

Logic and linear algebra: an introduction

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Abstract

We give an introduction to computation and logic tailored for algebraists, and use this as a springboard to discuss geometric models of computation and the role of cut-elimination in these models, following Girard’s geometry of interaction program. We discuss how to represent programs in the λ -calculus and proofs in linear logic as linear maps between infinite-dimensional vector spaces. The interesting part of this vector space semantics is based on the cofree cocommutative coalgebra of Sweedler [71] and the recent explicit computations of liftings in [62].

1 Introduction

In mathematical logic the objects of study are *proofs*, just as manifolds, knots or representations are the objects in other disciplines of mathematics. No mathematician needs to be told that a proof may be a complicated object, but it may come as a surprise that some of the techniques invented by logicians to study proofs are closely related to constructions in modern algebra, such as symmetric monoidal categories and functors between them. More specifically, in Girard’s *linear logic* [36] a proof determines a topological object called a proof-net which is similar to a bordism or a string diagram, and the semantics of linear logic [59] can be understood in terms of functors from a symmetric monoidal category of proofs to other monoidal categories, including the category of vector spaces.

This invites a comparison to subjects like topological field theory [6, 76] but while an algebraist encountering the semantics of linear logic will find much that is familiar, there is also much that is strange – and therefore interesting. Here is a puzzle that demonstrates what we mean: for a ring A what is the “kernel” that represents the operation

$$M \longmapsto M \otimes_A M \tag{1.1}$$

on A - A -bimodules M ? Since this assignment is not functorial in M it cannot be represented by tensoring with a bimodule. Nonetheless there *is* a good notion of such non-linear “kernels” – called *programs* – and these objects have been studied by logicians and computer scientists for decades; for example, the operation in (1.1) is an incarnation of the Church numeral $\underline{2}$ in the λ -calculus, as we will explain.

Our aim in this note is to give an opinionated introduction to linear logic, highlighting two aspects that we think are of particular interest for algebraists. We hope that this will help provide some background and motivation for the author’s recent paper [61] which is part of an ongoing project to categorify parts of linear logic using isolated hypersurface singularities and matrix factorisations. Most of what we have to say is well-known, with the exception of some aspects of the vector space semantics in Section 3.1. There are obviously many aspects of logic and its connections with other subjects that we cannot cover: for a well-written account of analogies between logic, topology and physics we recommend the survey of Baez and Stay [7], and for recent work on logic and homotopy theory see [74].

The first aspect of logic that we choose for special emphasis is the relationship between *duplication* and *non-linearity*. The string diagrams representing proofs in linear logic are complex, because the interpretation of a non-trivial proof requires more than a symmetric monoidal category: there must be a touch of the non-linear. In linear logic this enters via the exponential modality, which corresponds in the vector space semantics to forming from a vector space V the universal cocommutative coalgebra $!V$, whose coproduct is the universal way of duplicating elements of V . We explain the link between duplication and non-linearity in terms of the embedding of a prototypical programming language called the λ -calculus into linear logic. Through this embedding we will see how the exponential modality is the aspect of logic responsible for the capability of programs to use their inputs more than once. This reuse – which is demonstrated in the “program” (1.1) which uses the input bimodule M twice – is a form of non-linearity, which is moreover the source of all the interesting complexity of non-trivial programs.¹

The second particularly interesting aspect of logic is *cut-elimination*. This is a fundamental feature of logic going back to Gentzen [34] which may be described (superficially) as the answer to the following question: given two composable functions f, g given by algorithms, what is the simplest form of the algorithm computing $g \circ f$? This is linked to deep questions about the nature of computation, as elucidated by Girard [41]. Beyond giving an introduction to logic and computation, our main goal in this note is to sketch in Section 5 how geometric models of computation such as the one in [61] are beginning to reveal a connection between cut-elimination and basic questions in algebraic geometry and topological field theory. So far this natural point of contact between geometry and logic is almost completely unexplored.

The outline of the article is as follows: in Section 2 we introduce the λ -calculus, intuitionistic logic and linear logic, with an emphasis on the role of duplication. In Section 3 we assign to every proof in intuitionistic linear logic a string diagram and corresponding

¹It might seem odd that the first aspect of linear logic that we choose to emphasise is non-linearity. But the point of linear logic is not that everything is linear. Classical logic is a mix of linear and non-linear components, and the insight of Girard with linear logic is that it is possible to create a refinement where there is an explicit boundary between these two worlds, and there are special language features – such as the exponential modality – to manage transitions across this boundary.

linear map, and give a detailed example. In Section 4 we turn to cut-elimination, examining a mildly non-trivial example in detail. In the last section of the main text, Section 5, we use the foregoing to inform a discussion of Girard’s geometry of interaction and geometric models of computation. There are two appendices. In Appendix A we compute an example of the cut-elimination process, and in Appendix B we examine tangent maps in connection with proofs in linear logic.

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Throughout k is an algebraically closed field of characteristic zero.

2 Logic

In this brief introduction to logic we explain what a program is in the λ -calculus, in what sense proofs can be thought of as programs, and how a careful study of duplication in the λ -calculus and logic leads to the refinement by Girard in linear logic. We also introduce our basic example, the Church numeral $\underline{2}$, which in one form or another will occupy our attention for this entire note. For more details see [44, 59] or, for the reader with a lunch break to spare [66].

2.1 The λ -calculus

The theoretical underpinning of programming languages like Lisp [56] is the λ -calculus of Church [24, 68] which captures in a precise mathematical form the concepts of *variables* and *substitution*. The λ -calculus is determined by its terms and a rewrite rule on those terms. The terms are to be thought of as programs, and the rewrite rule as the method of execution of programs. A *term* in the λ -calculus is either one of a countable number of variables x_0, x_1, x_2, \dots or an expression of the type

$$(M\ N) \quad \text{or} \quad (\lambda x. M) \tag{2.1}$$

where M, N are terms and x is any variable. The terms of the first type are called *function applications* while those of the second type are called *lambda abstractions*. The rewrite rule, called β -reduction, is generated by the following basic rewrite rule

$$((\lambda x. M)\ N) \longrightarrow_{\beta} M[N/x] \tag{2.2}$$

where M, N are terms, x is a variable, and $M[N/x]$ denotes the term M with all free occurrences of x replaced by N .² This rewrite rule generates an equivalence relation on terms called β -equivalence which we will write as $M =_{\beta} N$ [68, §2.5].

²There is a slight subtlety here since we may have to rename variables in order to avoid free variables in N being “captured” as a result of this substitution, see [68, §2.3].

We think of the lambda abstraction $(\lambda x. M)$ as a program with *input* x and *body* M , so that the β -reduction step in (2.2) has the interpretation of our program being fed the input term N which is subsequently bound to x throughout M . A term is *normal* if there are no sub-terms of the type on the left hand side of (2.2). In the λ -calculus *computation* occurs when two terms are coupled by a function application in such a way as to create a term which is not in normal form: then (possibly numerous) β -reductions are performed until a normal form (the output) is reached.³

An important example is the following program⁴

$$T := (\lambda y. (\lambda x. (y (y x)))) .$$

We can understand the “meaning” of this term by seeing what happens under β -reduction when we pair it with other terms. For a term M , we have:

$$(T M) = ((\lambda y. (\lambda x. (y (y x)))) M) \longrightarrow_{\beta} (\lambda x. (M (M x))) . \quad (2.3)$$

We see that the result of feeding M to T is itself a program which takes a single input x and returns the result of computing $(M (M x))$. Let’s see what happens when we feed this resulting program some other input N

$$((T M) N) \longrightarrow_{\beta} ((\lambda x. (M (M x))) N) \longrightarrow_{\beta} (M (M N)) .$$

This calculation shows how $(T M)$ behaves like M^2 , in the sense that on an input N it returns M applied twice to N . Obviously we can modify T by nesting more than two function applications, and in this way one defines for each integer $n \geq 0$ a term \underline{n} called the *n th Church numeral* [68, §3.2]. This program has the property that $(\underline{n} M)$ behaves like M^n and in particular T is the Church numeral $\underline{2}$.

To put this into a broader context: once the integers have been translated into terms in the λ -calculus it makes sense to say that a program F *computes* a function $f : \mathbb{N} \longrightarrow \mathbb{N}$ if for each $n \geq 0$ we have $(F \underline{n}) =_{\beta} f(n)$. A function f is called *computable* if there is a term F in the λ -calculus with this property.

So far we have considered programs only in the *untyped* λ -calculus. The reader familiar with programming will know that functions in commonly used programming languages are typed: for instance, a function computing the n th Fibonacci number in C takes an input of type “int” – the integer n – and returns an output also of type “int”. In the *simply-typed* λ -calculus the Church numeral $\underline{2}$ is the same as before, but with type annotations

$$T_{typed} := (\lambda y^{A \rightarrow A}. (\lambda x^A. (y (y x)))) .$$

³Not every λ -term may be reduced to a normal form by β -reduction because this process does not necessarily terminate. However if it does terminate then the resulting reduced term is canonically associated to the original term; this is the content of Church-Rosser theorem [68, §4.2].

⁴In fact we deal throughout with terms up to an equivalence relation called α -conversion, which ensures that variable names are not important. For example, T is equivalent to $(\lambda z. (\lambda t. (z (z t))))$

These annotations indicate that the first input y is restricted to be of the type of a function from A to A (that is, of type $A \rightarrow A$) while x is restricted to be of type A . Overall T_{typed} takes a term of type $A \rightarrow A$ and returns another term of the same type, so it is a term of type $(A \rightarrow A) \rightarrow (A \rightarrow A)$. For a more complete discussion see [68, §6].

We have now defined the λ -calculus and introduced our basic example of a program, the Church numeral $\underline{2}$. Moreover, we have seen that it is natural to think about the “meaning” of programs as *functions* on equivalence classes of terms: for example, if D is the set of β -equivalence classes of terms of type $A \rightarrow A$ then there is a function

$$D \longrightarrow D, \quad [M] \mapsto [(T_{typed} M)]$$

where $[-]$ denotes β -equivalence classes. This function contains a great deal of information about the term T_{typed} , but this information is not very accessible in light of the fact that we have little handle on the set D . This situation may be compared to the problem of trying to understand a complicated group, and may be approached in the same way: by studying *representations* of programs in the λ -calculus as transformations on mathematical objects. This is referred to as *denotational semantics*, and was initiated as a field by Scott [65] who found a representation of the λ -calculus as continuous maps of certain lattices.

This motivates the following question, which we will keep in mind during the subsequent discussion of linear logic:

Question 2.1. Is there a natural representation of programs in the simply-typed λ -calculus, for example T_{typed} , as linear maps between vector spaces?

Here by a “natural” representation we have in mind something more interesting than linear maps between free vector spaces on sets like D . The obstruction to realising this aim is clear: it would be natural to associate to T_{typed} the map $\alpha \mapsto \alpha^2$ on endomorphisms of some vector space V , but this is not linear. This non-linearity can be traced to the duplication of terms that takes place during β -reduction. To see this, notice how in (2.3) a single occurrence of M on the left becomes a pair of M ’s on the right, so that during the substitution process the term M is duplicated. This duplication is not linear, at least not in any naive sense, because in general there is no linear map

$$\text{End}_k(V) \longrightarrow \text{End}_k(V) \otimes \text{End}_k(V) \tag{2.4}$$

sending α to $\alpha \otimes \alpha$ for all α , where $\text{End}_k(V)$ denotes the space of linear maps $V \longrightarrow V$. One way to represent T_{typed} as a linear map is to replace $\text{End}_k(V)$ by the universal vector space over it which *is* equipped with a duplication map satisfying some natural axioms; this is the universal cocommutative coalgebra $!\text{End}_k(V)$. Using this coalgebra we may associate to T_{typed} a linear map from which the non-linear map $\alpha \mapsto \alpha^2$ may be recovered; see Example 2.4 below and Lemma 3.7.

But we are getting ahead of ourselves. The first step is to reformulate the λ -calculus in terms of classical logic, then we identify the part of the logic that is responsible for this duplication – called the contraction rule – and explain how the contraction rule is refined in linear logic in such a way as to lead naturally to the coalgebra $!\text{End}_k(V)$.

This depiction is often referred to as a *proof tree*. Obviously this is not the only proof of this sequent, for example we could deduce it in two steps from an axiom rule $A \Rightarrow A \vdash A \Rightarrow A$ followed by the same final step as in (2.5). Usually a sequent has many proofs.

If γ denotes the proof (2.5) taken up to its penultimate step and τ denotes some proof of a sequent $\Gamma \vdash A \Rightarrow A$ then using an instantiation of the cut rule we may generate a new proof of $\Gamma \vdash A \Rightarrow A$ given by the proof tree

$$\begin{array}{c}
 \tau \qquad \qquad \gamma \\
 \vdots \qquad \qquad \vdots \\
 \hline
 \Gamma \vdash A \Rightarrow A \quad A \Rightarrow A \vdash A \Rightarrow A \quad \text{cut} \\
 \hline
 \Gamma \vdash A \Rightarrow A
 \end{array} \tag{2.6}$$

This yields up an interpretation of (2.5) as a *function* which maps proofs of $\Gamma \vdash A \Rightarrow A$ to other proofs of $\Gamma \vdash A \Rightarrow A$. At this point we notice the similarity between γ and the program T_{typed} which maps input terms of type $A \rightarrow A$ to output terms of type $A \rightarrow A$.

