure V:26, verify that $\det(B_{|B|-1}) = -\det(B_{|B|-2})$.
3. Verify that $A' = B_{|B|-1}$.
4. **Therefore verify that** $\det(A') = \det(B_{|B|-1}) = (-1)^1 \det(B_{|B|-2}) = \cdots = (-1)^j \det(B_0) = (-1)^j \det(A)$**.**

Procedure V:30(4.18)

Objective

Choose integers $0 \leq i < m$. Choose an integer $-i \leq j < m - i$. Choose a $m \times m$ matrix, A. Let A' be A but with row i moved j places. The objective of the following instructions is to show that $\det(A') = (-1)^j \det(A)$.

Implementation

Instructions are analogous to those of procedure V:29.

Declaration V:18(4.10)

The notation $C_k(A)$, where A is a $m \times n$ matrix and k is an integer such that $0 \leq k \leq \min(m, n)$, will be used to refer to the $\binom{m}{k} \times \binom{n}{k}$ matrix with the following specification:

1. The rows are labeled by the colexicographically sorted list of increasing length-k sequences whose elements are picked from $[0 : m]$.
2. The columns are labeled by the colexicographically sorted list of increasing length-k sequences whose elements are picked from $[0 : n]$.
3. For each row label I: For each column label J: The entry at position (I, J) is $\det(A_{I,J})$.

Declaration V:19(4.11)

The notation $A_{\underline{I},\underline{J}}$ will be used to refer to the entry of A with row label I and column label J.

Procedure V:31(4.19)

Objective

Choose two integers $0 \leq k \leq m$. The objective of the following instructions is to show that $C_k(1_m) = 1_{\binom{m}{k}}$.

Implementation

1. For each row label I of $C_k(1_m)$, for each column label J of $C_k(1_m)$, do the following:
   (a) If $I = J$, then do the following:
      i. Verify that $((1_m)_{I,J})_{i,j} = ((1_m)_{J,J})_{i,j} = (1_m)_{J_i,J_j} = [J_i = J_j] = [i = j]$ for $0 \leq i < k$, for $0 \leq j < k$.
      ii. Therefore verify that $(C_k(1_m))_{\underline{I},\underline{J}} = 1_k$.
      iii. **Therefore verify that** $(C_k(1_m))_{\underline{I},\underline{J}} = \det((1_m)_{I,J}) = \det(1_k) = 1$**.**
   (b) Otherwise, do the following:
      i. Verify that $I \neq J$.
      ii. Let i be the index of an element of I that is not an element of J.
      iii. Now verify that $(1_m)_{I_i,j} = [I_i = j] = 0$, for each j in J.
      iv. Therefore verify that $((1_m)_{I,J})_{i,*} = 0_{1 \times k}$.
      v. **Therefore verify that** $(C_k(1_m))_{\underline{I},\underline{J}} = \det((1_m)_{I,J}) = 0$**.**
2. **Therefore verify that** $C_k(1_m) = 1_{\binom{m}{k}}$**.**

Procedure V:32(4.20)

Objective

Choose an integer $0 \le k \le \min(m, n)$. Choose a $m \times m$ tilt, A, such that the off diagonal entry is the polynomial p at (i, j). Also choose a $m \times n$ matrix, B. The objective of the following instructions is to construct a $\binom{m}{k} \times \binom{m}{k}$ matrix D such that $C_k(AB) = DC_k(B)$.

Implementation

1. Let $D = C_k(1_m) = 1_{\binom{m}{k}}$.
2. Verify that AB equals B, but with its row i having p times B's row j added to it.
3. Go through the row labels, I, of $C_k(AB)$ and do the following:

(a) If $i \notin I$, then do the following:

i. Verify that $(AB)_{I,*} = B_{I,*}$.

ii. Therefore for each column label J, verify that $C_k(AB)_{\underline{I},\underline{J}} = \det((AB)_{I,J}) = \det(B_{I,J}) = C_k(B)_{\underline{I},\underline{J}}$.

iii. **Therefore verify that** $(C_k(AB))_{\underline{I},*} = (C_k(B))_{\underline{I},*}$**.**

(b) Otherwise, if $i \in I$, then:

i. Let I' be I but with an in-place replacement of i by j.

ii. For each column label J: Using procedure V:24, verify that $C_k(AB)_{\underline{I},\underline{J}} = \det((AB)_{I,J}) = \det(B_{I,J}) + p * \det(B_{I',J})$.

iii. If $j \in I$, then do the following:

A. Verify that the sequence I' contains two js.

B. For each column label J: Using procedure V:28 verify that $\det(B_{I',J}) = 0$.

C. Therefore for each column label J: verify that $C_k(AB)_{\underline{I},\underline{J}} = \det(B_{I,J}) = C_k(B)_{\underline{I},\underline{J}}$.

D. **Therefore verify that** $C_k(AB)_{\underline{I},*} = C_k(B)_{\underline{I},*}$**.**

iv. Otherwise if $j \notin I$, do the following:

A. Let l be the signed number of places that the j introduced above needs to be moved in order to make I' an increasing sequence.

B. Let I'' be obtained from I' by moving the integer j in I' by l places.

C. For each column label J: Using procedure V:30, verify that $\det(B_{I',J}) = (-1)^l \det(B_{I'',J})$.

D. Therefore for each column label J: Verify that $C_k(AB)_{\underline{I},\underline{J}} = \det(B_{I,J}) + p * \det(B_{I',J}) = \det(B_{I,J}) + (-1)^l p * \det(B_{I'',J})$.

E. Verify that I'' is a row label of $C_k(B)$.

F. Therefore for each column label J: Verify that $C_k(AB)_{\underline{I},\underline{J}} = \det(B_{I,J}) + (-1)^l p * \det(B_{I'',J}) = C_k(B)_{\underline{I},\underline{J}} + (-1)^l p * C_k(B)_{\underline{I''},\underline{J}}$.

G. **Therefore verify that** $(C_k(AB))_{\underline{I},*} = (C_k(B))_{\underline{I},*} + (-1)^l p (C_k(B))_{\underline{I''},*}$**.**

H. **Set** $D_{\underline{I},\underline{I''}}$ **to** $(-1)^l p$**.**

(c) **Therefore verify that** $C_k(AB)_{\underline{I},*} = D_{\underline{I},*} C_k(B)$**.**

4. **Therefore verify that** $C_k(AB) = DC_k(B)$**.**
5. **Yield** $\langle D \rangle$**.**

Procedure V:33(4.21)

Objective

Choose an $m \times n$ diagonal matrix, A. Also choose an $n \times n$ matrix, B. Also choose an integer $0 \le k \le \min(m, n)$. The objective of the following instructions is to construct an $\binom{m}{k} \times \binom{n}{k}$ diagonal matrix D such that $C_k(AB) = DC_k(B)$.

Implementation

1. Let $D = C_k(0_{m \times n}) = 0_{\binom{m}{k} \times \binom{n}{k}}$.
2. Verify that AB equals $B_{[0:\min(m,n)],*}$ with each row i multiplied by $A_{i,i}$.
3. Go through the row labels, I, of $C_k(AB)$ and do the following:

(a) If $I_k < \min(m, n)$, then do the following:

i. Verify that every element of I is less than $\min(m, n)$.

ii. Let $A_0 = A$.

iii. For i in $[0 : k]$: Let A_{i+1} equal A_i but with position (I_i, I_i) set to 1.

iv. For each column label J: Repeatedly using procedure V:24, verify that $C_k(AB)_{I,J}$

A. $= \det((AB)_{I,J})$

B. $= \det((A_0B)_{I,J})$

C. $= A_{I_0,I_0} \det((A_1B)_{I,J})$

D. $= A_{I_0,I_0}A_{I_1,I_1} \det((A_2B)_{I,J})$

E. $\vdots$

F. $= A_{I_0,I_0}A_{I_1,I_1} \cdots A_{I_{k-1},I_{k-1}} \det((A_kB)_{I,J})$

G. $= A_{I_0,I_0}A_{I_1,I_1} \cdots A_{I_{k-1},I_{k-1}} \det(B_{I,J})$

H. $= A_{I_0,I_0}A_{I_1,I_1} \cdots A_{I_{k-1},I_{k-1}} C_k(B)_{\underline{I},\underline{J}}$.

v. **Therefore verify that $(C_k(AB))_{\underline{I},*} = A_{I_1,I_1}A_{I_1,I_1} \cdots A_{I_k,I_k} * (C_k(B))_{\underline{I},*}$.**

vi. **Set $D_{\underline{I},\underline{I}}$ to $A_{I_0,I_0}A_{I_1,I_1} \cdots A_{I_{k-1},I_{k-1}}$.**

(b) Otherwise if $I_k \geq \min(m, n)$, then do the following:

i. Using the precondition, verify that $A_{I_k,*} = 0_{1\times n}$.

ii. Therefore verify that $(AB)_{I_k,*} = 0_{1\times n}$.

iii. Therefore verify that $((AB)_{I,*})_{k,*} = 0_{1\times n}$.

iv. Therefore for each column label J: verify that $C_k(AB)_{\underline{I},\underline{J}} = \det((AB)_{I,J}) = 0$.

v. **Therefore verify that $(C_k(AB))_{\underline{I},*}$ is zero.**

(c) **Therefore verify that $C_k(AB)_{\underline{I},*} = D_{\underline{I},*}C_k(B)$.**

4. **Verify that D is diagonal.**

5. **Verify that $C_k(AB) = DC_k(B)$.**

6. **Yield $\langle D \rangle$.**

Procedure V:34(4.22)

Objective

Choose an integer $0 \leq k \leq \min(m, n)$. Choose a $m \times m$ tilt, A. Also choose a $m \times n$ matrix, B. The objective of the following instructions is to show that $C_k(AB) = C_k(A)C_k(B)$.

Implementation

1. Execute procedure V:32 on matrices A and 1_m and let $\langle D \rangle$ receive.

2. Using procedure V:31, verify that $C_k(A) = C_k(A1_m) = DC_k(1_m) = D1_{\binom{m}{k}} = D$.

3. Execute procedure V:32 on $\langle A, B \rangle$ and let $\langle D' \rangle$ receive.

4. Verify that $D' = D = C_k(A)$.

5. **Therefore verify that $C_k(AB) = D'C_k(B) = C_k(A)C_k(B)$.**

Procedure V:35(4.23)

Objective

Choose an integer $0 \leq k \leq \min(m, n)$. Choose an $n\times n$ tilt, A. Also choose a $m\times n$ matrix, B. The objective of the following instructions is to show that $C_k(BA) = C_k(B)C_k(A)$.

Implementation

Instructions are analogous to those of procedure V:34.

Procedure V:36(4.24)

Objective

Choose an integer $0 \leq k \leq \min(m, n)$. Choose an $m \times n$ diagonal matrix, A. Also choose a $n \times n$ matrix, B. The objective of the following instructions is to show that $C_k(AB) = C_k(A)C_k(B)$.

Implementation

Instructions are analogous to those of procedure V:34.