This similarity is an instance of the Curry-Howard isomorphism [68, §6] which matches *types* in the simply-typed λ -calculus (e.g. $A \rightarrow A$) with *formulas* in propositional intuitionistic logic (e.g. $A \Rightarrow A$) and *programs* in the λ -calculus with *proofs* in logic. This correspondence pairs (2.5) and γ with T_{typed} . In light of this equivalence, in the proof γ of $A \Rightarrow A \vdash A \Rightarrow A$ it is natural to view the formula on the left hand side of the turnstile as the “input” and the one on the right hand side as the “output”. The contraction rule is therefore responsible for the duplication of inputs and, moreover, since the contraction rule may be used at any time on any formula to the left of the turnstile, the duplication of inputs is unrestricted.⁶ Although we will not explain the details, by going a little deeper into the content of the Curry-Howard isomorphism one can see how the use of the contraction rule in the penultimate step of (2.5) matches precisely with the duplication of the input term M that takes place in (2.3).

Here we touch on an important point: the feature of logic which corresponds under the Curry-Howard isomorphism to β -reduction in the λ -calculus. The type of a program does not change under β -reduction, so this must be some kind of transformation of proofs of a given sequent. This transformation is called *cut-elimination*. It consists of a collection of transformations on proofs, each of which, when applied to a proof with cuts, generates a new proof of the same sequent with cuts of lower complexity. Gentzen’s main theorem in [34] states that his cut-elimination algorithm produces, in a finite number of steps, a proof without any use of the cut rule at all; such a proof is called *cut-free*. Many important properties of logic such as consistency follow immediately from this fact; for more discussion see [59] and [44, Chapter 13]. We will have more to say about cut-elimination in linear logic in Section 4.

The upshot is that the simply-typed λ -calculus is “the same thing” as propositional intuitionistic logic, and the duplication of terms during substitution in the λ -calculus

⁶The significance of the contraction rule and duplication as the source of infinity in mathematics is beyond the scope of the present note, but see for instance [41, p.78].

matches with applications of the contraction rule in logic. Thus, if we want to represent programs as linear maps, it is sufficient to construct a linear representation of *logic*. Moreover, since we have identified duplication of terms as the main obstacle to linearisation of the λ -calculus, a detailed study of the contraction rule appears to be the key. Indeed, this is the insight of Girard with linear logic.

2.3 Linear logic

The linear logic of Girard [36, 59] is a refinement of classical logic in which the contraction rule is restricted to formulas that are prefixed with a new unary connective $!$ called the exponential modality. A hypothesis $!A$ may be used in a proof infinitely many times as in classical logic, but a bare formula A may only be used once⁷ (the proof is *linear* in A). The other connectives are also refined, for instance \Rightarrow is refined to a linear implication \multimap , with the former being recovered from the latter by the translation $A \Rightarrow B = !A \multimap B$.

We consider propositional intuitionistic linear logic without additives (henceforth referred to simply as *linear logic*). The adjective *intuitionistic* means that the right hand side of a sequent is constrained to have precisely one formula, while *propositional* means that we omit quantifiers.⁸ Linear logic has propositional variables x, y, z, \dots , two binary connectives \multimap (linear implication), \otimes (tensor) and a single unary connective $!$ (the exponential). There is a single constant 1 . Examples of formulas include

$$(x \multimap y) \otimes z, \quad !(x \multimap 1) \multimap y, \quad !!x \otimes !(y \multimap !z), \quad \dots$$

The deduction rules of linear logic are given on the left hand side of the following series of diagrams (2.7) – (2.19). The diagrams on the right should be ignored until Section 3. In all deduction rules, the sets Γ and Δ may be *empty* and, in particular, the promotion rule may be used with an empty premise. In the promotion rule, $!\Gamma$ stands for a list of formulas each of which is preceded by an exponential modality, for example $!A_1, \dots, !A_n$.

$$\text{(Axiom): } \frac{}{A \vdash A} \qquad \begin{array}{c} A \\ | \\ A \end{array} \qquad (2.7)$$

⁷To an algebraist, this may sound as strange as an admonition to only use Nakayama's lemma once a day. After all, isn't the truth endlessly reusable? In reply, we would ask the reader to consider again the interpretation of the proof γ in (2.6) as a function mapping input proofs to output proofs. The act of computing these outputs is a physical process, whether it takes place in a machine or a human mind, and it involves the allocation and deallocation of finite resources. The insight of Girard with linear logic is that far from being implementation or engineering details, these acts of allocation and deallocation are in fact logical, and of fundamental importance.

⁸The additives may be included in the obvious way, we omit them simply because our examples do not involve them. At the moment we do not understand quantifiers.

(Exchange): $\frac{\Gamma, A, B, \Delta \vdash C}{\Gamma, B, A, \Delta \vdash C}$

(2.8)

(Cut): $\frac{\Gamma \vdash A \quad A, \Delta \vdash B}{\Gamma, \Delta \vdash B} \text{ cut}$

(2.9)

(Right \otimes): $\frac{\Gamma \vdash A \quad \Delta \vdash B}{\Gamma, \Delta \vdash A \otimes B} \otimes\text{-}R$

(2.10)

(Left \otimes): $\frac{\Gamma, A, B \vdash C}{\Gamma, A \otimes B \vdash C} \otimes\text{-}L$

(2.11)

(Right \multimap): $\frac{A, \Gamma \vdash B}{\Gamma \vdash A \multimap B} \multimap_R$

(2.12)

(Left \multimap): $\frac{\Gamma \vdash A \quad B, \Delta \vdash C}{\Gamma, A \multimap B, \Delta \vdash C} \multimap_L$

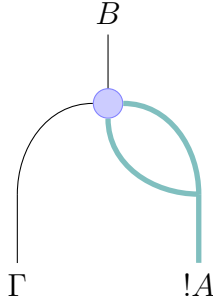
(2.13)

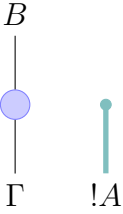
(Promotion): $\frac{! \Gamma \vdash A}{! \Gamma \vdash !A} \text{prom}$

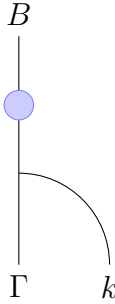
(2.14)

(Dereliction): $\frac{\Gamma, A \vdash B}{\Gamma, !A \vdash B} \text{der}$

(2.15)

$$(\text{Contraction}): \frac{\Gamma, !A, !A \vdash B}{\Gamma, !A \vdash B} \text{ctr} \quad (2.16)$$


$$(\text{Weakening}): \frac{\Gamma \vdash B}{\Gamma, !A \vdash B} \text{weak} \quad (2.17)$$


$$(\text{Left } 1): \frac{\Gamma \vdash A}{\Gamma, 1 \vdash A} 1-L \quad (2.18)$$


$$(\text{Right } 1): \frac{}{\vdash 1} 1-R \quad (2.19)$$


For the examples in this paper, the relevant deduction rules are the axiom rule, the cut rule, the right and left \multimap introduction rules, the contraction rule and the promotion and dereliction rules. With the exception of the last two, the others have the same form as the rules in classical logic, except with \multimap instead of \Rightarrow and with the contraction rule restricted to formulas $!A$. For more on classical versus linear logic, see Remark 2.5.

It is standard practice to use the words *formula* and *type* interchangeably in systems like linear logic, and this is especially convenient when a formula denotes a “data type” like integers or lists, as in the following example.

Example 2.2. For any type A the type of *integers on* A is

$$\mathbf{int}_A = !(A \multimap A) \multimap (A \multimap A). \quad (2.20)$$

The proof of the linear logic version of the Church numeral $\underline{2}$ is

$$\begin{array}{c}
\frac{}{A \vdash A} \quad \frac{}{A \vdash A} \\
\frac{}{A \vdash A} \quad \frac{}{A, A \multimap A \vdash A} \multimap L \\
\frac{}{A, A \multimap A, A \multimap A \vdash A} \multimap L \\
\frac{}{A \multimap A, A \multimap A \vdash A \multimap A} \multimap R \\
\frac{}{!(A \multimap A), !(A \multimap A), \vdash A \multimap A} \text{der} \\
\frac{}{!(A \multimap A) \vdash A \multimap A} \text{ctr} \\
\frac{}{\vdash \mathbf{int}_A} \multimap R
\end{array} \quad (2.21)$$

A doubled horizontal line stands for repeated applications of a deduction rule (in this case, dereliction is applied twice). Although the proof obviously has a structure similar to (2.5) notice that there is a conversion between $A \multimap A$ and its infinite version $!(A \multimap A)$, where the duplication occurs. For each integer $n \geq 0$ there is a proof \underline{n} of \mathbf{int}_A constructed along similar lines, see [36, §5.3.2] and [25, §3.1].

A *categorical semantics* of linear logic [59, 18] assigns to each type A an object $\llbracket A \rrbracket$ of some category and to each proof of $\Gamma \vdash A$ a morphism $\llbracket \Gamma \rrbracket \longrightarrow \llbracket A \rrbracket$ in such a way that two proofs equivalent under cut-elimination are assigned the same morphism; these objects and morphisms are called *denotations*. The connectives of linear logic become structure on the category of denotations, and compatibility with cut-elimination imposes identities relating these structures to one another. The upshot is that to define a categorical semantics the category of denotations must be a closed symmetric monoidal category equipped with a comonad, which is used to model the exponential modality [59, §7]. This is a refinement of the equivalence between simply-typed λ -calculus and cartesian closed categories due to Lambek and Scott [54]. The first semantics of linear logic were the coherence spaces of Girard [36, §3] which are a refined form of Scott’s model of the λ -calculus. Models of full linear logic with negation involve the \star -autonomous categories of Barr [9, 10, 11] and the extension to include quantifiers involves indexed monoidal categories [67].

Definition 2.3. The *denotation* $\llbracket A \rrbracket$ of a type A is defined inductively as follows:

- $\llbracket 1 \rrbracket = k$;
- $\llbracket A \otimes B \rrbracket = \llbracket A \rrbracket \otimes \llbracket B \rrbracket$;
- $\llbracket A \multimap B \rrbracket = \llbracket A \rrbracket \multimap \llbracket B \rrbracket$ which is notation for $\text{Hom}_k(\llbracket A \rrbracket, \llbracket B \rrbracket)$;
- $\llbracket !A \rrbracket = !\llbracket A \rrbracket$.

The denotation of a group of formulas $\Gamma = A_1, \dots, A_n$ is their tensor product

$$\llbracket \Gamma \rrbracket = \llbracket A_1 \rrbracket \otimes \dots \otimes \llbracket A_n \rrbracket.$$

If Γ is empty then $\llbracket \Gamma \rrbracket = k$.

We continue with the Church numeral $\underline{2}$ as our motivating example:

Example 2.4. Let A be a type whose denotation is $V = \llbracket A \rrbracket$. Then from (2.20),

$$\llbracket \mathbf{int}_A \rrbracket = \llbracket !(A \multimap A) \multimap (A \multimap A) \rrbracket = \text{Hom}_k(!\text{End}_k(V), \text{End}_k(V)).$$

Skipping ahead a little, the denotation of the proof $\underline{2}$ of $\vdash \mathbf{int}_A$ will be a morphism

$$\llbracket \underline{2} \rrbracket : k \longrightarrow \llbracket \mathbf{int}_A \rrbracket = \text{Hom}_k(!\text{End}_k(V), \text{End}_k(V)), \quad (2.22)$$

or equivalently, a linear map $!\text{End}_k(V) \longrightarrow \text{End}_k(V)$. What is this linear map? It turns out (see Example 3.5 below for details) that it is the composite

$$!\text{End}_k(V) \xrightarrow{\Delta} !\text{End}_k(V) \otimes !\text{End}_k(V) \xrightarrow{d \otimes d} \text{End}_k(V)^{\otimes 2} \xrightarrow{- \circ -} \text{End}_k(V) \quad (2.23)$$

where Δ is the coproduct, d is the universal map, and the last map is the composition. How to reconcile this linear map with the corresponding program in the λ -calculus, which has the meaning “square the input function”? As we will explain below, for $\alpha \in \text{End}_k(V)$ there is a naturally associated element $|o\rangle_\alpha \in !\text{End}_k(V)$ with the property that

$$\Delta|o\rangle_\alpha = |o\rangle_\alpha \otimes |o\rangle_\alpha, \quad d|o\rangle_\alpha = \alpha.$$

Then $\llbracket \underline{2} \rrbracket$ maps this element to

$$|o\rangle_\alpha \longmapsto |o\rangle_\alpha \otimes |o\rangle_\alpha \longmapsto \alpha \otimes \alpha \longmapsto \alpha \circ \alpha. \quad (2.24)$$

This demonstrates how the coalgebra $!\text{End}_k(V)$ may be used to encode nonlinear maps, such as squaring an endomorphism.

Remark 2.5. We have already mentioned the equivalence of the simply-typed λ -calculus and propositional intuitionistic logic under the Curry-Howard isomorphism [68, §6.5]. There is an embedding of propositional intuitionistic logic into propositional intuitionistic *linear* logic [36, §5.1] making use of the additive connectives of linear logic which we have

omitted in the above. This means that every program in the simply-typed λ -calculus may be assigned a proof in linear logic (with additives) in such a way that β -reduction in the λ -calculus corresponds to cut-elimination in linear logic. For more on linear logic proofs as computer programs, see [53, 1, 14].

For example, if A, B denote types in propositional intuitionistic logic, and A°, B° the corresponding types in linear logic, then $(A \Rightarrow B)^\circ := (!A^\circ) \multimap B^\circ$ where for atoms A we declare $A^\circ = A$. There is a corresponding translation of proofs of $\vdash A$ to proofs of $\vdash A^\circ$. The Church numeral $\underline{2}$ is a λ -term of type $(A \rightarrow A) \rightarrow (A \rightarrow A)$ which corresponds to a proof in intuitionistic logic of the sequent $\vdash (A \Rightarrow A) \Rightarrow (A \Rightarrow A)$. If A is atomic, the translation of this type to linear logic is $\mathbf{int}'_A = !(A \multimap A) \multimap (A \multimap A)$. Thus a Church numeral in the λ -calculus determines a proof of $\vdash \mathbf{int}'_A$ not $\vdash \mathbf{int}_A$ under this translation. However, this translation is not necessarily the most useful or economical one because of the over-use of exponentials [36, §5.3]. For reasons of clarity we follow standard practice in using the “linear logic version” of the Church numeral $\underline{2}$ in Example 2.2 above, rather than the literal translation.

3 Diagrams and denotations

In the previous section we introduced the connectives and deduction rules of linear logic, and we associated to each type A a vector space $\llbracket A \rrbracket$. In this section we complete the construction of the vector space semantics of linear logic by assigning to each proof π of a sequent $\Gamma \vdash B$ a linear map $\llbracket \Gamma \rrbracket \longrightarrow \llbracket B \rrbracket$. We have already sketched how this assignment works in the case of the Church numeral $\underline{2}$ in Example 2.4.

This is almost completely formal: the category of k -vector spaces has all the properties of a category of proof denotations described earlier, including the comonad $!$ given by taking cofree cocommutative coalgebras, so it is automatic that semantics of intuitionistic linear logic may be constructed within \mathcal{V} . However, to explicitly calculate the denotations of proofs we need formulas for promotion and dereliction which are not automatic: in fact, this paper seems to be the first time they have been written down. This is not as surprising as it might seem: although studying semantics of *linear* logic using vector spaces is an natural thing to do, research has focused on full linear logic with negation. This is more complicated than the intuitionistic case, because types must be interpreted by self-dual objects and this leads to topological vector spaces [9, 10, 16, 17, 43, 30, 31]. However these more sophisticated models have the disadvantage that it is inconvenient to write down denotations of proofs, which is why for this introduction we stick to the intuitionistic case. See Remark 3.9 for more on the existing literature.

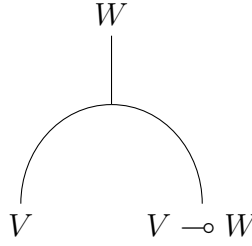
Our assignment of linear maps to proofs will be presented using string diagrams. One style of string diagrams, called *proof-nets*, were introduced by Girard and have been fundamental to linear logic since the beginning of the subject [36]. However proof-nets are designed for full linear logic and this does not match a semantics involving infinite-dimensional vector spaces. Instead we use a style of diagrams which is standard in category theory, following Joyal and Street [49, 50, 55, 52]. Our recommended reference for this

approach to proof-nets is Mellies [59, 58].

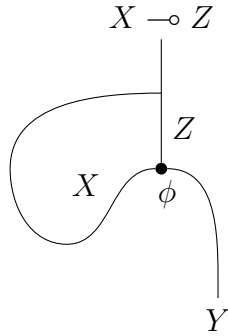
Let \mathcal{V} denote the category of k -vector spaces (not necessarily finite dimensional). Then \mathcal{V} is symmetric monoidal and for each object V the functor $V \otimes -$ has a right adjoint

$$V \multimap - := \text{Hom}_k(V, -).$$

In addition to the usual diagrammatics of a symmetric monoidal category, we draw the counit $V \otimes (V \multimap W) \longrightarrow W$ as


(3.1)

The adjoint $Y \longrightarrow X \multimap Z$ of a morphism $\phi : X \otimes Y \longrightarrow Z$ is depicted as follows:⁹


(3.2)

Next we present the categorical construct corresponding to the exponential modality in terms of an adjunction, following Benton [13], see also [59, §7]. Let \mathcal{C} denote the category of counital, coassociative, cocommutative coalgebras in \mathcal{V} . In this paper whenever we say *coalgebra* we mean an object of \mathcal{C} . This is a symmetric monoidal category in which the tensor product (inherited from \mathcal{V}) is cartesian, see [71, Theorem 6.4.5], [8] and [59, §6.5].

By results of Sweedler [71, Chapter 6] the forgetful functor $L : \mathcal{C} \longrightarrow \mathcal{V}$ has a right adjoint R and we set $! = L \circ R$, as in the following diagram:¹⁰

$$\mathcal{C} \begin{array}{c} \xrightarrow{L} \\ \xleftarrow{R} \end{array} \mathcal{V} \quad ! = L \circ R.$$

⁹This is somewhat against the spirit of the diagrammatic calculus, since the loop labelled X is not “real” and is only meant as a “picture” to be placed at a vertex between a strand labelled Y and a strand labelled $X \multimap Z$. This should not cause confusion, because we will never manipulate this strand on its own. The idea is that if X were a finite-dimensional vector space, so that $X \multimap Z \cong X^\vee \otimes Z$, the above diagram would be absolutely valid, and we persist with the same notation even when X is not dualisable. In our judgement the clarity achieved by this slight cheat justifies a little valour in the face of correctness.

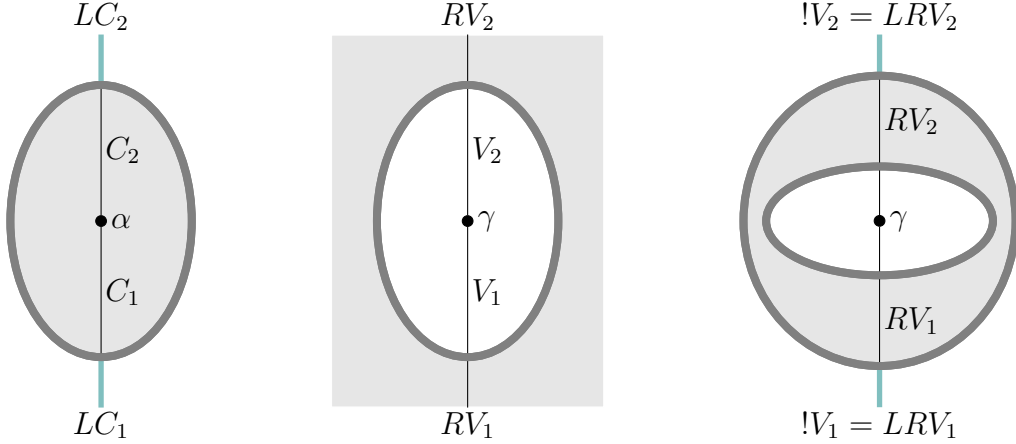
¹⁰The existence of a right adjoint to the forgetful functor can also be seen to hold more generally as a consequence of the adjoint functor theorem [8].

Both L and its adjoint R are monoidal functors.

For each V there is a coalgebra $!V$ and a counit of adjunction $d : !V \longrightarrow V$. Since this map will end up being the interpretation of the dereliction rule in linear logic, we refer to it as the *dereliction map*. In string diagrams it is represented by an empty circle. Although it is purely decorative, it is convenient to represent coalgebras in string diagrams drawn in \mathcal{V} by thick lines, so that for $!V$ the dereliction, coproduct and counit are drawn respectively as follows:

$$\begin{array}{ccc}
 \begin{array}{c} V \\ | \\ \circ \\ | \\ !V \end{array} &
 \begin{array}{c} !V \quad !V \\ \cup \\ | \\ !V \end{array} &
 \begin{array}{c} \bullet \\ | \\ !V \end{array}
 \end{array} \quad (3.3)$$

In this paper our string diagrams involve both \mathcal{V} and \mathcal{C} and our convention is that white regions represent \mathcal{V} and gray regions stand for \mathcal{C} . A standard way of representing monoidal functors between monoidal categories is using coloured regions [59, §5.7]. The image under L of a morphism $\alpha : C_1 \longrightarrow C_2$ in \mathcal{C} is drawn as a vertex in a grey region embedded into a white region. The image of a morphism $\gamma : V_1 \longrightarrow V_2$ under R is drawn using a white region embedded in a gray plane. For example, the diagrams representing $L(\alpha)$, $R(\gamma)$ and $! \gamma = LR(\gamma)$ are respectively



The adjunction between R and L means that for any coalgebra C and linear map $\phi : C \longrightarrow V$ there is a unique morphism of coalgebras $\Phi : C \longrightarrow !V$ making

$$\begin{array}{ccc}
 C & \xrightarrow{\phi} & V \\
 & \searrow \Phi & \uparrow d \\
 & & !V
 \end{array} \quad (3.4)$$

commute. The lifting Φ may be constructed as the unit followed by $!\phi$,

$$\Phi := C \longrightarrow !C \xrightarrow{!\phi} !V$$

and since we use an empty circle to denote the unit $C \longrightarrow !C$, this has the diagrammatic representation given on the right hand side of the following diagram. The left hand side is a convenient abbreviation for this morphism, that is, for the lifting Φ :

$$(3.5)$$

We follow the logic literature in referring to the grey circle denoting the induced map Φ as a *promotion box*. Commutativity of (3.4) is expressed by the identity

$$(3.6)$$

The coalgebra $!V$ and the dereliction map $!V \longrightarrow V$ satisfy a universal property and are therefore unique up to isomorphism. However, to actually understand the denotations of proofs, we will need the more explicit construction which follows from the work of Sweedler [71] and is spelt out in [62]. If V is finite-dimensional then

$$!V = \bigoplus_{P \in V} \text{Sym}_P(V) \quad (3.7)$$

where $\text{Sym}_P(V) = \text{Sym}(V)$ is the symmetric coalgebra. If e_1, \dots, e_n is a basis for V then as a vector space $\text{Sym}(V) \cong k[e_1, \dots, e_n]$. The notational convention in [62] is to denote, for elements $\nu_1, \dots, \nu_s \in V$, the corresponding tensor in $\text{Sym}_P(V)$ using kets

$$|\nu_1, \dots, \nu_s\rangle_P := \nu_1 \otimes \dots \otimes \nu_s \in \text{Sym}_P(V). \quad (3.8)$$

And in particular, the identity element of $\text{Sym}_P(V)$ is denoted by a vacuum vector

$$|o\rangle_P := 1 \in \text{Sym}_P(V). \quad (3.9)$$

We remark that if $\nu = 0$ then $|\nu\rangle_P = 0$ is the zero vector, which is distinct from $|o\rangle_P = 1$. We keep in mind that (3.9) denotes the case $s = 0$ of (3.8) and to avoid unwieldy notation we sometimes write $\nu_1 \otimes \dots \otimes \nu_s \cdot |o\rangle_P$ for $|\nu_1, \dots, \nu_s\rangle_P$. With this notation the universal map $d : !V \rightarrow V$ is defined by

$$d|o\rangle_P = P, \quad d|\nu\rangle_P = \nu, \quad d|\nu_1, \dots, \nu_s\rangle_P = 0 \quad s > 1.$$

The coproduct on $!V$ is defined by

$$\Delta|\nu_1, \dots, \nu_s\rangle_P = \sum_{I \subseteq \{1, \dots, s\}} |\nu_I\rangle_P \otimes |\nu_{I^c}\rangle_P \quad (3.10)$$

where I ranges over all subsets including the empty set, for a subset $I = \{i_1, \dots, i_p\}$ we denote by ν_I the sequence $\nu_{i_1}, \dots, \nu_{i_p}$, and I^c is the complement of I . In particular

$$\Delta|o\rangle_P = |o\rangle_P \otimes |o\rangle_P.$$

The counit $!V \rightarrow k$ is defined by $|o\rangle_P \mapsto 1$ and $|\nu_1, \dots, \nu_s\rangle_P \mapsto 0$ for $s > 0$.

When V is infinite-dimensional we may define $!V$ as the direct limit over the coalgebras $!W$ for finite-dimensional subspaces $W \subseteq V$. These are sub-coalgebras of $!V$, and we may therefore use the same notation as in (3.8) to denote arbitrary elements of $!V$. Moreover the coproduct, counit and universal map d are given by the same formulas; see [62, §2.1]. A proof of the fact that the map $d : !V \rightarrow V$ described above is universal among linear maps to V from cocommutative coalgebras is given in [62, Theorem 2.18], but as has been mentioned this is originally due to Sweedler [71], see [62, Appendix B].

To construct semantics of linear logic we also need an explicit description of liftings, as given by the next theorem which is [62, Theorem 2.20]. For a set X the set of partitions of X is denoted \mathcal{P}_X .