Procedure V:37(4.25)

Objective

Choose a $m \times n$ matrix, A. Let $D_{-1,-1} = 1$. The objective of the following instructions is to construct a list of $m \times m$ tilts, M, an $m \times n$ diagonal matrix, D, a list of polynomials, v, and a list of $n \times n$ tiltss, N, such that $M_*AN_* = D$, $A = M^{-1}{}_*DN^{-1}{}_*$, and $D_{i,i} = v_iD_{i-1,i-1}$ for i in $[0 : \min(m, n)]$.

Implementation

1. Let D be a copy of A.
2. Let $\langle M, N\rangle$ receive the results of executing procedure V:15 on the pair $\langle m, n\rangle$ and the following procedure:
   (a) Execute procedure V:22 on the matrix D and let $\langle v\rangle$ receive.
3. **Verify that** $D_{i,i} = v_i D_{i-1,i-1}$ **for** i **in** $[0 : \min(m, n)]$**.**
4. **Verify that** $M_* A N_* = D$**.**
5. Hence verify that $A = 1_m A 1_n = M^{-1}{}_* M_* A N_* N^{-1}{}_* = M^{-1}{}_* D N^{-1}{}_*$.
6. **Yield the tuple** $\langle M, D, v, N\rangle$**.**

Procedure V:38(4.26)

Objective

Choose integers $0 \leq k \leq \min(m, n, p)$. Choose a $m \times n$ matrix, A. Also choose a $n \times p$ matrix, B. The objective of the following instructions is to show that $C_k(AB) = C_k(A)C_k(B)$.

Implementation

1. Execute procedure V:37 on A and let $\langle M, D, , N\rangle$ receive.
2. Using repeated applications of procedure V:36, verify that $C_k(AB)$
   (a) $= C_k(M^{-1}{}_0 \cdots M^{-1}{}_{|M|-1} D N^{-1}{}_0 \cdots N^{-1}{}_{|N|-1} B)$
   (b) $= C_k(M^{-1}{}_0) \cdots C_k(M^{-1}{}_{|M|-1}) * C_k(D) * C_k(N^{-1}{}_0) \cdots C_k(N^{-1}{}_{|N|-1}) C_k(B)$
   (c) $= C_k(M^{-1}{}_0 \cdots M^{-1}{}_{|M|-1} D N^{-1}{}_0 \cdots N^{-1}{}_{|N|-1}) C_k(B)$
   (d) $= C_k(A)C_k(B)$.

Procedure V:39(4.27)

Objective

Choose a $m \times m$ matrix, A. Let D be a copy of A. Execute procedure V:22 on D. The objective of the following instructions is to show that $\det(A)$ is the product of the diagonal entries of D.

Implementation

1. Execute procedure V:37 on A and let $\langle M, D, , N\rangle$ receive.
2. Using procedure V:38, verify that $\det(A)$
   (a) $= C_m(A)$
   (b) $= C_m(M^{-1}{}_0 \cdots M^{-1}{}_{|M|-1} D N^{-1}{}_0 \cdots N^{-1}{}_{|N|-1})$
   (c) $= C_m(M^{-1}{}_0) \cdots C_m(M^{-1}{}_{|M|-1}) C_m(D) C_m(N^{-1}{}_0) \cdots C_m(N^{-1}{}_{|N|-1})$
   (d) $= 1 \cdots 1 C_m(D) 1 \cdots 1 = C_m(D)$
   (e) $= \det(D)$
   (f) $= \prod_r^{[0:m]} D_{r,r}$.

Declaration V:20(4.12)

The notation A^T, where A is a $m \times n$ matrix, will be used to refer to the $n \times m$ matrix such that $A^T{}_{i,j} = A_{j,i}$ for i in $[0 : n]$, for j in $[0 : m]$.

Procedure V:40(4.28)

Objective

Choose a $m \times n$ matrix, A, and a $n \times k$ matrix, B. The objective of the following instructions is to show that $B^T A^T = (AB)^T$.

Implementation

1. Verify that $B^T A^T$ and $(AB)^T$ have dimensions $k \times m$.
2. For i in $[0 : k]$: For j in $[0 : m]$:
   (a) Verify that $(B^T A^T)_{i,j} = \sum_l^{[0:n]} B_{l,i} A_{j,l} = \sum_l^{[0:n]} A_{j,l} B_{l,i} = (AB)_{j,i} = ((AB)^T)_{i,j}$.
3. **Therefore verify that** $B^T A^T = (AB)^T$**.**

Procedure V:41(4.29)

Objective

Choose a $m \times m$ matrix, A. The objective of the following instructions is to show that $\det(A^T) = \det(A)$.

Implementation

1. Execute procedure V:37 on A and let $\langle M, D, , N\rangle$ receive.

2. Therefore using procedures procedure V:39 and procedure V:40, verify that $\det(A^T)$

(a) $= \det((M^{-1}{}_0 \cdots M^{-1}{}_{|M|-1} D N^{-1}{}_0 \cdots N^{-1}{}_{|N|-1})^T)$

(b) $= \det((N^{-1}{}_{|N|-1})^T \cdots (N^{-1}{}_0)^T D^T (M^{-1}{}_{|M|-1})^T \cdots (M^{-1}{}_0)^T)$

(c) $= \det(D^T)$

(d) $= \det(D)$

(e) $= \det(M^{-1}{}_0 \cdots M^{-1}{}_{|M|-1} D N^{-1}{}_0 \cdots N^{-1}{}_{|N|-1})$

(f) $= \det(A)$.

Procedure V:42(4.30)

Objective

Choose a $m \times n$ matrix, A, and an integer $0 \leq k \leq \min(m, n)$. The objective of the following instructions is to show that $C_k(A)^T = C_k(A^T)$.

Implementation

1. For each row label I of $C_k(A^T)$, do the following:

   (a) For each column label J of $C_k(A^T)$, do the following:

      i. Using procedure V:41, verify that $(C_k(A^T))_{\underline{I},\underline{J}} = \det((A^T)_{I,J}) = \det(A_{J,I}) = (C_k(A))_{\underline{J},\underline{I}}$.

2. **Therefore verify that** $(C_k(A))^T = (C_k(A^T))$**.**

Chapter 18

Polynomials and Normal Forms

Procedure V:43(4.31)

Objective

Choose a $m \times n$ rational matrix, A, and a $m \times p$ rational matrix, B. Execute procedure V:37 on A and let $\langle M, D, , N\rangle$ receive the result. If the indices of the rows of D that are entirely zero are also the indices of the rows of $M_* B$ that are entirely zero, then the objective of the following instructions is to construct a $n \times p$ rational matrix E such that $AE = B$.

Implementation

1. Verify that $A = M^{-1}{}_* D N^{-1}{}_*$.
2. Verify that $M^{-1}{}_*$, D, and $N^{-1}{}_*$ are rational matrices.
3. Let C be an $n \times p$ matrix with its i^{th} row given as follows:
   (a) If $D_{i,i} \neq 0$, then do the following:
      i. Let row i be row i of $M_* B$ divided by $D_{i,i}$.
   (b) Otherwise, do the following:
      i. **Choose p rational numbers to fill up the row.**
4. Verify that $DC = M_* B$.
5. Let E be $N_* C$.
6. **Therefore using procedure V:17, verify that $AE = M^{-1}{}_* D N^{-1}{}_* E = M^{-1}{}_* D N^{-1}{}_* N_* C = M^{-1}{}_* D 1_n C = M^{-1}{}_* DC = M^{-1}{}_* M_* B = 1_m B = B$.**
7. **Yield the tuple $\langle E\rangle$.**

Declaration V:21(4.13)

The notation $A\backslash B$ will be used to refer to the result yielded by executing procedure V:43 on $\langle A, B\rangle$.

Procedure V:44(4.32)

Objective

Choose a $m \times n$ rational matrix, A, and a $p \times n$ rational matrix, B. Execute procedure V:37 on A and let $\langle M, D, , N\rangle$ receive the result. If the indices of the columns of D that are entirely zero are also the indices of the columns of BN_* that are entirely zero, then the objective of the following instructions is to construct a $p \times m$ rational matrix E such that $EA = B$.

Implementation

Instructions are analogous to those of procedure V:43.

Declaration V:22(4.14)

The notation A/B will be used to refer to the result yielded by executing procedure V:44 on $\langle A, B\rangle$.

Procedure V:45(4.33)

Objective

Choose a $m \times n$ rational matrix, A, a $n \times p$ rational matrix, E, and a $m \times p$ rational matrix, B such that $AE = B$. Execute procedure V:37 on A and let $\langle M, D, , N\rangle$ receive the result. If the indices of the rows of D that are entirely zero are not also the indices of the rows of $M_* B$ that are entirely zero, then the objective of the following instructions is to show that $0 \neq 0$.

Implementation

1. Verify that $M^{-1}{}_* DN^{-1}{}_* E = AE = B$.
2. Therefore verify that $DN^{-1}{}_* E = M_* B$.
3. Let i be an integer such that $D_{i,*}$ is zero and yet $(M_* B)_{i,*}$ is not zero.
4. Verify that $D_{i,*} = D_{i,*} N^{-1}{}_* E = (DN^{-1}{}_* E)_{i,*} = (M_* B)_{i,*}$.
5. Let j be an integer such that $(M_* B)_{i,j} \neq 0$.
6. **Now verify that** $0 = D_{i,j} = (M_* B)_{i,j} \neq 0$**.**

Procedure V:46(4.34)

Objective

Choose a $p \times m$ rational matrix, E, a $m \times n$ rational matrix, A, and a $p \times n$ rational matrix, B such that $EA = B$. Execute procedure V:37 on A and let $\langle M, D, , N\rangle$ receive the result. If the indices of the columns of D that are entirely zero are not also the indices of the columns of BN_* that are entirely zero, then the objective of the following instructions is to show that $0 \neq 0$.

Implementation

Instructions are analogous to those of procedure V:45.

Procedure V:47(4.35)

Objective

Choose two $m \times m$ rational matrices, A and B, such that $AB = 1_m$. The objective of the following instructions is to show that either $0 = 1$ or $BA = 1_m$.

Implementation

1. Execute procedure V:37 on B and let $\langle M, D, , N\rangle$ receive the result.
2. Verify that $B = M^{-1}{}_* DN^{-1}{}_*$.
3. If D has a zero on its diagonal, then do the following:
   (a) Using procedure V:39, verify that $\det(1_m) = \det(AB) = \det(A)\det(B) = \det(A)\det(D) = \det(A) * 0 = 0$.
   (b) Also verify that $\det(1_m) = 1^m = 1$.
   (c) Therefore verify that $0 = 1$.
   (d) **Abort procedure.**
4. Otherwise do the following:
   (a) Verify that D does not have a zero on its diagonal.
   (b) Verify that $B\backslash 1_m = 1_m(B\backslash 1_m) = AB(B\backslash 1_m) = A(B(B\backslash 1_m)) = A1_m = A$.
   (c) **Therefore verify that** $BA = B(B\backslash 1_m) = 1_m$**.**

Procedure V:48(4.36)

Objective

Choose an $m \times m$ matrix, M, and an $m \times m$ rational matrix, B. The objective of the following instructions is to construct a $m \times m$ matrix, Q, and a $m \times m$ rational matrix, R, such that $M = (\lambda 1_m - B)Q + R$.