Theorem 3.1. *Let W, V be vector spaces and $\phi : !W \rightarrow V$ a linear map. The unique lifting to a morphism of coalgebras $\Phi : !W \rightarrow !V$ is given by*

$$\Phi|\nu_1, \dots, \nu_s\rangle_P = \sum_{C \in \mathcal{P}_{\{1, \dots, s\}}} \phi|\nu_{C_1}\rangle_P \otimes \dots \otimes \phi|\nu_{C_l}\rangle_P \cdot |o\rangle_Q \quad (3.11)$$

for $P, \nu_1, \dots, \nu_s \in W$, where $Q = \phi|o\rangle_P$ and l denotes the length of the partition C .

Example 3.2. The simplest example of a coalgebra is the field k . Any $P \in V$ determines a linear map $k \rightarrow V$ whose lifting to a morphism of coalgebras $k \rightarrow !V$ sends $1 \in k$ to the vacuum $|o\rangle_P$, as shown in the commutative diagram

$$\begin{array}{ccc} k & \xrightarrow{P} & V \\ & \searrow |o\rangle_P & \uparrow d \\ & & !V \end{array} . \quad (3.12)$$

Such liftings arise from promotions with empty premises, e.g. the proof

$$\frac{\frac{\overline{A \vdash A}}{\vdash A \multimap A} \multimap R}{\vdash !(A \multimap A)} \text{prom}$$

Incidentally, this explains why $\llbracket !A \rrbracket = \text{Sym}(\llbracket A \rrbracket)$ does not lead to semantics of linear logic, since the denotation of the above proof is a morphism of coalgebras $k \rightarrow !\text{End}_k(\llbracket A \rrbracket)$ whose composition with dereliction yields the map $k \rightarrow \text{End}_k(\llbracket A \rrbracket)$ sending $1 \in k$ to the identity. But this map does not admit a lifting into the symmetric coalgebra, because it produces an infinite sum. However the symmetric coalgebra *is* universal in a restricted sense and is (confusingly) sometimes also called a cofree coalgebra; see [73, §4]. For further discussion of the symmetric coalgebra in the context of linear logic see [19, 60].

3.1 The vector space semantics

Recall from Definition 2.3 the definition of $\llbracket A \rrbracket$ for each type A .

Definition 3.3. The *denotation* $\llbracket \pi \rrbracket$ of a proof π of $\Gamma \vdash B$ is a linear map $\llbracket \Gamma \rrbracket \rightarrow \llbracket B \rrbracket$ defined by inductively assigning a string diagram to each proof tree; by the basic results of the diagrammatic calculus [49] this diagram unambiguously denotes a linear map. The inductive construction is described by the second column in (2.7) – (2.17).

In each rule we assume a morphism has already been assigned to each of the sequents in the numerator of the deduction rule. These inputs are represented by blue circles in the diagram, which computes the morphism to be assigned to the denominator. To simplify the appearance of diagrams, we adopt the convention that a strand labelled by a type A represents a strand labelled by the denotation $\llbracket A \rrbracket$. In particular, a strand labelled with a sequence $\Gamma = A_1, \dots, A_n$ represents a strand labelled by $\llbracket A_1 \rrbracket \otimes \dots \otimes \llbracket A_n \rrbracket$.

Some comments:

- The diagram for the axiom rule (2.7) depicts the identity of $\llbracket A \rrbracket$.
- The diagram for the exchange rule (2.8) uses the symmetry $\llbracket B \rrbracket \otimes \llbracket A \rrbracket \rightarrow \llbracket A \rrbracket \otimes \llbracket B \rrbracket$.
- The diagram for the cut rule (2.9) depicts the composition of the two inputs.

- The right tensor rule (2.10) depicts the tensor product of the two given morphisms, while the left tensor rule (2.11) depicts the identity, viewed as a morphism between two strands labelled $\llbracket A \rrbracket$ and $\llbracket B \rrbracket$ and a single strand labelled $\llbracket A \rrbracket \otimes \llbracket B \rrbracket$.
- The diagram for the right \multimap rule (2.12) denotes the adjoint of the input morphism, as explained in (3.2), while the left \multimap rule (2.13) uses the composition map of (3.1).
- The diagram for the promotion rule (2.14) depicts the lifting of the input to a morphism of coalgebras, as explained in (3.5).
- The diagram for the dereliction rule (2.15) depicts the composition of the input with the universal map out of the coalgebra $!V$. The notation for this map, and the maps in the contraction (2.16) and weakening rules (2.17) are as described in (3.3).

Remark 3.4. For this to be a valid semantics, two proofs related by cut-elimination must be assigned the same morphism. This is a consequence of the general considerations in [59, §7]. More precisely, \mathcal{V} is a Lafont category [59, §7.2] and in the terminology of *loc.cit.* the adjunction between \mathcal{V} and \mathcal{C} is a linear-nonlinear adjunction giving rise to a model of intuitionistic linear logic. For an explanation of how the structure of a symmetric monoidal category extrudes itself from the cut-elimination transformations, see [59, §2].

Given the embedding of the simply-typed λ -calculus into linear logic, recalled in Remark 2.5, and the above construction of an interpretation of linear logic in the category \mathcal{V} of k -vector spaces, we are finally in a position to answer Question 2.1 in the positive. With patience, the reader may use the above to translate any program into a linear map. To explain how this works in practice, we go through the details of assigning a diagram and the corresponding linear map to the proof tree (2.21) of the Church numeral $\underline{2}$.

Example 3.5. We convert the proof tree (2.21) to a diagram in stages, beginning with the leaves. Each stage is depicted in three columns: in the first is a partial proof tree, in the second is the diagram assigned to it by Definition 3.3, and in the third is the explicit linear map which is the value of the diagram.

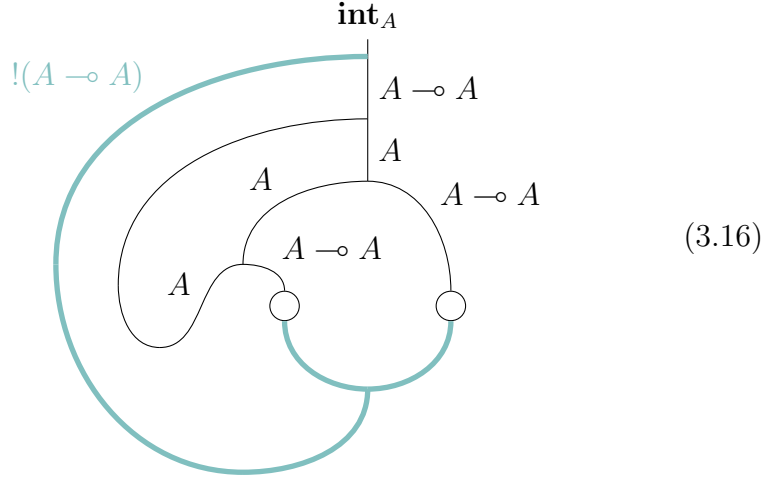
Recall that a strand labelled A actually stands for the vector space $V = \llbracket A \rrbracket$, so for instance the first diagram denotes a linear map $V \otimes \text{End}_k(V) \longrightarrow V$:

$$\begin{array}{ccc}
 \frac{\overline{A \vdash A} \quad \overline{A \vdash A}}{A, A \multimap A \vdash A} \multimap L &
 \begin{array}{c}
 A \\
 \text{---} \\
 \text{A} \quad \text{A} \multimap \text{A}
 \end{array} &
 a \otimes \alpha \mapsto \alpha(a)
 \end{array}$$

For example

$$|\nu\rangle_\alpha \mapsto |\nu\rangle_\alpha \otimes |o\rangle_\alpha + |o\rangle_\alpha \otimes |\nu\rangle_\alpha \mapsto \alpha \circ \nu + \nu \circ \alpha = \{\nu, \alpha\}.$$

The final step in the proof of $\underline{2}$ consists of moving the $!(A \multimap A)$ to the right side of the sequent, which yields the final diagram:



The denotation of this morphism is the map in (2.22). The reader might like to compare this style of diagram for $\underline{2}$ to the corresponding proof-net in [36, §5.3.2].

In Example 2.4 we sketched how to recover the function $\alpha \mapsto \alpha^2$ from the denotation of the Church numeral $\underline{2}$, but now we can put this on a firmer footing. The translation of the λ -calculus into linear logic encourages us to think of a proof π of a sequent $!B \vdash C$ as a program whose input of type B may be used multiple times. There is *a priori* no linear map $\llbracket B \rrbracket \rightarrow \llbracket C \rrbracket$ associated to π but there is a function $\llbracket \pi \rrbracket_{nl}$ defined on $P \in \llbracket B \rrbracket$ by lifting to $!\llbracket B \rrbracket$ and then applying $\llbracket \pi \rrbracket$:

$$\begin{array}{ccc} k & \xrightarrow{P} & \llbracket B \rrbracket \\ & \searrow |o\rangle_P & \uparrow d \\ & & !\llbracket B \rrbracket \end{array} \xrightarrow{\llbracket \pi \rrbracket} \llbracket C \rrbracket . \quad (3.17)$$

That is,

Definition 3.6. The function $\llbracket \pi \rrbracket_{nl} : \llbracket B \rrbracket \rightarrow \llbracket C \rrbracket$ is defined by $\llbracket \pi \rrbracket_{nl}(P) = \llbracket \pi \rrbracket |o\rangle_P$.

The discussion above shows that, with $V = \llbracket A \rrbracket$,

Lemma 3.7. $\llbracket \underline{2} \rrbracket_{nl} : \text{End}_k(V) \rightarrow \text{End}_k(V)$ is the map $\alpha \mapsto \alpha^2$.

This completes our explanation of how to represent the Church numeral $\underline{2}$ as a linear map (modulo the evasion discussed in Remark 3.9). From this presentation we see clearly that the non-linearity of the map $\alpha \mapsto \alpha^2$ is concentrated, in fact, not in the duplication step but in the “promotion” step (3.17) where the input vector α is turned into a vacuum $|o\rangle_\alpha \in !\text{End}_k(V)$. The promotion step is non-linear since $|o\rangle_\alpha + |o\rangle_\beta$ is not a morphism of coalgebras and thus cannot be equal to $|o\rangle_{\alpha+\beta}$. After this step, the duplication, dereliction and composition shown in (2.24) are all linear. Finally, when $k = \mathbb{C}$ it is interesting to compare $\llbracket 2 \rrbracket_{nl}$ with the map $\alpha \mapsto \alpha^2$ of smooth manifolds $\text{End}_k(V)$, see Appendix B.

Example 3.8. Let $\underline{2}'$ denote the proof of $!(A \multimap A) \vdash A \multimap A$ in (3.14). As discussed in Example 2.4, we may confuse the denotation of $\underline{2}$ and $\underline{2}'$. Applied to $\underline{2}'$ the promotion rule generates a new proof,

$$\begin{array}{c} \underline{2}' \\ \vdots \\ \frac{!(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash !(A \multimap A)} \text{prom} \end{array}$$

which we denote $\text{prom}(\underline{2}')$. By definition the denotation $\Phi := \llbracket \text{prom}(\underline{2}') \rrbracket$ of this proof is the unique morphism of coalgebras

$$\Phi : !\text{End}_k(V) \longrightarrow !\text{End}_k(V)$$

with the property that $d \circ \Phi = \phi$, where $\phi = \llbracket \underline{2} \rrbracket$ is as in (2.23). From (3.15) and Theorem 3.1 we compute that, for example

$$\begin{aligned} \Phi|o\rangle_\alpha &= |o\rangle_{\alpha^2}, \\ \Phi|\nu\rangle_\alpha &= \{\nu, \alpha\} \cdot |o\rangle_{\alpha^2}, \\ \Phi|\nu\mu\rangle_\alpha &= (\{\nu, \mu\} + \{\nu, \alpha\} \otimes \{\mu, \alpha\}) \cdot |o\rangle_{\alpha^2}, \\ \Phi|\nu\mu\theta\rangle_\alpha &= (\{\nu, \mu\} \otimes \{\theta, \alpha\} + \{\theta, \mu\} \otimes \{\nu, \alpha\} + \{\nu, \theta\} \otimes \{\mu, \alpha\} \\ &\quad + \{\nu, \alpha\} \otimes \{\mu, \alpha\} \otimes \{\theta, \alpha\}) \cdot |o\rangle_{\alpha^2}. \end{aligned}$$

Note that the commutators, e.g. $\{\nu, \alpha\}$ are defined using the product internal to $\text{End}_k(V)$, whereas inside the bracket in the last two lines, the terms $\{\nu, \alpha\}$ and $\{\mu, \alpha\}$ are multiplied in the algebra $\text{Sym}(\text{End}_k(V))$ before being made to act on the vacuum.

Remark 3.9. As we have already mentioned, there are numerous other semantics of linear logic defined using topological vector spaces. The reader curious about how these vector space semantics are related to the “relational” style of semantics such as coherence spaces should consult Ehrhard’s paper on finiteness spaces [30].

Indeed one can generate numerous examples of vector space semantics by looking at comonads on the category \mathcal{V} defined by truncations on the coalgebras $!V$. For example,

given a vector space V , let $!_0V$ denote the subspace of $!V$ generated by the vacua $|o\rangle_P$. This is the free space on the underlying *set* of V , and it is a subcoalgebra of $!V$ given as a coproduct of trivial coalgebras. It is easy to see that this defines an appropriate comonad and gives rise to a semantics of linear logic [72, §4.3]. However the semantics defined using $!V$ is more interesting, because universality allows us to mix in arbitrary coalgebras C . In Appendix B we examine the simplest example where C is the dual of the algebra $k[t]/t^2$ and relate this to tangent vectors.

4 Cut-elimination

We have now introduced the sequent calculus of intuitionistic linear logic, and seen how to represent linear logic in vector spaces. But so far we have only talked about denotations of types and proofs which, to borrow an insightful analogy from [41, §III], together play a role analogous to that of statics within classical mechanics. The *dynamical* part of linear logic is the cut-elimination process, which is the subject of this section. Unfortunately, while fundamental, the cut-elimination process is defined by a list of proof transformations which is delicate and takes many pages [59, Section 3]. In order to help the reader grasp the core idea, we present in this section a worked example where some of these proof transformations are presented using transformations of string diagrams.

A proof in linear logic is *cut-free* if it contains no occurrences of the cut rule. For each sequent $\Gamma \vdash A$ there is an equivalence relation on the set of proofs of the sequent, generated by a series of proof transformations that are together called *cut-elimination*. Each of these transformations generates a proof that is “closer” to being cut-free, according to a certain measure of cut complexity.

Theorem 4.1 (Girard). *Every proof in linear logic may be related via cut-elimination to a unique cut-free proof of the same sequent.*

Proof. See [44, Chapter 13] for a sketch of Gentzen’s cut-elimination in classical logic, and [59, §3] for the case of intuitionistic linear logic. \square

Given a proof π the unique cut-free proof in the same equivalence class is called the *cut-free normalisation* of π . Before the main example, we examine two proof transformations from the list in [59, Section 3] which will be needed.

Example 4.2. The cut-elimination transformation [59, §3.11.10] tells us that

$$\begin{array}{c}
 \pi_1 \qquad \qquad \pi_2 \\
 \vdots \qquad \qquad \vdots \\
 \frac{\Gamma \vdash A \quad \frac{B, A \vdash C}{A \vdash B \multimap C} \multimap R}{\Gamma \vdash B \multimap C} \text{cut}
 \end{array}
 \qquad
 \begin{array}{c}
 B \multimap C \\
 | \\
 \bullet \llbracket \pi_2 \rrbracket \\
 \curvearrowright \\
 \bullet \llbracket \pi_1 \rrbracket \\
 | \\
 \Gamma
 \end{array}
 \tag{4.1}$$

is transformed to the proof

$$\begin{array}{c}
\pi_1 \quad \pi_2 \\
\vdots \quad \vdots \\
\frac{\Gamma \vdash A \quad B, A \vdash C}{B, \Gamma \vdash C} \text{cut} \\
\frac{B, \Gamma \vdash C}{\Gamma \vdash B \multimap C} \multimap R
\end{array}
\quad
\begin{array}{c}
B \multimap C \\
| \\
\bullet \text{ } [[\pi_2]] \circ [[\pi_1]] \\
| \\
\Gamma
\end{array}
\quad (4.2)$$

and thus the two corresponding diagrams are equal. In this case, the equality generated by cut-elimination expresses the fact that the Hom-tensor adjunction is natural.

The transformation [59, §3.8.2] tells us that

$$\begin{array}{c}
\pi_2 \quad \pi_1 \quad \pi_3 \\
\vdots \quad \vdots \quad \vdots \\
\frac{A \vdash B}{\vdash A \multimap B} \multimap R \quad \frac{\Gamma \vdash A \quad B \vdash C}{\Gamma, A \multimap B \vdash C} \multimap L \\
\frac{\vdash A \multimap B \quad \Gamma, A \multimap B \vdash C}{\Gamma \vdash C} \text{cut}
\end{array}
\quad
\begin{array}{c}
C \\
| \\
\bullet \text{ } [[\pi_3]] \\
| \\
\bullet \text{ } [[\pi_1]] \quad \bullet \text{ } [[\pi_2]] \\
| \\
\Gamma
\end{array}
\quad (4.3)$$

may be transformed to

$$\begin{array}{c}
\pi_1 \quad \pi_2 \quad \pi_3 \\
\vdots \quad \vdots \quad \vdots \\
\frac{\Gamma \vdash A \quad A \vdash B}{\Gamma \vdash B} \text{cut} \quad \frac{B \vdash C}{B \vdash C} \text{cut} \\
\frac{\Gamma \vdash B \quad B \vdash C}{\Gamma \vdash C} \text{cut}
\end{array}
\quad
\begin{array}{c}
C \\
| \\
\bullet \text{ } [[\pi_3]] \\
| \\
\bullet \text{ } [[\pi_2]] \\
| \\
\bullet \text{ } [[\pi_1]] \\
| \\
\Gamma
\end{array}
\quad (4.4)$$

which is again an obvious property of the Hom-tensor adjunction.

Example 4.3. The following proof $\underline{\text{mult}}_2$ represents multiplication by 2 on A -integers:

$$\begin{array}{c}
\underline{2'} \\
\vdots \\
\frac{!(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash !(A \multimap A)} \text{prom} \quad \frac{A \multimap A \vdash A \multimap A}{A \multimap A \vdash A \multimap A} \\
\frac{!(A \multimap A) \vdash !(A \multimap A) \quad A \multimap A \vdash A \multimap A}{!(A \multimap A), \text{int}_A \vdash A \multimap A} \multimap L \\
\frac{!(A \multimap A), \text{int}_A \vdash A \multimap A}{\text{int}_A \vdash \text{int}_A} \multimap R
\end{array}
\quad
\begin{array}{c}
\text{int}_A \\
| \\
\text{Diagram of } \underline{\text{mult}}_2 \text{ proof} \\
| \\
\text{int}_A
\end{array}$$

where $\underline{2}'$ is the proof in (3.14). We feed $\underline{2}$ as input to $\underline{\text{mult}}_2$ by cutting:

$$\begin{array}{c}
 \underline{2} \quad \underline{\text{mult}}_2 \\
 \vdots \quad \vdots \\
 \hline
 \vdash \text{int}_A \quad \text{int}_A \vdash \text{int}_A \quad \text{cut} \\
 \hline
 \vdash \text{int}_A
 \end{array}
 \quad
 \begin{array}{c}
 \text{int}_A \\
 \downarrow \\
 \text{Diagram (4.5)}
 \end{array}
 \quad (4.5)$$

We denote this cut of the two proofs by $\underline{\text{mult}}_2 \mid \underline{2}$. Not surprisingly, the cut-free normalisation of $\underline{\text{mult}}_2 \mid \underline{2}$ is the Church numeral $\underline{4}$. Each of the proof transformations generated by the cut-elimination algorithm applied to $\underline{\text{mult}}_2 \mid \underline{2}$ (given in Appendix A) yields a new proof with the same denotation, and this sequence of proofs represents a particular sequence of manipulations of the string diagram.

We now enumerate these diagrammatic transformations. From (4.5) the first step is to use naturality of the Hom-tensor adjunction, as in the manipulation from (4.1) to (4.2). Then we are in the position of (4.3), with π_2 a part of $\underline{2}$ and π_1 the promoted Church numeral. The manipulation from (4.3) to (4.4) is to take the left leg and feed it as an input to the right leg. This yields the first equality below. The second equality follows from the fact that a promotion box represents a morphism of coalgebras, and thus can be commuted past the coproduct whereby it is duplicated:

$$(4.5) = \text{Diagram 1} = \text{Diagram 2} \quad (4.6)$$

At this point the promotions cancel with the derelictions by the identity (3.6), “releasing” the pair of Church numerals contained in the promotion boxes. This yields the first equality below, while the second is an application of the general form of the identity represented by the transformation of diagrams in (4.3) – (4.4):

$$(4.6) = \text{Diagram 1} = \text{Diagram 2}$$

This last diagram is the denotation of $\underline{4}$, so we conclude that (at least at the level of the denotations) the output of the program $\underline{\text{mult}}_2$ on the input $\underline{2}$ is $\underline{4}$. See Appendix A for references to the precise proof transformations responsible for each of these steps.

5 The geometry of interaction

One of the most interesting aspects of linear logic is Girard’s program to study the semantics of the cut-elimination process. He calls this the geometry of interaction; see [41, §III] and [38, 39, 40]. The purpose of this section is to explain some of his ideas and how they have motivated the author’s search for geometric models of computation.

After the work of Turing, Gödel and Church [70] computation has become a fundamental concept in mathematics. But what is it, really? One answer is that computation is *what happens* when a Turing machine is iterated, or what happens during the β -reduction process of the λ -calculus, or the cut-elimination process of logic. These three models of computation are all equivalent, but each is tied to specific syntax. What is the common essence of these processes? This is a question at least as deep as “What is space?” and it would be absurd to expect a final answer [28]. Nonetheless the search for answers generates interesting mathematics. At a first approach we notice that common to all three of the models of computation listed above is a tension between the *implicit* and the *explicit*. Let us use the computation of Example 4.3 to explain.

Consider the proofs $\underline{\text{mult}}_2$ and $\underline{2}$ and their cut $\underline{\text{mult}}_2 \mid \underline{2}$. The latter is equivalent under cut-elimination to the cut-free proof $\underline{4}$. Since this answer is derived from a deterministic algorithm – cut-elimination – the knowledge is certainly *implicit* in the proof $\underline{\text{mult}}_2 \mid \underline{2}$. But some work was necessary to convert this implicit truth into *explicit* truth. Although this example is a trivial one, the reader can easily imagine a similar calculation whose

answer is not as apparent as $2 \times 2 = 4$ – or, put aside arithmetic and note that the answer $\underline{4}$ is not obvious from a glance at the diagram (4.5). This conversion of implicit truth to explicit truth, or *explicitation*, is a fundamental aspect of computation.

However, this explicitation process is missing from most mathematical models of computation, which assign to the syntactical gadgets of Turing machines, λ -calculus or logic mathematical objects and transformations between them. To elaborate: suppose that in linear logic that we have proofs π of $A \vdash B$ and ρ of $B \vdash C$, and let $\rho | \pi$ denote the cut of one against the other, as displayed in the following proof tree:

$$\begin{array}{c} \pi \qquad \rho \\ \vdots \qquad \vdots \\ \frac{A \vdash B \quad B \vdash C}{A \vdash C} \text{ cut} \end{array} \quad (5.1)$$

Let $\widetilde{\rho | \pi}$ denote the cut-free proof of $A \vdash C$ produced from $\rho | \pi$ by the cut-elimination process. We regard this as the output of the program ρ computed on the input π . In the vector space semantics there is a commutative diagram of linear maps

$$\begin{array}{ccc} & \llbracket B \rrbracket & \\ \llbracket \pi \rrbracket \nearrow & & \searrow \llbracket \rho \rrbracket \\ \llbracket A \rrbracket & \xrightarrow{\llbracket \rho | \pi \rrbracket = \llbracket \widetilde{\rho | \pi} \rrbracket} & \llbracket C \rrbracket \end{array}$$

On this level, the calculation of output from input is a one-step affair $\llbracket \pi \rrbracket \mapsto \llbracket \rho \rrbracket \circ \llbracket \pi \rrbracket$. This may be contrasted with the syntax, where two steps are involved

$$\pi \mapsto \rho | \pi \mapsto \widetilde{\rho | \pi}. \quad (5.2)$$

The point is that this second step, cut-elimination, is completely invisible in the semantics since both $\rho | \pi$ and its normalisation have the same denotation – by construction. The explicitation that happens in the syntax is absent in the semantics.

Girard proposed [41] that we should look instead for semantics in which the denotations of $\rho | \pi$ and $\widetilde{\rho | \pi}$ are distinct and there are “dynamics” which generate the latter from the former. He refers to the field of study of such dynamics as the *geometry of interaction*.¹¹ The first example of such a semantics, constructed by Girard in [38], has been very influential – and not only in shedding light on the nature of computation. Since the λ -calculus may be translated into intuitionistic logic, and from there into intuitionistic linear logic, any semantics of linear logic yields a method for the execution of programs in the λ -calculus. The geometry of interaction model of linear logic (see below) yields a

¹¹The categorically minded reader may detect a hint of higher-categories: it would be natural to expect that the denotations of a proof and its cut-free normalisation should be 1-morphisms connected by some structure on the level of 2-morphisms which models cut-elimination. We will return to this topic below.

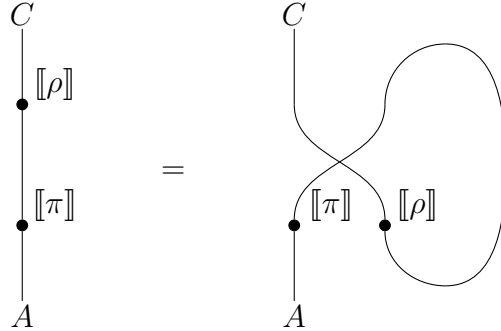
method of executing programs in which the elementary reduction steps are local – that is, they do not depend on global coordination [26, 27]. This is closely related to famous work of Lamping on optimal reduction in the λ -calculus [45].