Implementation

1. Let $M_0\lambda^b + M_1\lambda^{b-1} + \cdots + M_b\lambda^0 = M$, where the M_i are $m \times m$ rational matrices.
2. Now let $R = B^b M_0 + B^{b-1}M_1 + \cdots + B^0 M_b$.
3. Let $Q = \sum_k^{[1:b]}(\lambda^{k-1}1_m B^0 + \lambda^{k-2}1_m B^1 + \cdots + \lambda^0 1_m B^{k-1})M_k$.
4. Verify that $M - R = (\lambda 1_m - B)\sum_k^{[1:b]}(\lambda^{k-1}1_m B^0 + \lambda^{k-2}1_m B^1 + \cdots + \lambda^0 1_m B^{k-1})M_k = (\lambda 1_m - B)Q$.
5. **Verify that** $M = (\lambda 1_m - B)Q + R$**.**
6. **Yield the tuple** $\langle Q, R\rangle$**.**

Procedure V:49(4.37)

Objective

Choose an $m \times m$ matrix, M, and an $m \times m$ rational matrix, B. The objective of the following instructions is to construct a $m \times m$ matrix, Q, and a $m \times m$ rational matrix, R, such that $M = Q(\lambda 1_m - B) + R$.

Implementation

The instructions are analogous to those of procedure V:48.

Procedure V:50(4.38)

Objective

Choose two $m \times m$ rational matrices, B, A, and two lists of $m \times m$ tilts such that $\lambda 1_m - B = M(\lambda 1_m - A)N$. The objective of the following instructions is to either show that $0 = 1$ or to construct $m \times m$ rational matrices R_1 and R_3 such that $1_m = R_1 R_3$ and $B = R_1 A R_3$.

Implementation

1. Verify that $(\lambda 1_m - B)N^{-1} = M(\lambda 1_m - A)NN^{-1} = M(\lambda 1_m - A)1_m = M(\lambda 1_m - A)$.
2. Execute procedure V:49 on $\langle M, B\rangle$ and let $\langle Q_1, R_1\rangle$ receive.
3. Verify that $M = (\lambda 1_m - B)Q_1 + R_1$.
4. Execute procedure V:49 on $\langle N^{-1}, A\rangle$ and let $\langle Q_2, R_2\rangle$ receive.
5. Verify that $N^{-1} = Q_2(\lambda 1_m - A) + R_2$.
6. By substituting M and N^{-1} into (2), verify that $(\lambda 1_m - B)(Q_2(\lambda 1_m - A) + R_2) = ((\lambda 1_m - B)Q_1 + R_1)(\lambda 1_m - A)$.
7. By rearranging both sides, verify that $(\lambda 1_m - B)(Q_2 - Q_1)(\lambda 1_m - A) = R_1(\lambda 1_m - A) - (\lambda 1_m - B)R_2$.
8. By equating the coefficients of different powers of λ both sides, verify that $Q_2 - Q_1 = 0_{m\times m}$.
9. Verify that $R_1(\lambda 1_m - A) - (\lambda 1_m - B)R_2 = (\lambda 1_m - B)(Q_2 - Q_1)(\lambda 1_m - A) = (\lambda 1_m - B)0_{m\times m}(\lambda 1_m - A) = 0_{m\times m}$.
10. Therefore by adding $(\lambda 1_m - B)R_2$ to both sides, verify that $\lambda R_1 - R_1 A = R_1(\lambda 1_m - A) = (\lambda 1_m - B)R_2 = \lambda R_2 - BR_2$.
11. By equating the coefficients of λ on both sides, verify that $R_1 = R_2$.
12. Therefore verify that $R_1 A = BR_1$.
13. Execute procedure V:49 on $\langle M^{-1}, A\rangle$ and let $\langle Q_3, R_3\rangle$ receive.
14. Verify that $M^{-1} = (\lambda 1_m - A)Q_3 + R_3$.
15. Verify that $1_m = MM^{-1} = ((\lambda 1_m - B)Q_1 + R_1)M^{-1} = (\lambda 1_m - B)Q_1 M^{-1} + R_1 M^{-1} = (\lambda 1_m - B)Q_1 M^{-1} + R_1(\lambda I - A)Q_3 + R_1 R_3 = (\lambda 1_m - B)Q_1 M^{-1} + (\lambda I - B)R_1 Q_3 + R_1 R_3 = (\lambda 1_m - B)(Q_1 M^{-1} + R_1 Q_3) + R_1 R_3$.
16. By equating the powers of λ on both sides, verify that $Q_1 M^{-1} + R_1 Q_3 = 0$.
17. By substituting zero for $Q_1 M^{-1} + R_1 Q_3$, **verify that $1_m = (\lambda 1_m - B)0_{m\times m} + R_1 R_3 = R_1 R_3$.**
18. **Therefore using procedure V:47, verify that $R_3 R_1 = 1_m$.**
19. **Also, verify that $B = B1_m = BR_1 R_3 = R_1 A R_3$.**
20. **Yield the pair (R_1, R_3).**

Procedure V:51(4.39)

Objective

Choose a $m \times n$ matrix, A. Choose two integers $0 \le i, j < m$ such that $i \ne j$. The objective of the following instructions is to negate row i and swap it with row j using only elementary row operations.

Implementation

1. Let A be our working matrix.
2. Subtract row j from row i.
3. Add row i to row j.
4. Subtract row j from row i.
5. **Verify that the i^{th} row has been negated and swapped with the j^{th} row.**

Procedure V:52(4.40)

Objective

Choose a $m \times n$ matrix, A. Choose two integers $0 \le i, j < n$ such that $i \ne j$. The objective of the following instructions is to negate column i and swap it with row j using only elementary column operations.

Implementation

The instructions are analogous to those of procedure V:51.

Procedure V:53(4.41)

Objective

Choose an $m \times n$ diagonal matrix, A. Choose two integers $0 \leq i, j < \min(m, n)$ such that $i \neq j$. The objective of the following instructions is to swap $B_{i,i}$ and $B_{j,j}$ using only elementary row and column operations.

Implementation

1. Let A be our working matrix.
2. Use procedure V:52 to negate the i^{th} row and swap it with the j^{th} row.
3. Use procedure V:52 to negate the i^{th} column and swap it with the j^{th} column.
4. **Therefore, overall verify that $B_{i,i}$ and $B_{j,j}$ have been swapped.**

Procedure V:54(4.42)

Objective

Choose an $m \times n$ diagonal matrix, A. Choose two integers $0 \leq i, j < \min(m, n)$ such that $i \neq j$. Choose a rational $k \neq 0$. The objective of the following instructions is to multiply $B_{i,i}$ by k and $B_{j,j}$ by $\frac{1}{k}$ using only elementary row and column operations.

Implementation

1. Let A be our working matrix.
2. Add k times row i to row j.
3. Subtract $\frac{1}{k}$ times row j from row i.
4. Add k times row i to row j.
5. Verify that the i^{th} row has been scaled by k, the j^{th} row by $-\frac{1}{k}$, and that both these rows are swapped.
6. Use procedure V:52 to negate the i^{th} row and swap it with the j^{th} row.
7. **Therefore, overall verify that $B_{i,i}$ has been multiplied by k, and $B_{j,j}$ by $\frac{1}{k}$.**

Procedure V:55(4.43)

Objective

Choose a $m \times m$ rational matrix, A. Execute procedure V:22 on the polynomial matrix $\lambda I - A$ and let $\langle B \rangle$ be the result. The objective of the following instructions is to show that either none of the diagonal entries of B are equal to zero, or $1 = 0$.

Implementation

1. Verify that $\det(\lambda I - A)$ is a monic polynomial of degree m.
2. Therefore using procedure V:39, verify that $\det(B) = \det(\lambda I - A)$.
3. Therefore verify that $\det(B)$ is a monic polynomial of degree m.
4. If any of the diagonal entries of B equal zero, then do the following:
   (a) Verify that $\det(B) = B_{0,0}B_{1,1} \cdots B_{m-1,m-1} = 0$.
   (b) Therefore using (3) and (4a), verify that $1 = 0$.
   (c) **Abort procedure.**
5. Otherwise do the following:
   (a) **Verify that none of the diagonal entries of B equal zero.**

Procedure V:56(4.44)

Objective

Choose a positive integer m and an $m \times m$ rational matrix, A. Execute procedure V:37 on the polynomial matrix $\lambda 1_m - A$ and let $\langle, B, v, \rangle$ be the result. The objective of the following instructions is to either show that $0 < 0$ or to construct an integer a such that $\sum_i^{[a:m]} \deg(B_{i,i}) = m$, $\deg(B_{i,i}) > 0$ for i in $[a : m]$, and $\deg(B_{i,i}) = 0$ for i in $[0 : a]$.

Implementation

1. Execute procedure V:55 on A.
2. If $\deg(B_{i,i}) = 0$ for i in $[0 : m]$, then do the following:
   (a) Verify that $\det(\lambda 1_m - A) = \det(B) = B_{0,0}B_{1,1} \cdots B_{m-1,m-1}$.
   (b) **Therefore verify that $0 < m = \deg(\det(\lambda 1_m - A)) = \deg(B_{0,0}B_{1,1} \cdots B_{m-1,m-1}) = 0 + 0 + \cdots + 0 = 0$.**
   (c) **Abort procedure.**

3. Otherwise do the following:

   (a) Let $0 \leq a < m$ be the least integer such that $\deg(B_{a,a}) > 0$.

   (b) **Verify that** $\deg(B_{i,i}) = 0$ **for** i **in** $[0 : a]$**.**

   (c) **Verify that** $\sum_i^{[a:m]} \deg(B_{i,i}) = \sum_i^{[0:m]} \deg(B_{i,i}) = \deg(B_{0,0}B_{1,1} \cdots B_{m-1,m-1}) = \deg(\det(B)) = \deg(\lambda 1_m - A) = m$**.**

   (d) For i in $[a+1 : m]$, do the following:

      i. Verify that $B_{i,i} = u_i B_{i-1,i-1}$.

      ii. Verify that $B_{i,i} \neq 0$.

      iii. Therefore verify that $u_i \neq 0$.

      iv. **Therefore verify that** $\deg(B_{i,i}) = \deg(u_i B_{i-1,i-1}) \geq \deg(B_{i-1,i-1}) > 0$**.**

   (e) **Yield the tuple** $\langle a \rangle$**.**

Declaration V:23(4.19)

The notation $(e_i)_{k\times 1}$ will be used to refer to the $k \times 1$ rational matrix such that its i^{th} entry, 1, is the only non-zero entry.

Declaration V:24(4.22)

The notation $\mathrm{mat}_t(p)$ will be used as a shorthand for $\sum_j^{[0:t]} p_j e_j$.