Girard’s original geometry of interaction model [38] works as follows: if \mathbb{H} is the Hilbert space of square-summable sequences in \mathbb{C} then he assigns to each proof (in full linear logic) of a sequent $\vdash A_1, \dots, A_n$ with cuts on formulas B_1, \dots, B_m a bounded linear operator on \mathbb{H}^{2m+n} . Tracing out the $2m$ factors of \mathbb{H} yields an operator on \mathbb{H}^n which agrees with the operator assigned to the cut-free normalisation of the original proof. This operation of “tracing out the cuts” is the dynamics which models the process of cut-elimination; it can be rephrased as a sum over paths in a graph associated to the proof [27].

A simplified example using the vector space semantics can capture the key idea. Let us suppose in the above that $\llbracket B \rrbracket$ is a finite-dimensional vector space. Then $\llbracket \rho \rrbracket \circ \llbracket \pi \rrbracket$ may be computed as a trace

$$\llbracket \rho \rrbracket \circ \llbracket \pi \rrbracket = \text{tr}_{\llbracket B \rrbracket} (\sigma \circ (\llbracket \pi \rrbracket \otimes \llbracket \rho \rrbracket)) \quad (5.3)$$

where $\sigma : \llbracket B \rrbracket \otimes \llbracket C \rrbracket \longrightarrow \llbracket C \rrbracket \otimes \llbracket B \rrbracket$ is the symmetry map and $\text{tr}_{\llbracket B \rrbracket}$ is a partial trace. Using the standard notation for traces in string diagrams [51] this reads:



The upshot is that we may view the tensor $\llbracket \pi \rrbracket \otimes \llbracket \rho \rrbracket$ together with the information of the tensor factor $\llbracket B \rrbracket$ as an intermediate step between $\llbracket \pi \rrbracket$ and the composite $\llbracket \rho \rrbracket \circ \llbracket \pi \rrbracket$. That is, the two syntactical steps of (5.2) correspond to the sequence

$$\llbracket \pi \rrbracket \longmapsto (\llbracket \pi \rrbracket \otimes \llbracket \rho \rrbracket, \llbracket B \rrbracket) \longmapsto \text{tr}_{\llbracket B \rrbracket} (\sigma \circ (\llbracket \pi \rrbracket \otimes \llbracket \rho \rrbracket)) = \llbracket \rho \rrbracket \circ \llbracket \pi \rrbracket.$$

Since traces are only available for finite-dimensional spaces this idea cannot be extended to arbitrary $\llbracket B \rrbracket$ and is therefore not to be taken seriously, but there are numerous traced monoidal categories where a similar construction can be formalised [4, 2, 3]. In particular, Girard’s original model using Hilbert spaces can be formulated in these terms; see the introductory notes by Shirahata [69] and Haghverdi-Scott [46].

Next we consider examples of “explicitation” in geometry, which leads to a discussion of semantics of cut-elimination in bicategories of geometric spaces and the ideas behind [61].

In modern geometry we often understand spaces via the vector bundles living on them, and these we in turn understand via their characteristic classes, which are elements in finite-dimensional vector spaces called cohomology groups. However, *implicit* knowledge of a vector in some cohomology group, say produced from a series of abstract maps, should be distinguished from *explicit* knowledge, say coefficients in a preferred basis.

The prototypical example is Hodge theory. Let M be an n -dimensional compact oriented smooth manifold. The de Rham cohomology of M [20] is the cohomology of the complex of global sections of the sheaf of differential forms

$$0 \longrightarrow \Omega^0(M) \xrightarrow{d^0} \cdots \longrightarrow \Omega^p(M) \xrightarrow{d^p} \Omega^{p+1}(M) \longrightarrow \cdots \longrightarrow \Omega^n(M) \longrightarrow 0 .$$

If $Z^p(M) = \text{Ker}(d^p)$ denotes the closed p -forms and $B^p(M) = \text{Im}(d^{p-1})$ the exact p -forms, then the p th de Rham cohomology group is

$$H^p(M) = \frac{Z^p(M)}{B^p(M)} .$$

By a theorem of Hodge a preferred basis is given for each p by the subspace of harmonic forms $\mathcal{H}^p(M) \subseteq Z^p(M)$. That is, there is an isomorphism

$$\mathcal{H}^p(M) \longrightarrow Z^p(M) \longrightarrow Z^p(M)/B^p(M) = H^p(M) .$$

Giving an equivalence class of vectors in $Z^p(M)$ is therefore equivalent to specifying an element in $\mathcal{H}^p(M)$, but since $Z^p(M)$ is infinite-dimensional these two forms of knowledge have a different character. For example, exhibiting the coefficients of the equivalence class of a vector $\eta \in Z^p(M)$ in a chosen basis $\{\omega_i\}_i$ of harmonic forms requires additional work, which takes the form of computing integrals:

$$\eta \equiv \sum_i \langle \eta, \omega_i \rangle \omega_i, \quad \langle \eta, \omega_i \rangle = \int_M \eta \wedge \star \omega_i . \quad (5.4)$$

To connect this back to computation and the sequence (5.2), let M, N be smooth projective varieties over \mathbb{C} . Any cohomology class $\rho \in H^*(M \times N)$ determines a linear map of finite-dimensional vector spaces

$$\begin{aligned} I_\rho : H^*(M) &\longrightarrow H^*(N) , \\ \pi &\longmapsto (p_N)_*(\rho \cup p_M^*(\pi)) \end{aligned}$$

where p_M, p_N denote the projections from $M \times N$. Suppose that we insist on dealing only with harmonic forms. Then to compute I_ρ on some “input” harmonic form π and get a harmonic form as “output” we apply the following composite

$$\begin{aligned} \mathcal{H}^*(M) &\xrightarrow{\cong} H^*(M) \xrightarrow{I_\rho} H^*(N) \xrightarrow{\cong} \mathcal{H}^*(N) \\ \pi &\longmapsto I_\rho(\pi) \longmapsto \sum_j \langle I_\rho(\pi), \omega_j \rangle \omega_j . \end{aligned}$$

A comparison of this process – first compute I_ρ and then project onto harmonic forms using the integrals in (5.4) – with the two syntactical steps of (5.2) suggests a natural starting point for a search for semantics of cut-elimination in geometry, with integration playing the role of explicitation.

However, given the expectation previously expressed of higher-categorical semantics of cut-elimination, it is natural to start the search not with cohomology and linear maps but categories and functors. In this setting the relationship between the space of harmonic forms $\mathcal{H}^*(M)$ and the de Rham cohomology $H^*(M)$ may be compared to that between the bounded derived category of coherent sheaves $\mathbf{D}^b(\text{coh } M)$ and the full subcategory $\mathbf{D}_{\text{coh}}^b(\text{Qco } M)$ of complexes with bounded, coherent cohomology in the unbounded derived category of quasi-coherent sheaves $\mathbf{D}(\text{Qco } M)$.¹² These are equivalent categories

$$\mathbf{D}^b(\text{coh } M) \xrightarrow{\cong} \mathbf{D}_{\text{coh}}^b(\text{Qco } M) \subset \mathbf{D}(\text{Qco } M) \quad (5.5)$$

which means that for any object \mathcal{G} of $\mathbf{D}_{\text{coh}}^b(\text{Qco } M)$ there exists an isomorphic bounded complex of coherent sheaves $\mathcal{G}_{\text{finite}}$ which we call a *finite model* of \mathcal{G} . But given \mathcal{G} it is not obvious how to produce this finite model in any reasonably algorithmic way.¹³ Consider that in the special case where M is a point, (5.5) is an equivalence

$$\mathbf{D}^b(\text{vect } \mathbb{C}) \xrightarrow{\cong} \mathbf{D}_{\text{fd}}^b(\text{Vect } \mathbb{C}) \subset \mathbf{D}(\text{Vect } \mathbb{C})$$

between bounded complexes of finite-dimensional vector spaces and unbounded complexes of (infinite-dimensional) vector spaces with finite-dimensional cohomology. For general M , if $f : M \rightarrow \mathbb{C}$ denotes the structure map then for a coherent sheaf \mathcal{F} on M the derived pushforward $\mathbb{R}f_*(\mathcal{F})$ may be defined as an object of $\mathbf{D}_{\text{fd}}^b(\text{Vect } \mathbb{C})$ by a simple universal property, but explicitly computing the isomorphic *finite* complex in $\mathbf{D}^b(\text{vect } \mathbb{C})$ – that is, computing the cohomology of \mathcal{F} – requires work to be performed.

To complete the analogy with the above, suppose we are given a complex of coherent sheaves $\mathcal{R} \in \mathbf{D}^b(\text{coh } M \times N)$, which will play the role of ρ . There is a naturally associated triangulated functor

$$I_{\mathcal{R}} : \mathbf{D}_{\text{coh}}^b(\text{Qco } M) \longrightarrow \mathbf{D}_{\text{coh}}^b(\text{Qco } N), \quad (5.6)$$

$$\mathcal{F} \longmapsto (p_N)_*(\mathcal{R} \otimes p_M^*(\mathcal{F})) \quad (5.7)$$

¹²We do not intend to compare harmonic forms with arbitrary complexes of coherent sheaves. The point of the analogy is that $\mathcal{H}^*(M)$ provides an explicit finite-dimensional model for de Rham cohomology. The precise nature of the classes that make up this model is of secondary importance.

¹³Unfortunately this is not a very precise statement, since it depends what we mean by “reasonable”. While we can reconstruct a complex up to quasi-isomorphism from truncations and in this way construct an explicit complex of coherent sheaves, this is not an algorithm of the kind that we want – consider the enormous complexity of the complexes produced by taking global sections of an explicit resolution of a sheaf \mathcal{F} by injective quasi-coherent sheaves on a non-trivial scheme. In principle the data in this resolution is determined by \mathcal{F} , but it would be madness to build a model of computation on top of objects that are so difficult to handle.

where $p_N : M \times N \longrightarrow N$ and $p_M : M \times N \longrightarrow M$ are the projections and $(p_N)_*, p_M^*$ denote derived functors. Note that the functor $I_{\mathcal{R}}$ naturally produces infinite complexes of quasi-coherent sheaves with bounded coherent cohomology; rarely will the construction output an actual bounded complex of coherent sheaves. If we want to work with finite objects, computing $I_{\mathcal{R}}$ on some input therefore requires two steps

$$\mathbf{D}^b(\mathrm{coh} M) \xrightarrow{\cong} \mathbf{D}_{\mathrm{coh}}^b(\mathrm{Qco} M) \xrightarrow{I_{\mathcal{R}}} \mathbf{D}_{\mathrm{coh}}^b(\mathrm{Qco} N) \xrightarrow{\cong} \mathbf{D}^b(\mathrm{coh} N) \quad (5.8)$$

$$\mathcal{F} \longmapsto I_{\mathcal{R}}(\mathcal{F}) \longmapsto I_{\mathcal{R}}(\mathcal{F})_{\mathrm{finite}}. \quad (5.9)$$

That is, given the input complex \mathcal{F} we first compute $I_{\mathcal{R}}$ and then we take a finite model, which is the form of explicitation natural to algebraic geometry.

This suggests that in a model of computation where proofs or programs are interpreted by functors between triangulated categories, cut-elimination should be interpreted as the algorithmic construction of finite models. But what do we mean when we say that some kind of mathematical structure “interprets” cut-elimination? Since categories, functors and natural transformations form a bicategory, our answer is given in terms of bicategorical semantics where types are assigned objects and proofs are assigned 1-morphisms.

Taking Girard’s geometry of interaction as our guide, we ask for (at least) the following two desiderata. The algorithm computing finite models should be compatible with

- (A) the structure of ambient symmetric monoidal bicategory, and
- (B) the comonad interpreting the exponential modality.

The precise form of these requirements will depend on the bicategory under consideration. In the rest of this section we first sketch the kind of bicategorical semantics of linear logic that we have in mind, and then we explain how the cut systems of [61] provide one way of making precise the notion of an “algorithm for computing finite models”. In the present discussion the two most relevant examples of bicategories are

- The bicategory $\mathcal{V}ar$ [21] where objects are smooth projective varieties M, N, \dots and 1-morphisms $M \longrightarrow N$ are bounded complexes of coherent sheaves

$$\mathcal{V}ar(M, N) = \mathbf{D}^b(\mathrm{coh} M \times N).$$

For an example of the composition rule, note that if $\mathcal{R} \in \mathcal{V}ar(M, N)$ and S is a point then composition with \mathcal{R} in this bicategory is a functor $\mathcal{V}ar(S, M) \longrightarrow \mathcal{V}ar(S, N)$ which is in fact (5.6).

- The bicategory \mathcal{LG} of Landau-Ginzburg models [57, 22, 23] where objects are isolated hypersurface singularities W, V, \dots and 1-morphisms $W \longrightarrow V$ are finite-rank matrix factorisations of $V - W$

$$\mathcal{LG}(W, V) = \mathrm{hmf}(V - W)^\omega.$$

Here $\text{hmf}(V - W)$ denotes the homotopy category of matrix factorisations, and $(-)^{\omega}$ the idempotent completion [75].

The bicategories $\mathcal{V}ar$ and $\mathcal{L}\mathcal{G}$ are symmetric monoidal but do not have enough colimits to interpret the exponential modality. However, suitable enlargements of both examples yield bicategories \mathcal{C} which are symmetric monoidal with an internal Hom and admit a cofree cocommutative coalgebra $!V$ for each object V . It therefore makes sense to define a semantics of intuitionistic linear logic in \mathcal{C} (or at least, in the classifying category of \mathcal{C}) where the denotation of a proof is a 1-morphism. For example, the interpretation of the Church numeral $\underline{2}$ is a 1-morphism

$$! \text{End}(V) \xrightarrow{\Delta} ! \text{End}(V) \otimes ! \text{End}(V) \xrightarrow{d \otimes d} \text{End}(V)^{\otimes 2} \xrightarrow{- \circ -} \text{End}(V) \quad (5.10)$$

where $\text{End}(V)$ denotes an object of \mathcal{C} computed using the internal Hom. If we had started with a bicategory of rings and bimodules, this construction would yield the program (1.1) from the introduction.

To explain the interpretation of cut-elimination in such bicategorical semantics we begin by supposing that we have a bicategory \mathcal{B} and for each pair of objects M, N a full subcategory $\mathcal{A}(M, N) \subseteq \mathcal{B}(M, N)$ such that the inclusion is an equivalence. The intuition is that \mathcal{A} is a collection of “finite models” and that every 1-morphism is isomorphic to some finite model. We do not assume that \mathcal{A} is a sub-bicategory: the whole point is that the composition in \mathcal{B} of 1-morphisms in \mathcal{A} will not in general belong to \mathcal{A} .

Example 5.1. In the case of $\mathcal{B} = \mathcal{V}ar$,

$$\mathcal{A}(M, N) = \mathbf{D}^b(\text{coh } M \times N), \quad \mathcal{B}(M, N) = \mathbf{D}_{\text{coh}}^b(\text{Qco } M \times N). \quad (5.11)$$

In the case of $\mathcal{B} = \mathcal{L}\mathcal{G}$ both W, V are the defining equations of singularities and

$$\mathcal{A}(W, V) = \text{hmf}(V - W)^{\omega}, \quad \mathcal{B}(W, V) = \text{HMF}_{\text{fd}}(V - W) \quad (5.12)$$

where $\text{HMF}_{\text{fd}}(W)$ denotes the homotopy category of infinite-rank matrix factorisations which are direct summands of finite rank ones.

The guiding principle is that the denotation in \mathcal{B} of a cut-free proof should be *finite*, that is, it should be a 1-morphism in \mathcal{A} . Denotations of proofs with cuts will be defined using the composition operation in \mathcal{B} and may generate 1-morphisms outside of \mathcal{A} . The idea is to look for the shadow of the cut-elimination process in \mathcal{B} in terms of the algorithm which reflects these 1-morphisms back into \mathcal{A} . We refine this idea into precise mathematics in a series of steps. For any object S the composition in \mathcal{B} gives a functor

$$\mathcal{A}(S, M) \otimes \mathcal{A}(M, N) \longrightarrow \mathcal{B}(S, N), \quad (5.13)$$

$$\mathcal{F} \otimes \mathcal{R} \mapsto \mathcal{R} \circ \mathcal{F}. \quad (5.14)$$

By assumption there is an object $(\mathcal{R} \circ \mathcal{F})_{\text{finite}}$ of $\mathcal{A}(S, N)$ isomorphic to $\mathcal{R} \circ \mathcal{F}$. Adding this step of taking these finite models to the end of (5.13) we have

$$\mathcal{A}(S, M) \otimes \mathcal{A}(M, N) \longrightarrow \mathcal{B}(S, N) \longrightarrow \mathcal{A}(S, N) \quad (5.15)$$

$$\mathcal{F} \otimes \mathcal{R} \longmapsto \mathcal{R} \circ \mathcal{F} \longmapsto (\mathcal{R} \circ \mathcal{F})_{\text{finite}}. \quad (5.16)$$

The problem with this construction is that in the examples of interest there is no algorithmic construction of these finite models (of the kind we need) starting from just the data of the object $\mathcal{R} \circ \mathcal{F}$. But what we can do for \mathcal{LG} is refine the composition operation so that it lands not in $\mathcal{B}(S, N)$ but in an auxiliary category, the Clifford thickening of $\mathcal{A}(S, N)$, for which an algorithmic construction of objects in $\mathcal{A}(S, N)$ is under good control.

From now on we assume that \mathcal{B} is a superbcategory [61, §2.1], which is true of \mathcal{LG} but not of \mathcal{Var} . In particular the $\mathcal{A}(M, N)$ are all supercategories. The Clifford thickening of a supercategory is defined using Clifford algebras A_n of dimension 2^{2n} with $A_0 = k$. Each of these algebras has a basic representation, the spinor representation S_n , such that $A_n = \text{End}_k(S_n)$. This means that every representation Q of A_n in the category of vector spaces is of the form $Q \cong S_n \otimes_k V$ for some \mathbb{Z}_2 -graded vector space V , but the crucial point is that there is some computational “cost” associated with extracting the vector space V from Q . This may be represented either as computing a tensor product with the dual of the spinor representation $S_n^* = \text{Hom}_k(S_n, k)$

$$V \cong S_n^* \otimes_{A_n} Q \quad (5.17)$$

or equivalently as splitting idempotents on Q arising from the Clifford action. When Q is not a vector space but an object of the supercategory $\mathcal{A}(M, N)$ this extraction process is the form of explicitation which models cut-elimination in a cut-system.

To elaborate, we need to use the *Clifford thickening* $\mathcal{A}(M, N)^\bullet$ which is the category of all representations of the various Clifford algebras A_n in $\mathcal{A}(M, N)$. More precisely, an object of this category is object of $\mathcal{A}(M, N)$ together with the action of a Clifford algebra A_n for some $n \geq 0$. There is an equivalence of supercategories

$$\mathcal{A}(M, N) \xrightarrow{\cong} \mathcal{A}(M, N)^\bullet \quad (5.18)$$

which sends an object \mathcal{F} of $\mathcal{A}(M, N)$ to itself viewed as a representation of $A_0 = k$. The point is that the inverse of this equivalence has a very regular form: given an object (\mathcal{G}, ζ) of $\mathcal{A}(M, N)^\bullet$, which is an object \mathcal{G} together with a morphism of algebras

$$\zeta : A_n \longrightarrow \text{End}_{\mathcal{A}(M, N)}^*(\mathcal{G})$$

for some n , the tensor product

$$\tilde{\mathcal{G}} := S_n^* \otimes_{A_n} \mathcal{G} \quad (5.19)$$

is an object of $\mathcal{A}(M, N)$ and the map $(\mathcal{G}, \zeta) \mapsto \tilde{\mathcal{G}}$ gives an inverse to (5.18). This inverse is analogous to the extraction of the vector space V from the representation Q . Note that

while \mathcal{G} and $\tilde{\mathcal{G}}$ are isomorphic objects in the Clifford thickening they represent different states of knowledge: in \mathcal{G} the underlying object of $\mathcal{A}(M, N)$ is still implicit, while in $\tilde{\mathcal{G}}$ it has been made explicit. Let us now assume that there is an algorithm for computing the tensor product (5.19) so that the inverse to (5.18) is under control.¹⁴ Thus it only remains to refine the composition in (5.13) to land in $\mathcal{A}(S, N)^\bullet$.

That is, we ask for a collection of functors, indexed by triples M, N, S

$$\mathcal{A}(S, M) \otimes \mathcal{A}(M, N) \longrightarrow \mathcal{A}(S, N)^\bullet, \quad (5.20)$$

$$\mathcal{F} \otimes \mathcal{R} \longmapsto \mathcal{R} \mid \mathcal{F} \quad (5.21)$$

which satisfy some natural axioms. We call $\mathcal{F} \mid \mathcal{R}$ the *cut* of \mathcal{F} and \mathcal{R} . It is an object of $\mathcal{A}(S, N)$ together with the action of some Clifford algebra. To say that these cut functors refine the composition operation in \mathcal{B} is to ask that the following diagram commutes up to natural isomorphism:

$$\begin{array}{ccc} \mathcal{B}(S, M) \otimes \mathcal{B}(M, N) & \xrightarrow{- \circ -} & \mathcal{B}(S, N) \xleftarrow{\cong} \mathcal{A}(S, N) \\ \cong \uparrow & & \downarrow \cong \\ \mathcal{A}(S, M) \otimes \mathcal{A}(M, N) & \xrightarrow{- \mid -} & \mathcal{A}(S, N)^\bullet \end{array} \quad (5.22)$$

Commutativity of this diagram allows us to replace the sequence of steps in (5.15), that is, the clockwise direction from the bottom left of the diagram (5.22) to the top right

$$\mathcal{F} \otimes \mathcal{R} \longmapsto \mathcal{R} \circ \mathcal{F} \longmapsto (\mathcal{R} \circ \mathcal{F})_{\text{finite}} \quad (5.23)$$

with the series of steps in the anti-clockwise direction

$$\mathcal{F} \otimes \mathcal{R} \longmapsto \mathcal{R} \mid \mathcal{F} \longmapsto \widetilde{\mathcal{R} \mid \mathcal{F}} := S_n^* \otimes_{A_n} (\mathcal{R} \mid \mathcal{F}) \quad (5.24)$$

The point is that the last step of (5.23) is not under algorithmic control, but every step of (5.24) is algorithmic.

In summary the *cut system* \mathcal{A} which is the collection of categories $\mathcal{A}(M, N)$ and the cut functors (5.20) gives a precise meaning to the idea of an algorithmic construction of finite models for the result of composition of 1-morphisms in \mathcal{B} , and this is the structure in the bicategorical semantics which we intend as a model of cut-elimination. The main result of [61] is that in the case $\mathcal{B} = \mathcal{LG}$ there is a natural cut system realising the above. Regarding the desiderata A and B, which must be present before we can call this a model of cut-elimination: while compatibility with the basic structure of the bicategory is part of the axiomatics of a cut system [61, §3], this first paper does not include the compatibility with the tensor product, the internal Hom or finite products. These arguments, together with the verification of desiderata B, will be the subject of future work.

¹⁴This algorithm depends on the underlying algebraic objects that make up the bicategory. In the case of \mathcal{LG} , computing the tensor product is done by splitting idempotents, which reduces to a computation in commutative algebra using well-understood algorithms.

To connect this explicitly back to Girard's ideas in the geometry of interaction, suppose that \mathcal{B} carries an interpretation of linear logic and that we have a pair of proofs π, ρ as in (5.1). Then using the cut system structure we would make the assignments

$$\begin{aligned} \llbracket \rho \rrbracket &= \mathcal{R}, \\ \llbracket \pi \rrbracket &= \mathcal{F}, \\ \llbracket \rho \mid \pi \rrbracket &= \mathcal{R} \mid \mathcal{F}, \\ \widetilde{\llbracket \rho \mid \pi \rrbracket} &= \widetilde{\mathcal{R} \mid \mathcal{F}}. \end{aligned}$$

The “dynamics” which generates $\widetilde{\mathcal{R} \mid \mathcal{F}}$ from $\mathcal{R} \mid \mathcal{F}$ is the computation of the tensor product with the dual of the spinor representation S_n^* [61, §3.1].

Example 5.2. The polynomial 0 is an object of $\mathcal{B} = \mathcal{LG}$ and with \mathcal{A} as in (5.12) for any hypersurface singularity W , we have

$$\begin{aligned} \mathcal{A}(0, W) &= \text{hmf}(W)^\omega, & \mathcal{A}(W, 0) &= \text{hmf}(-W)^\omega, \\ \mathcal{A}(0, 0) &= \mathcal{C}_2(k), & \mathcal{B}(0, 0) &= \mathcal{C}_2^\infty(k). \end{aligned}$$

where $\mathcal{C}_2(k)$ is the homotopy category of \mathbb{Z}_2 -graded complexes of finite-dimensional k -vector spaces and $\mathcal{C}_2^\infty(k)$ is the homotopy category of infinite-rank complexes with finite-dimensional cohomology. Moreover $\mathcal{A}(0, 0)^\bullet$ is the category of A_n -representations in $\mathcal{C}_2(k)$ for various n . In this case the diagram (5.22) becomes

$$\begin{array}{ccc} \mathcal{C}_2^\infty(k) & \xleftarrow{\cong} & \mathcal{C}_2(k) \\ \uparrow -\otimes- & & \downarrow \cong \\ \text{hmf}(W)^\omega \otimes \text{hmf}(-W)^\omega & \xrightarrow{-|-} & \mathcal{C}_2(k)^\bullet \end{array} \quad (5.25)$$

The vertical functor on the left, which comes from the composition in \mathcal{B} , is simply a tensor product. Every matrix factorisation of $-W$ is the dual Y^\vee of some matrix factorisation Y of W , and the functor sends $X \otimes Y^\vee$ to $\text{Hom}(Y, X) \in \mathcal{C}_2^\infty(k)$. The clockwise direction around this square is the sequence (5.23)

$$X \otimes Y^\vee \mapsto \text{Hom}(Y, X) \mapsto H^* \text{Hom}(Y, X)$$

whereas the anti-clockwise direction is (5.24)

$$X \otimes Y^\vee \mapsto Y^\vee \mid X \mapsto S_n^* \otimes_{A_n} (Y^\vee \mid X).$$

The cut $Y^\vee \mid X$ is a representation of some Clifford algebra A_n in \mathbb{Z}_2 -graded complexes of finite-dimensional vector spaces, that is, there are closed operators $a_1, \dots, a_n, a_1^\dagger, \dots, a_n^\dagger$ on $Y^\vee \mid X$ satisfying the anti-commutation relations

$$a_i a_j = a_j a_i, \quad a_i^\dagger a_j^\dagger = a_j^\dagger a_i^\dagger, \quad a_i a_j^\dagger = \delta_{ij} + a_j^\dagger a_i.$$

An example with explicit matrices for these operators is given in [61, Example 4.15]. Since A_n is Morita trivial we know that this representation must be of the form $S_n \otimes_k V$ for some complex V , and the point of the commutativity of (5.25) is that this V is precisely the cohomology $H^* \text{Hom}(Y, X)$. One can show that V is the image of the following idempotent on the complex $Y^\vee | X$ constructed from the Clifford action [61, Definition 2.18]

$$e_n := a_1^\dagger \cdots a_n^\dagger a_n \cdots a_1 .$$

The content of the cut system in this special case is that splitting this idempotent provides a more controlled way of extracting the vector space $H^* \text{Hom}(Y, X)$ from the data of X, Y than taking cohomology. In particular, the cut system links invariants of the cohomology (such as the Euler characteristic) to invariants of X and Y (such as the Chern characters) in a way that is obscured by taking cohomology; see below.