Declaration V:25(4.16)

The notation $\mathrm{comp}(p)$, where $p \neq 0$ is a monic polynomial such that $\deg(p) > 0$, will be used as a shorthand for the $\deg(p) \times \deg(p)$ rational matrix of the following constitution:

1. Its first $\deg(p) - 1$ columns equal the last $\deg(p) - 1$ columns of 1_k.
2. Its last column is $-\mathrm{mat}_{\deg(p)}(p)$.

Procedure V:57(4.45)

Objective

Choose a monic polynomial, p such that $\deg(p) > 0$. Let $k = \deg(p)$. Choose a $k \times k$ matrix, D, such that $D = \lambda 1_k - \mathrm{comp}(p)$. The objective of the following instructions is to transform D into $\mathrm{diag}(1, \cdots, 1, p)$ by a sequence of elementary operations.

Implementation

1. Let the matrix D be our working matrix.
2. For i in $[k : 1]$, add λ times row i to row $i-1$.
3. Verify that D's first $k-1$ columns are now the last $k-1$ columns of -1_k.
4. Verify that D's last column is p followed by some other polynomials.
5. For i in $[1 : k]$, subtract $D_{i,k-1}$ times column $i-1$ from column $k-1$.
6. Verify that D's last column is now p followed by zeros.
7. For i in $[1 : k]$, negate row $i-1$ and exchange it with row i using procedure V:52.
8. **Therefore verify that** $D = \mathrm{diag}(1, \cdots, 1, p)$**.**

Procedure V:58(4.46)

Objective

Choose a positive integer m and an $m \times m$ rational matrix, A. Execute procedure V:15 on the polynomial matrix $\lambda 1_m - A$ and let $\langle , B, , \rangle$ receive the result. Execute procedure V:56 on A and let $\langle a \rangle$ receive the result. Let $E_i = \mathrm{comp}(\mathrm{mon}(B_{a+i,a+i}))$ for i in $[0 : m-a]$. The objective of the following instructions is to first show that $\mathrm{cols}(\mathrm{diag}(E)) = m$, and second to apply a sequence of elementary operations on $\lambda 1_m - \mathrm{diag}(E)$ to obtain the matrix B.

Implementation

1. Verify that the diagonal of B comprises a rationals followed by $B_{a,a}, B_{a+1,a+1}, \cdots, B_{m-1,m-1}$.
2. **Using procedure V:57, verify that** $\mathrm{cols}(\mathrm{diag}(E)) = \sum_i^{[0:|E|]} \mathrm{cols}(E_i) = \sum_i^{[0:|E|]} \mathrm{cols}(\mathrm{comp}(\mathrm{mon}(B_{a+i,a+i}))) = \sum_i^{[0:|E|]} \deg(\mathrm{mon}(B_{a+i,a+i})) = \sum_i^{[0:m-a]} \deg(B_{a+i,a+i}) = \sum_i^{[a:m]} \deg(B_{i,i}) = m$**.**
3. Let $F = \lambda 1_m - \mathrm{diag}(E)$.
4. Now for i in $[0 : |E|]$:

   (a) Let $j = \sum_r^{[0:i]} \mathrm{cols}(E_r)$.

   (b) Let $k = j + \mathrm{cols}(E_i)$.

(c) Apply procedure V:57 on the tuple $\langle \text{mon}(B_{a+i,a+i}), F_{[j:k],[j:k]} \rangle$.

5. Now verify that F is an $m \times m$ diagonal rational matrix.
6. Also verify that the diagonal of F comprises $\text{mon}(B_{a,a}), \text{mon}(B_{a+1,a+1}), \cdots, \text{mon}(B_{m-1,m-1})$ and a 1s.
7. Rearrange the diagonal of F so that $\text{mon}(B_{i,i})$ is at the i^{th} position on the diagonal for i in $[a : m]$ by doing pairwise swaps. In general, swap the i^{th} and j^{th} diagonal entries using procedure V:53.
8. For i in $[0 : m-1]$, do the following:

(a) Let $k = \frac{(B_{i,i})_{\deg(B_{i,i})}}{(F_{i,i})_{\deg(F_{i,i})}}$.

(b) Scale $B_{i,i}$ by k and $B_{i+1,i+1}$ by $\frac{1}{k}$ using procedure V:54.

(c) Now verify that $F_{i,i} = B_{i,i}$.

9. Now verify that $\det(F)_m = \det(\lambda 1_m - \text{diag}(E))_m = 1 = \det(\lambda 1_m - A)_m = \det(B)_m$.
10. Therefore verify that $(F_{m,m})_{\deg(F_{m,m})}$

(a) $= \frac{\det(F)_m}{(\det(F_{[1:m],[1:m]}))_{m-\deg(F_{m,m})}}$

(b) $= \frac{\det(B)_m}{(\det(B_{[1:m],[1:m]}))_{m-\deg(B_{m,m})}}$

(c) $= (B_{m,m})_{\deg(B_{m,m})}$.

11. Therefore verify that $F_{m,m} = B_{m,m}$.
12. **Therefore verify that $F = B$.**

Procedure V:59(4.47)

Objective

Choose a $m \times m$ rational matrix, A. Execute procedure V:56 on A and let $\langle a \rangle$ receive the result. Let $E_i = \text{comp}(\text{mon}(B_{a+i,a+i}))$ for i in $[0 : m-a]$. The objective of the following instructions is to either show that $0 = 1$ or to construct $m \times m$ rational matrices R, T such that $A = R\,\text{diag}(E)T$, $RT = 1_m$, and $TR = 1_m$.

Implementation

1. Execute procedure V:37 on the polynomial matrix $\lambda 1_m - A$ and let $\langle P, B, , Q \rangle$ be the result.
2. Verify that $P_*(\lambda 1_m - A)Q_* = B$.
3. Verify that $\lambda 1_m - A = P^{-1}{}_* B Q^{-1}{}_*$.
4. Let Z be a variant of procedure V:37 where every occurence of procedure V:22 in its instructions is replaced with procedure V:58, and where every mention of v is ignored.
5. Execute procedure Z on the matrix $\lambda 1_m - \text{diag}(E)$ and let $\langle M, , , N \rangle$ receive the result.
6. Verify that $M_*(\lambda 1_m - \text{diag}(E))N_* = B$.
7. Verify that $\lambda 1_m - A = P^{-1}{}_* B Q^{-1}{}_* = P^{-1}{}_* M(\lambda 1_m - \text{diag}(E))NQ^{-1}{}_*$.
8. Execute procedure V:50 on the matrices $\langle A, P^{-1}M, \text{diag}(E), NQ^{-1} \rangle$. Let the tuple $\langle R, T \rangle$ be the result.
9. **Verify that $A = R\,\text{diag}(E)T$.**
10. **Verify that $RT = 1_m$.**
11. **Verify that $TR = 1_m$.**
12. **Yield the tuple $\langle R, E, T \rangle$.**

Procedure V:60(4.86)

Objective

Choose two polynomials a, b and an $m \times m$ matrix C such that $a = b$. The objective of the following instructions is to show that $\Lambda(a, C) = \Lambda(b, C)$.

Implementation

Implementation is analogous to that of procedure II:67.

Procedure V:61(4.87)

Objective

Choose two polynomials a, b and an $m \times n$ matrix C. The objective of the following instructions is to show that $\Lambda(a + b, C) = \Lambda(a, C) + \Lambda(b, C)$.

Implementation

Implementation is analogous to that of procedure II:72.

Procedure V:62(4.88)

Objective

Choose a polynomial a and an $m\times m$ matrix B. The objective of the following instructions is to show that $\Lambda(-a,B) = -\Lambda(a,B)$.

Implementation

Implementation is analogous to that of procedure II:78.

Procedure V:63(4.89)

Objective

Choose two polynomials a,b and an $m \times m$ matrix C. The objective of the following instructions is to show that $\Lambda(ab,C) = \Lambda(a,C)\Lambda(b,C)$.

Implementation

Implementation is analogous to that of procedure II:81.

Procedure V:64(4.48)

Objective

Choose a polynomial, r, and $m \times m$ rational matrices, R, A, S such that $SR = 1_m$. The objective of the following instructions is to show that $\Lambda(r, RAS) = R\Lambda(r,A)S$.

Implementation

1. Verify that $\Lambda(r, RAS)$

(a) $= \sum_j^{[0:|r|]} r_j (RAS)^j$

(b) $= \sum_j^{[0:|r|]} r_j RA^j S$

(c) $= R(\sum_j^{[0:|r|]} r_j A^j)S$

(d) $= R\Lambda(r,A)S$.

Procedure V:65(4.49)

Objective

Choose a list of $m \times m$ rational matrices, A, and a polynomial, r. The objective of the following instructions is to show that $\Lambda(r, \text{diag}(A)) = \text{diag}(\Lambda(r, A))$.

Implementation

1. For $i = 0$ up to $i = t$, by repeated applications of procedure V:21, verify that $\text{diag}(A)^i$ evaluates to $\text{diag}(A^i)$.

2. Therefore verify that $\Lambda(r, \text{diag}(A))$

(a) $= \sum_j^{[0:|r|]} r_j \,\text{diag}(A)^j$

(b) $= \sum_j^{[0:|r|]} r_j \,\text{diag}(A^j)$

(c) $= \sum_j^{[0:|r|]} \text{diag}(r_j A^j)$

(d) $= \text{diag}(\sum_j^{[0:|r|]} r_j A^j)$

(e) $= \text{diag}(\Lambda(r,A))$.

Procedure V:66(4.50)

Objective

Choose a $m \times m$ rational matrix, A, and a polynomial, r. Execute procedure V:59 on the matrix A and let the tuple $\langle R_1, E, R_3\rangle$ receive the result. The objective of the following instructions is to show that $\Lambda(r,A) = R_1 \,\text{diag}(\Lambda(r,E))R_3$.

Implementation

1. Verify that $R_3R_1 = 1_m$.

2. Using procedure V:64, verify that $\Lambda(r,A) = \Lambda(r, R_1 \,\text{diag}(E)R_3) = R_1\Lambda(r, \text{diag}(E))R_3$.

3. Using procedure V:65, verify that $\Lambda(r, \text{diag}(E)) = \text{diag}(\Lambda(r,E))$.

4. **Therefore verify that** $\Lambda(r,A) = R_1 \,\text{diag}(\Lambda(r,E))R_3$**.**

Procedure V:67(4.51)

Objective

Choose a monic polynomial $p \neq 0$ such that $\deg(p) > 0$. The objective of the following instructions is to show that $\Lambda(p, \text{comp}(p)) = 0_{\deg(p)\times\deg(p)}$.

Implementation

1. Let $G = \text{comp}(p)$.

2. For i in $[0 : \deg(p)]$, verify that $G^i e_0 = G^{i-1}e_1 = \cdots = G^0 e_i = e_i$.

3. Therefore, for $i \in [0 : \deg(p)]$, do the following:

(a) Using (1), verify that $\Lambda(p, G)e_i$

i. $= (\sum_j^{[0:|p|]} p_j G^j)e_i$

ii. $= (\sum_j^{[0:|p|]} p_j G^j)G^i e_0$

iii. $= G^i(GG^{\deg(p)-1} + \sum_j^{[0:\deg(p)]} p_j G^j)e_0$

iv. $= G^i(Ge_{\deg(p)-1} + \sum_j^{[0:\deg(p)]} p_j e_j)$

v. $= G^i 0_{\deg(p)\times 1}$

vi. $= 0_{\deg(p)\times 1}$.

4. **Therefore verify that** $\Lambda(p, \mathrm{comp}(p)) = \Lambda(p, G) = 0_{\deg(p)\times\deg(p)}$**.**

Declaration V:26(4.20)

The notation last_A, where A is an $m \times m$ rational matrix, will be used as a shorthand for the polynomial yielded by executing the following instructions:

1. Execute procedure V:37 on the polynomial matrix $\lambda 1_m - A$ and let the tuple $\langle , B, , \rangle$ receive the result.
2. Yield $\langle B_{m-1,m-1} \rangle$.

Procedure V:68(4.52)

Objective

Choose a $m \times m$ rational matrix, A. The objective of the following instructions is to show that either $1 = 0$ or $\mathrm{last}_A \neq 0$.

Implementation

1. Execute procedure V:55 on A.
2. **Therefore verify that** $\mathrm{last}_A \neq 0$**.**

Procedure V:69(4.53)

Objective

Choose a $m \times m$ rational matrix, A. The objective of the following instructions is to either show that $0 < 0$ or to show that $\Lambda(\mathrm{last}_A, A) = 0_{m\times m}$.

Implementation

1. Execute procedure V:37 on the matrix A and let the tuple $\langle M, B, v, N\rangle$ receive the result.
2. Execute procedure V:56 on A and let $\langle a\rangle$ receive.
3. Execute procedure V:59 on A and let $\langle R, E, T\rangle$ receive.
4. For j in $[0 : |E|]$:
   (a) Verify that $E_j = \mathrm{comp}(\mathrm{mon}(B_{a+j,a+j}))$.
   (b) Verify that $\mathrm{last}_A = B_{m-1,m-1} = B_{a+j,a+j}\prod_r^{[a+j+1:m]} v_r$.
   (c) Let $k = \deg(\mathrm{mon}(B_{a+j,a+j}))$.
   (d) Therefore using procedure V:67 verify that $\Lambda(\mathrm{last}_A, E_j) = \Lambda(B_{m-1,m-1}, E_j) = \Lambda(B_{a+j,a+j}, \mathrm{comp}(\mathrm{mon}(B_{a+j,a+j})))\prod_r^{[a+j+1:m]} \Lambda(v_r, E_j) = 0_{k\times k}\prod_r^{[a+j+1:m]}\Lambda(v_r, E_j) = 0_{k\times k}$.
5. **Therefore using procedure V:66 verify that** $\Lambda(\mathrm{last}_A, A) = R\,\mathrm{diag}(\Lambda(\mathrm{last}_A, E))T = R\,\mathrm{diag}(\Lambda(B_{m-1,m-1}, E))T = R0_{m\times m}T = 0_{m\times m}$**.**

Procedure V:70(4.54)

Objective

Choose a monic polynomial p such that $\deg(p) > 0$. Choose a polynomial $g \neq 0$ such that $\deg(g) < \deg(p)$. The objective of the following instructions is to show that $\Lambda(g, \mathrm{comp}(p)) \neq 0_{\deg(p)\times\deg(p)}$.

Implementation

1. Let $G = \mathrm{comp}(p)$.
2. Therefore using declaration V:25, verify that $\Lambda(g, G)e_0 = (\sum_j^{[0:\deg(g)+1]} g_j G^j)e_0 = \sum_j^{[0:\deg(g)+1]} g_j e_j \neq 0_{\deg(p)\times 1}$.
3. **Therefore verify that** $\Lambda(g, G) \neq 0_{\deg(p)\times\deg(p)}$**.**

Procedure V:71(4.55)

Objective

Choose a polynomial g and a monic polynomial p such that $\deg(p) = \deg(g) > 0$ and $\Lambda(g, \mathrm{comp}(p)) = 0_{\deg(g)\times\deg(g)}$. The objective of the following instructions is to show that $g = g_{\deg(g)}p$.

Implementation

1. Let $G = \text{comp}(p)$.
2. Using declaration V:25, verify that $0_{\deg(g)\times 1} = \Lambda(g, G)e_0 = (\sum_j^{[0:|g|]} g_j G^j)e_0 = g_{\deg(g)} G e_{\deg(g)-1} + \sum_j^{[0:\deg(g)]} g_j e_j$.
3. Therefore for i in $[0 : \deg(g)]$, do the following:
   (a) Verify that $0 = (g_{\deg(g)} G e_{\deg(g)-1} + \sum_j^{[0:\deg(g)]} g_j e_j)_{i,0}$.
   (b) Therefore using declaration V:25, verify that $-g_{\deg(g)} p_i + g_i = 0$.
   (c) Therefore verify that $g_i = g_{\deg(g)} p_i$.
4. **Therefore verify that $g = g_{\deg(g)} p$.**

Procedure V:72(4.56)

Objective

Choose a $m \times m$ rational matrix, A. Choose a polynomial $p \neq 0$, such that $\Lambda(p, A) = 0_{m\times m}$. The objective of the following instructions is to either show that $0 \neq 0$ or to construct a polynomial f such that $p = f \,\text{last}_A$.

Implementation

1. Let F be the 1×2 matrix $\langle\langle p, \text{last}_A\rangle\rangle$.
2. Execute procedure V:37 on F and let $\langle M, D, , N\rangle$ receive the result.
3. Verify that $D_{0,0} \neq 0$.
4. Let $g = D_{0,0}$.
5. Verify that $F = M^{-1}{}_* D N^{-1}{}_* = D N^{-1}{}_*$.
6. Verify that $\text{last}_A = F_{0,1} = D_{0,0} N^{-1}{}_{*0,1} + D_{0,1} N^{-1}{}_{*1,1} = D_{0,0} N^{-1}{}_{*0,1} = g N^{-1}{}_{*0,1}$.
7. Therefore verify that $N^{-1}{}_{*0,1} \neq 0$.
8. Let $u = \deg(\text{last}_A)$.
9. Now verify that $u = \deg(\text{last}_A) = \deg(D_{0,0} N^{-1}{}_{*0,1}) \geq \deg(D_{0,0}) = \deg(g)$.
10. Verify that $D = M_* F N_* = F N_*$.
11. Therefore verify that $g = D_{0,0} = N_{*0,0} p + N_{*1,0} \,\text{last}_A$.
12. Therefore using procedure V:67, verify that $\Lambda(g, A) = \Lambda(N_{*0,0}, A)\Lambda(p, A) + \Lambda(N_{*1,0}, A)\Lambda(\text{last}_A, A) = \Lambda(N_{*0,0}, A) 0_{m\times m} + \Lambda(N_{*1,0}, A) 0_{m\times m} = 0_{m\times m}$.
13. Execute procedure V:59 on the matrix A and let the tuple $\langle R_1, E, R_3\rangle$ receive the result.
14. Using procedure V:66, and procedure V:59, verify that $\text{diag}(\Lambda(g, E)) = 1_m \,\text{diag}(\Lambda(g, E)) 1_m = R_3 R_1 \,\text{diag}(\Lambda(g, E)) R_3 R_1 = R_3 \Lambda(g, A) R_1 = R_3 0_{m\times m} R_1 = 0_{m\times m}$.
15. Let $G = \text{comp}(\text{mon}(\text{last}_A))$.
16. Verify that $\Lambda(g, G) = \Lambda(g, E_{|E|-1}) = \text{diag}(\Lambda(g, E))_{[m-u:m],[m-u:m]} = 0_{u\times u}$.
17. If $\deg(g) < u$, then:
    (a) Using procedure V:70, verify that $\Lambda(g, G) \neq 0_{u\times u}$.
    (b) **Therefore using (16), verify that $0_{u\times u} = \Lambda(g, G) \neq 0_{u\times u}$.**
    (c) **Abort procedure.**
18. Otherwise, do the following:
    (a) Verify that $\deg(g) = u$.
    (b) Using procedure V:71, verify that $g = g_{\deg(g)} \,\text{last}_A$.
    (c) **Therefore verify that $p = F_{0,0} = D_{0,0} N^{-1}{}_{*0,0} + D_{0,1} N^{-1}{}_{*1,0} = N^{-1}{}_{*0,0} g + N^{-1}{}_{*1,0} * 0 = N^{-1}{}_{*0,0} g = N^{-1}{}_{*0,0} g_{\deg(g)} \,\text{last}_A$.**
    (d) **Yield the tuple $\langle N^{-1}{}_{*0,0} g_{\deg(g)}\rangle$.**

Procedure V:73(4.57)

Objective

Choose an $m \times n$ rational matrix, A, and an $n \times m$ rational matrix, B, such that $AB = 1_m$. The objective of the following instructions is to show that either $0 = 1$ or every column of B is non-zero.

Implementation

1. If any column i of B, Be_i, is equal to zero, then:
   (a) Verify that $0_{n\times 1} = A 0_{n\times 1} = A(Be_i) = (AB)e_i = 1_m e_i = e_i$.
   (b) **Therefore verify that 0=1.**

(c) **Abort procedure.**

Procedure V:74(4.58)

Objective

Choose a $m \times m$ rational matrix, A. Choose a polynomial p such that $p \neq 0$, $\Lambda(p, A) = 0$, and $\deg(p) < \deg(\text{last}_A)$. The objective of the following instructions is to show that $0 < 0$.

Implementation

1. Execute procedure V:72 on A and p and let f receive.
2. Now verify that $p = f \, \text{last}_A$.
3. Now using the precondition and (2), verify that $f \neq 0$ and $\text{last}_A \neq 0$.
4. **Therefore using the precondition, (2), and (3), verify that** $\deg(\text{last}_A) > \deg(p) = \deg(f \, \text{last}_A) \geq \deg(\text{last}_A)$**.**
5. **Abort procedure.**

Declaration V:27(4.21)

The notation pows(A), where A is a $m \times m$ rational matrix, will be used as a shorthand for the result yielded by executing the following instructions:

1. Let $t = \deg(\text{last}_A)$.
2. Make an $m^2 \times t$ matrix, B, whose i^{th} column is the sequential concatenation of the columns of A^i.
3. **Yield** $\langle B \rangle$**.**

Procedure V:75(4.59)

Objective

Choose a $m \times m$ rational matrix, A. Execute procedure V:37 on $\text{pows}(A)$ and let the tuple $\langle M, D, , N \rangle$ receive the result. Let $t = \text{cols}(\text{pows}(A))$. The objective of the following instructions is to show that either $0 < 0$ or to show that $C_t(D) = C_t(D)_{0,0} e_0 \neq 0$.