This concludes our sketch of the links between cut-elimination and geometry. While Girard’s original geometry of interaction model immediately yielded insight into the execution of programs in the λ -calculus, it is not clear what geometric models have to say about practical questions in computer science. But it is intriguing that in the example of \mathcal{LG} the Clifford actions, which we may view as algorithmic structure “hidden inside” the composition operation, are both the natural interpretation of cut-elimination and also encode fundamental geometric properties of matrix factorisations such as the analogue of Hirzebruch-Riemann-Roch theorem. Roughly, this arises as follows: in the situation of Example 5.2 the cut system provides a diagram of morphisms of complexes

$$H^* \text{Hom}(Y, X) \begin{array}{c} \xrightarrow{g} \\ \xleftarrow{f} \end{array} Y^\vee | X$$

with $f \circ g = 1$ and $g \circ f = e_n$. Then

$$\begin{aligned} \chi(H^* \text{Hom}(Y, X)) &= \text{str}(1_{H^* \text{Hom}(Y, X)}) \\ &= \text{str}(f \circ g) \\ &= \text{str}(g \circ f) \\ &= \text{str}(a_1^\dagger \cdots a_n^\dagger a_n \cdots a_1) . \end{aligned}$$

At this point the fact that the operators a_i^\dagger are Atiyah classes allows us to transform this supertrace into a residue, which presents the Euler characteristic as an integral involving the Chern characters of X and Y . The details are given in [29], see also [61, Remark 4.13]. This recovers the Hirzebruch-Riemann-Roch formula for matrix factorisations proven by Polishchuk-Vaintrob [63] and hints at a link between cut-elimination in logic and index theorems in geometry, which may ultimately help to shed light on fundamental questions about the tension between local and global aspects of computation.¹⁵

¹⁵What does an algebraist stand to learn from bicategorical models of logic? The interaction with logic

A An example of cut-elimination

To begin, we expose the first layer of structure within `mult2` to obtain

[illegible]

can lead to ideas that might otherwise go unexplored – for instance, from the logical perspective it is natural to take an isolated hypersurface singularity W and form the universal cocommutative coalgebra $!W$ mapping to W , but otherwise the importance of this construction would not be obvious. To take this particular example a bit further: in *implicit computational complexity* restrictions on the use of the exponential modality are used to characterise complexity classes of programs, such as polynomial time [42] and elementary time [25]. In the vector space semantics of this paper, where proofs or programs are interpreted as morphisms, this provides some notion of complexity for linear maps. But in a bicategorical semantics where proofs are interpreted as objects in cocomplete triangulated categories of 1-morphisms one should study the complexity of programs constructing objects from a set of fixed objects.

$$\begin{array}{c}
\underline{2} \qquad \qquad \underline{\text{mult}}'_2 \\
\vdots \qquad \qquad \vdots \\
\frac{\vdash \mathbf{int}_A \quad !(A \multimap A), \mathbf{int}_A \vdash A \multimap A}{\frac{!(A \multimap A) \vdash A \multimap A}{\vdash \mathbf{int}_A} \multimap R} \text{cut}
\end{array} \tag{A.2}$$

If we fill in the content of $\underline{\text{mult}}'_2$, this proof may be depicted as follows:

$$\begin{array}{c}
\underline{2'} \\
\vdots \\
\vdots \\
\frac{!(A \multimap A) \vdash A \multimap A}{\vdash \mathbf{int}_A} \quad \frac{\frac{!(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash !(A \multimap A)} \text{prom} \quad \frac{}{A \multimap A \vdash A \multimap A}}{\frac{!(A \multimap A), \mathbf{int}_A \vdash A \multimap A}{\vdash \mathbf{int}_A} \text{cut}} \multimap L
\end{array} \tag{A.3}$$

The next cut-elimination step [59, §3.8.2] transforms this proof to

$$\begin{array}{c}
\underline{2'} \qquad \qquad \underline{2'} \\
\vdots \qquad \qquad \vdots \\
\frac{!(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash !(A \multimap A)} \text{prom} \quad \frac{!(A \multimap A) \vdash A \multimap A}{\vdash \mathbf{int}_A} \text{cut} \quad \frac{}{A \multimap A \vdash A \multimap A} \text{cut}
\end{array} \tag{A.4}$$

As may be expected, cutting against an axiom rule does nothing, so this is equivalent to

$$\begin{array}{c}
\underline{2'} \qquad \qquad \underline{2''} \\
\vdots \qquad \qquad \vdots \\
\frac{!(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash !(A \multimap A)} \text{prom} \quad \frac{!(A \multimap A), !(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash A \multimap A} \text{ctr}
\end{array}$$

$$\frac{\frac{!(A \multimap A) \vdash A \multimap A}{\vdash \mathbf{int}_A} \multimap R}{\vdash \mathbf{int}_A} \text{cut}$$

where $\underline{2''}$ is a sub-proof of $\underline{2}$. Here is the important step: cut-elimination replaces a cut of a promotion against a contraction by a pair of promotions [59, §3.9.3]. This step corresponds to the doubling of the promotion box in (4.6)

$$\begin{array}{c}
\begin{array}{ccc}
\underline{2}' & \underline{2}' & \underline{2}'' \\
\vdots & \vdots & \vdots \\
\frac{!(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash !(A \multimap A)} & \frac{!(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash !(A \multimap A)} & \frac{!(A \multimap A), !(A \multimap A) \vdash A \multimap A}{!(A \multimap A), !(A \multimap A) \vdash A \multimap A} \text{ cut} \\
\hline
\frac{!(A \multimap A), !(A \multimap A) \vdash A \multimap A}{!(A \multimap A), !(A \multimap A) \vdash A \multimap A} \text{ cut} & & \\
\hline
\frac{!(A \multimap A), !(A \multimap A) \vdash A \multimap A}{!(A \multimap A) \vdash A \multimap A} \text{ ctr} & & \\
\hline
\frac{!(A \multimap A) \vdash A \multimap A}{\vdash \mathbf{int}_A} \multimap R
\end{array}
\end{array}$$

We only sketch the rest of the cut-elimination process: next, the derelictions in $\underline{2}''$ will be annihilated with the promotions in the two copies of $\underline{2}'$ according to [59, §3.9.1]. Then there are numerous eliminations involving the right and left \multimap introduction rules.

B Tangents and proofs

Example B.1. Let \mathcal{T} denote the dual of the finite-dimensional algebra $k[t]/(t^2)$. It has a k -basis $1 = 1^*$ and $\varepsilon = t^*$ and coproduct Δ and counit u defined by

$$\Delta(1) = 1 \otimes 1, \quad \Delta(\varepsilon) = 1 \otimes \varepsilon + \varepsilon \otimes 1, \quad u(1) = 1, \quad u(\varepsilon) = 0.$$

Recall that a tangent vector at a point x on a scheme X is a morphism $\mathrm{Spec}(k[t]/t^2) \rightarrow X$ sending the closed point to x . Given a finite-dimensional vector space V and $R = \mathrm{Sym}(V^*)$ with $X = \mathrm{Spec}(R)$, this is equivalent to a morphism of k -algebras

$$\varphi : \mathrm{Sym}(V^*) \rightarrow k[t]/t^2$$

with $\varphi^{-1}((t)) = x$. Such a morphism of algebras is determined by its restriction to V^* , which as a linear map $\varphi|_{V^*} : V^* \rightarrow k[t]/t^2$ corresponds to a pair of elements (P, Q) of V , where $\varphi(\tau) = \tau(P) \cdot 1 + \tau(Q) \cdot t$. Then φ sends a polynomial f to

$$\varphi(f) = f(P) \cdot 1 + \partial_Q(f)|_P \cdot t.$$

The map $\varphi|_{V^*}$ is also determined by its dual, which is a linear map $\phi : \mathcal{T} \rightarrow V$. By the universal property, this lifts to a morphism of coalgebras $\Phi : \mathcal{T} \rightarrow !V$. If ϕ is determined by a pair of points $(P, Q) \in V^{\oplus 2}$ as above, then it may be checked directly that

$$\Phi(1) = |o\rangle_P, \quad \Phi(\varepsilon) = |Q\rangle_P$$

is a morphism of coalgebras lifting ϕ .

Motivated by this example, we make a preliminary investigation into tangent vectors at proof denotations. Let A, B be types with finite-dimensional denotations $\llbracket A \rrbracket, \llbracket B \rrbracket$.

Definition B.2. Given a proof π of $\vdash A$ a *tangent vector* at π is a morphism of coalgebras $\theta : \mathcal{T} \longrightarrow !\llbracket A \rrbracket$ with the property that $\theta(1) = |o\rangle_{\llbracket \pi \rrbracket}$, or equivalently that the diagram

$$\begin{array}{ccc} k & \xrightarrow{\llbracket \pi \rrbracket} & \llbracket A \rrbracket \\ \downarrow 1 & & \uparrow d \\ \mathcal{T} & \xrightarrow{\theta} & !\llbracket A \rrbracket \end{array} \quad (\text{B.1})$$

commutes. The space of tangent vectors at π is denoted T_π .

It follows from Example B.1 that there is a linear isomorphism

$$\llbracket A \rrbracket \longrightarrow T_\pi$$

sending $Q \in \llbracket A \rrbracket$ to the coalgebra morphism θ with $\theta(1) = |o\rangle_{\llbracket \pi \rrbracket}$ and $\theta(\varepsilon) = |Q\rangle_{\llbracket \pi \rrbracket}$.

Note that the denotation of a program not only maps inputs to outputs (if we identify inputs and outputs with vacuum vectors) but also tangent vectors to tangent vectors. To wit, if ρ is a proof of a sequent $!A \vdash B$ with denotation $\lambda : !\llbracket A \rrbracket \longrightarrow \llbracket B \rrbracket$, then composing a tangent vector θ at a proof π of $\vdash A$ with the lifting Λ of λ leads to a tangent vector at the cut of ρ against the promotion of π . That is, the linear map

$$\mathcal{T} \xrightarrow{\theta} !\llbracket A \rrbracket \xrightarrow{\Lambda} !\llbracket B \rrbracket \quad (\text{B.2})$$

is a tangent vector at the following proof, which we denote $\rho \mid \pi$

$$\frac{\frac{\vdash A}{\vdash !A} \text{ prom} \quad \frac{\rho}{!A \vdash B} \text{ cut}}{\vdash B}$$

By Theorem 3.1 the linear map of tangent spaces induced in this way by ρ is

$$\begin{aligned} \llbracket A \rrbracket &\cong T_\pi \longrightarrow T_{\rho \mid \pi} \cong \llbracket B \rrbracket \\ Q &\longmapsto \lambda |Q\rangle_{\llbracket \pi \rrbracket} \end{aligned} \quad (\text{B.3})$$

When ρ computes a smooth map of differentiable manifolds, this map can be compared with an actual map of tangent spaces. We examine $\rho = \underline{2}$ below. It would be interesting to understand these maps in more complicated examples; this seems to be related to the differential λ -calculus [32, 33], but we have not tried to work out the precise connection.

Example B.3. When $k = \mathbb{C}$ and $Z = \llbracket \underline{2} \rrbracket_{nl}$ we have by Lemma 3.7

$$Z : M_n(\mathbb{C}) \longrightarrow M_n(\mathbb{C}), \quad Z(\alpha) = \alpha^2.$$

The tangent map of the smooth map of manifolds Z at α is $(Z_*)_\alpha(\nu) = \{\nu, \alpha\}$. When α is the denotation of some proof π of $\vdash A \multimap A$ this agrees with the tangent map assigned in (B.3) to the proof $\underline{2}$ at π , using (3.15).

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