Implementation

1. Execute procedure V:37 on $\text{pows}(A)$ and let the tuple $\langle M, D, , N \rangle$ receive the result.
2. Verify that $M_* \, \text{pows}(A) N_* = D$.
3. Using procedure V:17, verify that ${M^{-1}}_* M_* \, \text{pows}(A) N_* = 1_{m^2} \, \text{pows}(A) N_* = \text{pows}(A) N_* = {M^{-1}}_* D$.
4. If $C_t(D)_{0,0} = 0$, then:
   (a) Verify that for some $0 \leq i < t$, $D_{i,i} = 0$.
   (b) Therefore verify that $De_i = 0_{m^2 \times 1}$.
   (c) Therefore verify that $\text{pows}(A)(Ne_i) = (\text{pows}(A) N) e_i = (M^{-1} D) e_i = M^{-1}(De_i) = 0_{m^2 \times 1}$.
   (d) Let $p = N_{0,i} \lambda^0 + N_{1,i} \lambda^1 + \cdots + N_{t-1,i} \lambda^{t-1}$.
   (e) Therefore verify that $\Lambda(p, A) = 0_{m \times m}$.
   (f) Execute procedure V:73 on ${N^{-1}}_*$ and N_*.
   (g) Therefore verify that $p \neq 0$.
   (h) Execute procedure V:74 on A and p.
   (i) **Abort procedure.**
5. Otherwise, do the following:
   (a) Execute procedure V:33 on $\langle D, 1_t, t \rangle$ and let E receive.
   (b) Verify that $C_t(D) = C_t(D 1_t) = E C_t(1_t) = E * 1 = E$.
   (c) Verify that E is a $\binom{m^2}{t} \times \binom{t}{t}$ diagonal matrix.
   (d) Therefore verify that $C_t(D)$ is a $\binom{m^2}{t} \times 1$ diagonal matrix.
   (e) **Therefore verify that** $C_t(D) = C_t(D)_{0,0} e_0 \neq 0$**.**

Procedure V:76(4.60)

Objective

Choose a $m \times m$ rational matrix, A. Let $t = \text{cols}(\text{pows}(A))$. The objective of the following instructions is to show that either $0 < 0$ or to show that $C_t(\text{pows}(A)) \neq 0$.

Implementation

1. Execute procedure V:37 on $\text{pows}(A)$ and let the tuple $\langle M, D, , N \rangle$ receive the result.
2. Verify that $\text{pows}(A) = {M^{-1}}_* D {N^{-1}}_*$.
3. Execute procedure V:73 on $C_t(M_*)$, $C_t({M^{-1}}_*)$.

4. Hence verify that all columns of $C_t(M^{-1}{}_*)$ are non-zero.
5. Execute procedure V:75 on A.
6. Verify that $C_t(D) = C_t(D)_{0,0}e_0 \neq 0$.
7. Therefore verify that $C_t(D)_{0,0} \neq 0$.
8. Execute procedure V:73 on $C_t(N_*), C_t(N^{-1}{}_*)$.
9. Hence verify that $C_t(N^{-1}) \neq 0$.
10. **Verify that** $C_t(\text{pows}(A)) = C_t(M^{-1}{}_*DN^{-1}{}_*) = C_t(M^{-1}{}_*)C_t(D)C_t(N^{-1}{}_*) = C_t(M^{-1}{}_*)C_t(D)_{0,0}e_0C_t(N^{-1}{}_*) = C_t(D)_{0,0}C_t(N^{-1}{}_*)C_t(M^{-1}{}_*)e_0 \neq 0_{\binom{m^2}{t}\times 1}$.

Declaration V:28(4.26)

The notation tr(A), where A is a square matrix, will be used as a shorthand for the sum of its diagonal entries.

Procedure V:77(4.68)

Objective

Choose two $m \times m$ matrices A, B. The objective of the following instructions is to show that $\text{tr}(A + B) = \text{tr}(A) + \text{tr}(B)$.

Implementation

1. Verify that $\text{tr}(A + B)$
   (a) $= \sum_r^{[0:m]}(A + B)_{r,r}$
   (b) $= \sum_r^{[0:m]}(A_r + B_r)_{r,r}$
   (c) $= \sum_r^{[0:m]} A_{r,r} + \sum_r^{[0:m]} B_{r,r}$
   (d) $= \text{tr}(A) + \text{tr}(B)$.

Procedure V:78(4.69)

Objective

Choose a polynomial b and an $m \times m$ matrix A. The objective of the following instructions is to show that $\text{tr}(bA) = b\,\text{tr}(A)$.

Implementation

1. Verify that $\text{tr}(bA)$
   (a) $= \text{tr}(b_{m\times m}A)$
   (b) $= \sum_r^{[0:m]}(b_{m\times m}A)_{r,r}$
   (c) $= \sum_r^{[0:m]} \sum_t^{[0:m]}(b_{m\times m})_{r,t}A_{t,r}$
   (d) $= \sum_r^{[0:m]}(b_{m\times m})_{r,r}A_{r,r}$
   (e) $= \sum_r^{[0:m]} bA_{r,r}$
   (f) $= b\sum_r^{[0:m]} A_{r,r}$
   (g) $= b\,\text{tr}(A)$.

Procedure V:79(4.70)

Objective

Choose an $m \times n$ matrix A and an $n \times m$ matrix B. The objective of the following instructions is to show that $\text{tr}(AB) = \text{tr}(BA)$.

Implementation

1. Verify that $\text{tr}(AB)$
   (a) $= \sum_r^{[0:m]}(AB)_{r,r}$
   (b) $= \sum_r^{[0:m]} \sum_t^{[0:n]} A_{r,t}B_{t,r}$
   (c) $= \sum_t^{[0:n]} \sum_r^{[0:m]} B_{t,r}A_{r,t}$
   (d) $= \sum_t^{[0:n]}(BA)_{t,t}$
   (e) $= \text{tr}(BA)$.

Procedure V:80(4.71)

Objective

Choose an $m\times n$ matrix A such that $A \neq 0$. The objective of the following instructions is to show that $\text{tr}(A^TA) > 0$.

Implementation

1. Verify that $\text{tr}(A^TA)$
   (a) $= \sum_r^{[0:n]}(A^TA)_{r,r}$
   (b) $= \sum_r^{[0:n]} \sum_t^{[0:m]}(A^T)_{r,t}A_{t,r}$
   (c) $= \sum_r^{[0:n]} \sum_t^{[0:m]} A_{t,r}A_{t,r}$
   (d) $= \sum_r^{[0:n]} \sum_t^{[0:m]}(A_{t,r})^2$
   (e) > 0.

Declaration V:29(4.27)

The phrase "symmetric matrix" will be used to refer to matrices A such that "$A^T = A$".

Procedure V:81(4.61)

Objective

Choose a symmetric $m \times m$ rational matrix, A. Let $t = \deg(\mathrm{last}_A)$. Choose two polynomials u, w such that $\deg(u) < t$ and $\deg(w) < t$. The objective of the following instructions is to show that $\mathrm{tr}(\Lambda(uw, A)) = \mathrm{mat}(u)^T \,\mathrm{pows}(A)^T \,\mathrm{pows}(A)\,\mathrm{mat}_t(w)$.

Implementation

1. Verify that $\mathrm{tr}(\Lambda(uw, A))$
   (a) $= \mathrm{tr}(\Lambda(u, A)\Lambda(w, A))$
   (b) $= \mathrm{tr}((\sum_p^{[0:t]} u_p A^p)(\sum_q^{[0:t]} w_q A^q))$
   (c) $= \mathrm{tr}(\sum_p^{[0:t]} \sum_q^{[0:t]} u_p w_q A^p A^q)$
   (d) $= \sum_p^{[0:t]} \sum_q^{[0:t]} u_p w_q \,\mathrm{tr}(A^p A^q)$
   (e) $= \sum_p^{[0:t]} \sum_q^{[0:t]} u_p w_q \sum_e^{[0:m]} \sum_f^{[0:m]} {A^p}_{e,f} \cdot {A^q}_{f,e}$
   (f) $= \sum_p^{[0:t]} \sum_q^{[0:t]} u_p w_q \sum_e^{[0:m]} \sum_f^{[0:m]} {A^p}_{f,e} \cdot {A^q}_{f,e}$
   (g) $= \sum_p^{[0:t]} \sum_q^{[0:t]} u_p w_q \sum_g^{[0:m^2]} \mathrm{pows}(A)_{g,p} \mathrm{pows}(A)_{g,q}$
   (h) $= \sum_p^{[0:t]} \sum_q^{[0:t]} u_p w_q (\mathrm{pows}(A)^T \,\mathrm{pows}(A))_{p,q}$
   (i) $= \sum_p^{[0:t]} u_p (\mathrm{pows}(A)^T \,\mathrm{pows}(A)\,\mathrm{mat}_t(w))_p$
   (j) $= \mathrm{mat}_t(u)^T \,\mathrm{pows}(A)^T \,\mathrm{pows}(A)\,\mathrm{mat}_t(w)$

Declaration V:30(4.25)

The notation sel_A, where A is an $m \times m$ rational matrix, will be used as a shorthand for the result yielded by executing the following instructions:

1. Using procedure V:42, procedure V:76, and procedure V:80, verify that $C_t(\mathrm{pows}(A)^T \,\mathrm{pows}(A)) = C_t(\mathrm{pows}(A)^T) C_t(\mathrm{pows}(A)) = C_t(\mathrm{pows}(A))^T C_t(\mathrm{pows}(A)) = \mathrm{tr}(C_t(\mathrm{pows}(A))^T C_t(\mathrm{pows}(A))) > 0$.
2. Let $t = \deg(\mathrm{last}_A)$.
3. Let $H = (\mathrm{pows}(A)^T \,\mathrm{pows}(A)) \backslash e_{t-1}$.
4. **Yield** $\langle \frac{\sum_j^{[0:t]} H_{j,0} \lambda^j}{(\mathrm{last}_A)_t} \rangle$.

Procedure V:82(4.62)

Objective

Choose a symmetric $m \times m$ rational matrix, A. Let $t = \deg(\mathrm{last}_A)$. Choose a polynomial u such that $\deg(u) < t$. The objective of the following instructions is to show that $\mathrm{tr}(\Lambda(u\,\mathrm{sel}_A, A)) = \frac{u_{t-1}}{(\mathrm{last}_A)_t}$.

Implementation

1. Using procedure V:81, verify that $\mathrm{tr}(\Lambda(u\,\mathrm{sel}_A, A))$
   (a) $= \mathrm{mat}(u)^T \,\mathrm{pows}(A)^T \,\mathrm{pows}(A)\,\mathrm{mat}_t(\mathrm{sel}_A)$
   (b) $= \frac{\mathrm{mat}(u)^T \,\mathrm{pows}(A)^T \,\mathrm{pows}(A)((\mathrm{pows}(A)^T \,\mathrm{pows}(A)) \backslash e_{t-1})}{(\mathrm{last}_A)_t}$
   (c) $= \frac{\mathrm{mat}(u)^T e_{t-1}}{(\mathrm{last}_A)_t}$
   (d) $= \frac{\mathrm{mat}(u)_{t-1,0}}{(\mathrm{last}_A)_t}$
   (e) $= \frac{u_{t-1}}{(\mathrm{last}_A)_t}$.

Procedure V:83(4.63)

Objective

Choose a symmetric $m \times m$ rational matrix, A. The objective of the following instructions is to either show that $0 \neq 0$ or construct polynomials u, v such that $u\,\mathrm{last}_A + v\,\mathrm{sel}_A = 1$.

Implementation

1. Let $t = \deg(\mathrm{last}_A)$.
2. Let G be the 1×2 matrix $\langle\langle \mathrm{last}_A, \mathrm{sel}_A \rangle\rangle$.
3. Execute procedure V:37 on G and let the tuple $\langle M, D, , N \rangle$ receive.
4. Verify that $G = {M^{-1}}_* D {N^{-1}}_*$.
5. Verify that $\mathrm{last}_A \neq 0$.
6. Therefore verify that $D_{0,0} \neq 0$.
7. If $\deg(D_{0,0}) > 0$, then do the following:
   (a) Let $b = {N^{-1}}_{*0,0}$.
   (b) Verify that $\mathrm{last}_A = b D_{0,0}$.
   (c) Therefore verify that $b \neq 0$.
   (d) Let $z = \deg(b)$.
   (e) Verify that $t = \deg(\mathrm{last}_A) = \deg(b D_{0,0}) = \deg(b) + \deg(D_{0,0}) > \deg(b) = z$.

(f) Let $c = N^{-1}{}_{*0,1}$.

(g) Verify that $\mathrm{sel}_A = cD_{0,0}$.

(h) Let $u = \lambda^{t-z-1}b$.

(i) Execute procedure V:82 on A and u.

(j) Hence verify that $(\mathrm{last}_A)_t \operatorname{tr}(\Lambda(u \,\mathrm{sel}_A, A)) = u_{t-1} = b_z \neq 0$.

(k) Also verify that $\operatorname{tr}(\Lambda(u \,\mathrm{sel}_A, A))$

i. $= \operatorname{tr}(\Lambda(\lambda^{t-z-1}bcD_{0,0}, A))$

ii. $= \operatorname{tr}(\Lambda(\lambda^{t-z-1}c \,\mathrm{last}_A, A))$

iii. $= \operatorname{tr}(\Lambda(\lambda^{t-z-1}c, A)\Lambda(\mathrm{last}_A, A))$

iv. $= \operatorname{tr}(\Lambda(\lambda^{t-z-1}c, A)0_{m\times m})$

v. $= \operatorname{tr}(0_{m\times m})$

vi. $= 0$.

(l) **Therefore verify that $0 \neq 0$.**

(m) **Abort procedure.**

8. Otherwise, do the following:

(a) Verify that $\deg(D_{0,0}) = 0$.

(b) Let $u = \frac{N_{0,0}}{D_{0,0}}$.

(c) Let $v = \frac{N_{1,0}}{D_{0,0}}$.

(d) **Verify that $u \,\mathrm{last}_A + v \,\mathrm{sel}_A = 1$.**

(e) **Yield the tuple $\langle u, v\rangle$.**

Procedure V:84(4.64)

Objective

Choose a symmetric $m\times m$ rational matrix A, where $m > 0$. Let $t = \deg(\mathrm{last}_A)$. The objective of the following instructions is to either show that $0 \neq 0$ or to construct lists of polynomials s, q such that

1. For $i = 0$ to $i = t$, $\deg(s_i) = i$.
2. For $i = 0$ to $i = t$, $\operatorname{sgn}((s_i)_i) = \operatorname{sgn}((s_t)_t)$.
3. For $i = 1$ to $i = t-1$, $s_{i-1} + s_{i+1} = q_i s_i$.
4. $s_t = \mathrm{last}_A$.

Implementation

1. Let $s_t = \mathrm{last}_A$.
2. Execute procedure V:83 on A and let $\langle u, s_{t+1}\rangle$ receive the result.
3. Hence verify that $us_t + s_{t+1} \,\mathrm{sel}_A = 1$.
4. Let $q_t = s_{t+1} \operatorname{div} s_t$.
5. Let $s_{t-1} = s_{t+1} \bmod s_t$.
6. Verify that $s_{t+1} = q_t s_t + s_{t-1}$, where $\deg(s_{t-1}) < \deg(s_t) = t$.
7. Therefore verify that $us_t + (q_t s_t + s_{t-1}) \,\mathrm{sel}_A = 1$.
8. Therefore verify that $\Lambda(s_{t-1} \,\mathrm{sel}_A, A) = \Lambda(us_t + (q_t s_t + s_{t-1}) \,\mathrm{sel}_A, A) = \Lambda(1, A) = 1_m$.
9. Therefore using procedure V:82, verify that $\frac{(s_{t-1})_{t-1}}{(s_t)_t} = \operatorname{tr}(\Lambda(s_{t-1} \,\mathrm{sel}_A, A) = \operatorname{tr}(1_m) = m > 0$.
10. For $i \in [t : 1]$, do the following:

(a) Let $q_i = (-s_{i+1}) \operatorname{div}(-s_i)$.

(b) Let $s_{i-1} = (-s_{i+1}) \bmod (-s_i)$.

(c) Verify that $\deg(q_i) = 1$.

(d) Verify that $(q_i)_1 = \frac{(s_{i+1})_{i+1}}{(s_i)_i}$.

(e) Also verify that $-s_{i+1} = -q_i s_i + s_{i-1}$.

(f) Therefore verify that $q_i s_i = s_{i+1} + s_{i-1}$.

(g) Therefore verify that $q_i s_i - s_{i+1} = s_{i-1}$.

(h) Execute procedure II:125 on the tuple $\langle s, q, i-1\rangle$ and let $\langle p, j\rangle$ receive.

(i) Verify that $s_{i-1} = ps_{t-1} + js_t$.

(j) Verify that $\deg(p) = t - 1 - (i - 1) = t - i$.

(k) Verify that $\deg(j) = t - 2 - (i - 1) = t - 1 - i$

(l) Therefore verify that $\Lambda(s_{i-1}, A) = \Lambda(ps_{t-1} + js_t, A) = \Lambda(ps_{t-1}, A) + \Lambda(j, A)\Lambda(s_t, A) = \Lambda(ps_{t-1}, A) + \Lambda(j, A)0_{m\times m} = \Lambda(ps_{t-1}, A)$.

(m) If $\Lambda(p, A) = 0$, then do the following:

i. Execute procedure V:74 on A and p.

ii. **Abort procedure.**

(n) Otherwise, if $\Lambda(s_{i-1}, A) = 0_{m\times m}$, then do the following:

i. Verify that $\Lambda(ps_{t-1} \,\mathrm{sel}_A, A) = \Lambda(ps_{t-1}, A)\Lambda(\mathrm{sel}_A, A) = \Lambda(s_{i-1}, A)\Lambda(\mathrm{sel}_A, A) = 0_{m\times m}\Lambda(\mathrm{sel}_A, A) = 0_{m\times m}$.

ii. Verify that $\Lambda(ps_{t-1}\,\mathrm{sel}_A, A) = \Lambda(p, A)\Lambda(s_{t-1}\,\mathrm{sel}_A, A) = \Lambda(p, A)1_m = \Lambda(p, A) \neq 0_{m\times m}$.

iii. Therefore verify that $0 \neq 0$.

iv. **Abort procedure.**

(o) Otherwise if $\Lambda(s_{i-1}\,\mathrm{sel}_A, A) = 0_{m\times m}$, then do the following:

i. Verify that $\Lambda(s_{i-1}\,\mathrm{sel}_A\, s_{t-1}, A) = \Lambda(s_{i-1}\,\mathrm{sel}_A, A)\Lambda(s_{t-1}, A) = 0_{m\times m}\Lambda(s_{t-1}, A) = 0_{m\times m}$.

ii. Verify that $\Lambda(s_{i-1}\,\mathrm{sel}_A\, s_{t-1}, A) = \Lambda(s_{i-1}, A)\Lambda(\mathrm{sel}_A\, s_{t-1}, A) = \Lambda(s_{i-1}, A)1_m = \Lambda(s_{i-1}, A) \neq 0_{m\times m}$.

iii. Therefore verify that $0_{m\times m} \neq 0_{m\times m}$.

iv. **Abort procedure.**

(p) Otherwise, do the following:

i. Verify that $\deg(s_{i-1}) < i$.

ii. Verify that $\Lambda(s_{i-1}\,\mathrm{sel}_A, A) \neq 0_{m\times m}$.

iii. Execute the subprocedure V:85:0 on the tuple $(i-1, s_{i-1})$.

iv. Hence using procedure V:80, verify that $\frac{(s_{i-1})_{i-1}}{(s_i)_i} = \mathrm{tr}(\Lambda({s_{i-1}}^2{\mathrm{sel}_A}^2, A)) = \mathrm{tr}((\Lambda(s_{i-1}\,\mathrm{sel}_A, A))^2) = \mathrm{tr}((\Lambda(s_{i-1}\,\mathrm{sel}_A, A))^T(\Lambda(s_{i-1}\,\mathrm{sel}_A, A))) > 0$.

v. **Therefore verify that** $\mathrm{sgn}((s_{i-1})_{i-1}) = \mathrm{sgn}((s_i)_i)$**.**

11. Yield the tuple $\langle s_{[0:t+1]}, q_{[0:t]}\rangle$.

Subprocedure V:85:0

Objective Choose an integer $0 \leq k \leq t$ such that polynomial s_k is defined. Choose a polynomial g such that $\deg(g) \leq \min(k, t-1)$. The objective of the following instructions is to show that $\mathrm{tr}(\Lambda(gs_k{\mathrm{sel}_A}^2, A)) = \frac{g_k}{(s_{k+1})_{k+1}}$.

Implementation

1. If $k = t$, then verify that $\mathrm{tr}(\Lambda(gs_k{\mathrm{sel}_A}^2, A))$

(a) $= \mathrm{tr}(\Lambda(gs_t{\mathrm{sel}_A}^2, A))$

(b) $= \mathrm{tr}(\Lambda(g{\mathrm{sel}_A}^2, A)\Lambda(s_t, A))$

(c) $= \mathrm{tr}(\Lambda(g{\mathrm{sel}_A}^2, A)0_{m\times m})$

(d) $= 0$

(e) $= \frac{g_k}{(s_{k+1})_{k+1}}$.

2. Otherwise if $k = t-1$, then verify that $\mathrm{tr}(\Lambda(gs_k{\mathrm{sel}_A}^2, A))$

(a) $= \mathrm{tr}(\Lambda(gs_{t-1}{\mathrm{sel}_A}^2, A))$

(b) $= \mathrm{tr}(\Lambda(g\mathrm{sel}_A, A)\Lambda(s_{t-1}\mathrm{sel}_A, A))$

(c) $= \mathrm{tr}(\Lambda(g\,\mathrm{sel}_A, A)1_m)$

(d) $= \mathrm{tr}(\Lambda(g\,\mathrm{sel}_A, A))$

(e) $= \frac{g_k}{(s_{k+1})_{k+1}}$.

3. Otherwise if $k < t-1$, then do the following:

(a) Verify that $\deg(gq_{k+1}) = k+1 \leq t-1$.

(b) Execute the subprocedure V:85:0 on the tuple $\langle k+1, gq_{k+1}\rangle$.

(c) Now verify that $\mathrm{tr}(\Lambda((gq_{k+1})s_{k+1}{\mathrm{sel}_A}^2, A)) = \frac{\frac{(s_{k+2})_{k+2}}{(s_{k+1})_{k+1}}g_k}{(s_{k+2})_{k+2}} = \frac{g_k}{(s_{k+1})_{k+1}}$.

(d) Verify that $\deg(g) \leq k \leq t-2$.

(e) Execute the subprocedure V:85:0 on the tuple $\langle k+2, g\rangle$.

(f) Now verify that $\mathrm{tr}(\Lambda(gs_{k+2}{\mathrm{sel}_A}^2, A)) = \frac{g_{k+2}}{(s_{k+3})_{k+3}} = \frac{0}{(s_{k+3})_{k+3}} = 0$.

(g) Therefore verify that $\mathrm{tr}(\Lambda(gs_k{\mathrm{sel}_A}^2, A))$

i. $= \mathrm{tr}(\Lambda(g(q_{k+1}s_{k+1} + s_{k+2}){\mathrm{sel}_A}^2, A))$

ii. $= \mathrm{tr}(\Lambda(gq_{k+1}s_{k+1}{\mathrm{sel}_A}^2 + gs_{k+2}{\mathrm{sel}_A}^2, A))$

iii. $= \mathrm{tr}(\Lambda(gq_{k+1}s_{k+1}{\mathrm{sel}_A}^2, A) + \Lambda(gs_{k+2}{\mathrm{sel}_A}^2, A))$

iv. $= \mathrm{tr}(\Lambda(gq_{k+1}s_{k+1}{\mathrm{sel}_A}^2, A)) + \mathrm{tr}(\Lambda(gs_{k+2}{\mathrm{sel}_A}^2, A))$

v. $= \frac{g_k}{(s_{k+1})_{k+1}} + 0$

vi. $= \frac{g_k}{(s_{k+1})_{k+1}}$.

Procedure V:85(4.65)

Objective

Choose a symmetric $m \times m$ rational matrix, A. Let $t = \deg(\mathrm{last}_A)$. The objective of the following instructions is to either show that $0 < 0$ or to construct two lists of rational numbers c, d such that $c_0 < d_0 \leq c_1 < d_1 \leq \cdots \leq c_{t-1} < d_{t-1}$ and $0 \neq \mathrm{sgn}(\Lambda(\mathrm{last}_A, c_i)) = -\mathrm{sgn}(\Lambda(\mathrm{last}_A, d_i))$ for i in $[0:t]$.

Implementation

1. Execute procedure V:84 on the matrix A and let the tuple $\langle s, q\rangle$ receive the result.
2. Execute procedure II:124 supplying the tuple $\langle s, q\rangle$. Let the tuple $\langle c, d\rangle$ receive the result.
3. **Verify that** $c_0 < d_0 \leq c_1 < d_1 \leq \cdots \leq c_{t-1} < d_{t-1}$**.**
4. **Verify that** $\operatorname{sgn}(\Lambda(\text{last}_A, c_i)) = -\operatorname{sgn}(\Lambda(\text{last}_A, d_i))$ **for** i **in** $[0 : t]$**.**
5. **Yield** $\langle c, d\rangle$**.**

Procedure V:86(4.66)

Objective

Choose a symmetric $m \times m$ rational matrix, A. Let $t = \deg(\text{last}_A)$. Execute procedure V:85 on A and let the tuple $\langle c, d\rangle$ receive the result. Execute procedure V:37 on A and let the tuple $\langle , , u, \rangle$ receive the result. The objective of the following instructions is to either show that $1 = -1$ or to construct a list of non-negative integers k such that $0 \neq \operatorname{sgn}(\Lambda(u_{k_i}, c_i)) = -\operatorname{sgn}(\Lambda(u_{k_i}, d_i))$ for i in $[0 : t]$.

Implementation

1. Verify that $\text{last}_A = u_0 u_1 \cdots u_{m-1}$.
2. For i in $[0 : t]$, do the following:
   (a) Using the precondition, verify that $0 \neq \operatorname{sgn}(\Lambda(\text{last}_A, c_i)) = -\operatorname{sgn}(\Lambda(\text{last}_A, d_i))$.
   (b) If $0 \in \operatorname{sgn}(\Lambda(u, c_i))$, then do the following:
      i. Verify that 0
         A. $= \operatorname{sgn}(\Lambda(u_0, c_i)) \operatorname{sgn}(\Lambda(u_1, c_i)) \cdots \operatorname{sgn}(\Lambda(u_{m-1}, c_i))$
         B. $= \operatorname{sgn}(\Lambda(u_0, c_i)\Lambda(u_1, c_i) \cdots \Lambda(u_{m-1}, c_i))$
         C. $= \operatorname{sgn}(\Lambda(u_0 u_1 \cdots u_{m-1}, c_i))$
         D. $= \operatorname{sgn}(\Lambda(\text{last}_A, c_i))$
         E. $\neq 0$.
   (c) If $0 \in \operatorname{sgn}(\Lambda(u, d_i))$, then do the following:
      i. Verify that 0
         A. $= \operatorname{sgn}(\Lambda(u_0, d_i)) \operatorname{sgn}(\Lambda(u_1, d_i)) \cdots \operatorname{sgn}(\Lambda(u_{m-1}, d_i))$
         B. $= \operatorname{sgn}(\Lambda(u_0, d_i)\Lambda(u_1, d_i) \cdots \Lambda(u_{m-1}, d_i))$
         C. $= \operatorname{sgn}(\Lambda(u_0 u_1 \cdots u_{m-1}, d_i))$
         D. $= \operatorname{sgn}(\Lambda(\text{last}_A, d_i))$
         E. $\neq 0$.
   (d) If $\operatorname{sgn}(\Lambda(u_j, c_i)) = \operatorname{sgn}(\Lambda(u_j, d_i))$ for $j \in [0 : m]$, then do the following:
      i. Verify that $\operatorname{sgn}(\Lambda(\text{last}_A, c_i))$
         A. $= \operatorname{sgn}(\Lambda(u_0 u_1 \cdots u_{m-1}, c_i))$
         B. $= \operatorname{sgn}(\Lambda(u_0, c_i)) \operatorname{sgn}(\Lambda(u_1, c_i)) \cdots \operatorname{sgn}(\Lambda(u_{m-1}, c_i))$
         C. $= \operatorname{sgn}(\Lambda(u_0, d_i)) \operatorname{sgn}(\Lambda(u_1, d_i)) \cdots \operatorname{sgn}(\Lambda(u_{m-1}, d_i))$
         D. $= \operatorname{sgn}(\Lambda(u_0 u_1 \cdots u_{m-1}, d_i))$
         E. $= \operatorname{sgn}(\Lambda(\text{last}_A, d_i))$.
      ii. **Therefore verify that** $1 = -1$**.**
      iii. **Abort procedure.**
   (e) Otherwise do the following:
      i. **Let** k_i **be the least integer such that** $0 \neq \operatorname{sgn}(\Lambda(u_{k_i}, c_i)) = -\operatorname{sgn}(\Lambda(u_{k_i}, d_i))$**.**
3. **Yield** $\langle k\rangle$**.**

Procedure V:87(4.67)

Objective

Choose a symmetric $m \times m$ rational matrix, A. Execute procedure V:37 on A and let the tuple $\langle , , u, \rangle$ receive the result. Execute procedure II:112 on A and let k receive. Let $t = \deg(\text{last}_A)$. Let $n_j = \sum_i^{[0:t]} [k_i = j]$ for j in $[0 : m]$. The objective of the following instructions is to either show that $0 < 0$, or to show that $n_i = \deg(u_i)$ for i in $[0 : m]$.

Implementation

1. Verify that $\sum_j^{[0:m]} n_j = \sum_j^{[0:m]} \sum_i^{[0:t]} [k_i = j] = \sum_i^{[0:t]} \sum_j^{[0:m]} [k_i = j] = \sum_i^{[0:t]} 1 = t$.
2. If for any i in $[0 : m]$, $n_i > \deg(u_i)$, then do the following:
   (a) Execute procedure II:112 on the polynomial u_i along with $\deg(u_i)+1$ of the distinct pairs $\langle c_l, d_l\rangle$ such that $k_l = i$.

(b) **Abort procedure.**

3. Otherwise if for any i in $[0:m]$, $n_i < \deg(u_i)$, then do the following:

(a) Verify that $\sum_i^{[0:m]} n_j < \sum_i^{[0:m]} \deg(u_j) = t$.

(b) Therefore using (1) and (a), verify that $\sum_i^{[0:m]} n_j < \sum_i^{[0:m]} n_j$.

(c) **Abort procedure.**

4. Otherwise, do the following:

(a) **For all** i **in** $[0:m]$**, verify that** $n_i = \deg(u_i)$**.**

Procedure V:88(4.72)

Objective

Choose a symmetric $m \times m$ rational matrix, A. Let $t = \deg(\mathrm{last}_A)$. Execute procedure V:86 on the matrix A and let the tuple $\langle k \rangle$ receive the result. The objective of the following instructions is to either show that $0 < 0$ or to show that $\sum_i^{[0:t]}(m - k_i) = m$.

Implementation

1. Execute procedure V:37 on the matrix A and let the tuple $\langle, D, u, \rangle$.

2. Using procedure V:87, verify that $\sum_i^{[0:t]}(m - k_i)$

(a) $= \sum_i^{[0:t]} \sum_j^{[0:m]} [k_i \leq j]$

(b) $= \sum_j^{[0:m]} \sum_i^{[0:t]} [k_i \leq j]$

(c) $= \sum_j^{[0:m]} \sum_i^{[0:t]} [k_i \leq j] \sum_l^{[0:m]} [k_i = l]$

(d) $= \sum_j^{[0:m]} \sum_l^{[0:m]} \sum_i^{[0:t]} [k_i \leq j][k_i = l]$

(e) $= \sum_j^{[0:m]} \sum_l^{[0:m]} \sum_i^{[0:t]} [l \leq j][k_i = l]$

(f) $= \sum_j^{[0:m]} \sum_l^{[0:m]} [l \leq j] \sum_i^{[0:t]} [k_i = l]$

(g) $= \sum_j^{[0:m]} \sum_l^{[0:m]} [l \leq j] \deg u_l$

(h) $= \sum_j^{[0:m]} \sum_l^{[0:j+1]} \deg u_l$

(i) $= \sum_j^{[0:m]} \deg D_{j,j}$

(j) $= m$

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