

Deep Inference for Graphical Theorem Proving

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The ultimate meaning of logic is this ability to manipulate.

– **Jean-Yves Girard.** TODO: Move this as the epigraph of some chapter (either Introduction or Proof-by-Action)

Abstract

Proof assistants are software which allow for the precise checking of mathematical reasoning. They can be general purpose (like Coq, Lean, Isabelle...) or more specialized like EasyCrypt. They enable a level of accuracy which certifies that no error can occur, have given birth to a wide range of practical and theoretical works, and have been used in a wide range of applications. But they remain difficult to use.

We propose a new paradigm of formal proof construction through actions performed in a graphical user interface, in order to enable a more comfortable and intuitive use. Our paradigm builds upon direct manipulation principles, combining both old (Proof-by-Pointing) and new (Proof-by-Linking) interaction techniques that exploit recent advances in deep inference proof theory. We implement this paradigm in a prototype of graphical user interface called Actema, using modern web-based technologies. We also design a generic protocol for plugging Actema on any proof system that supports first-order intuitionistic logic. This protocol is deployed inside the Coq proof assistant through the coq-actema plugin, offering to users the ability to integrate graphical proofs into existing textual developments.

Then, driven by the will to improve the various interaction techniques of Actema in a unified formalism, we explore a series of deep inference proof systems that give more structure to the notion of logical goal. These systems share the ability to represent goals in two alternative ways: either textually through a standard inductive syntax, or graphically through a metaphorical notation well-suited to direct manipulation.

The first family of systems, called bubble calculi, is an extension of the theory of nested sequents, that we reframe as local rewriting systems with a graphical and topological interpretation. Bubble calculi enable an efficient sharing of contexts between subgoals, making them well-suited to the factorization of both forward and backward reasoning steps in proofs. The second system, called flower calculus, is an intuitionistic refinement of C.S. Peirce's theory of existential graphs, understood as a system for interactive, goal-directed proof building. It provides more iconic and economical means of reasoning than bubble calculi, by exposing fewer inference rules that all work directly on the goals themselves, removing the need for logical connectives. Both types of systems are shown to be analytic and fully invertible, making them amenable to proof automation techniques.

We finally go back to practical experimentation with the Flower Prover, another web-based prototype of GUI based on the flower calculus, which has the property of working well on modern mobile devices equipped with touchscreens of varying sizes.

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SYMBOLIC MANIPULATIONS

Note

Most of the content in this chapter has been previously published in [47].

In this chapter, we focus on how both *click* and *drag-and-drop* (DnD) actions upon the formulas of a sequent can implement proof construction operations corresponding to the core logic; that is how they deal with logical connectives, quantifiers and equality. We present these core principles through various illustrations and examples in first-order logic. The technical and proof-theoretical foundations for the semantics of DnD actions will be investigated more thoroughly in Chapter ?? . More advanced features of the proof-by-action paradigm that go beyond the core logic are illustrated in Chapter ?? , and Chapter ?? explains how it can be integrated in a mainstream proof assistant.

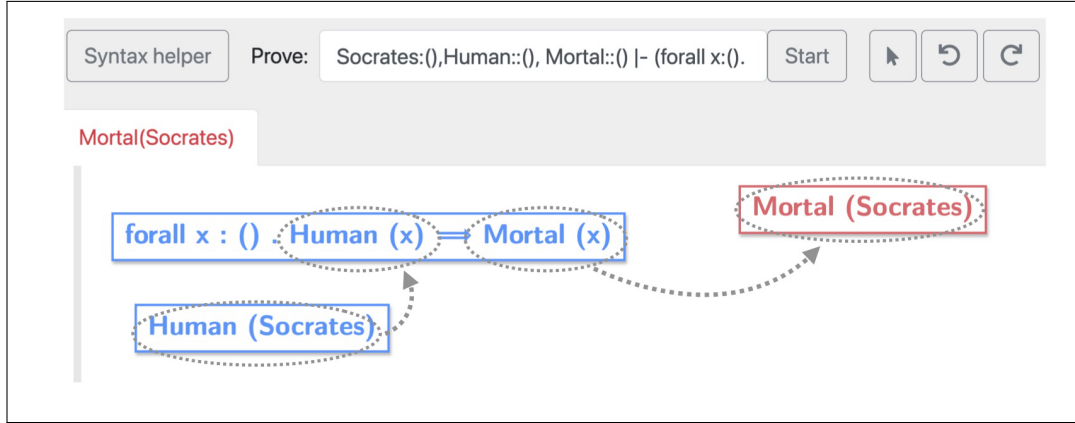
We have started to implement the paradigm in a prototype named *Actema* (for Active Mathematics) running through a web HTML5/JavaScript interface. At the time of writing, a standalone version of the prototype (i.e. which does not use an existing theorem prover as its backend) is publicly available online [48]. This possibility to experiment in practice, even though yet on a small scale, gave valuable feedback for crafting the way DnD actions are to be translated into proof construction steps in an intuitive and practical way. A description of the overall architecture and implementation design of Actema will be provided in Chapter ?? .

The chapter is organized as follows. Section ?? briefly outlines its logical setting. Section ?? describes the basic features of a graphical proof interface based on our principles, and illustrates them with a famous syllogism from Aristotle. Section ?? shows how it can integrate proof-by-pointing capabilities through click actions. Section ?? shows very briefly how one can add new formulas and objects to the current goal. The last two sections explain, through further examples, how drag-and-drop actions work; first for so-called *rewrite* actions involving equalities, then for actions involving logical connectives and quantifiers.

1.1 Logical setting

Any proof system must implement a given logical formalism. What we describe here ought to be applied to a wide range of formalisms, but in this chapter we focus mainly on the core of intuitionistic first-order logic with equality (FOL). This allows us to consider sequents where hypotheses are unordered which, in turn, simplifies the technical presentation. We will thus write $\Gamma, A \Rightarrow C$ for a sequent where A is among the hypotheses.

We use and do not recall the usual definitions of terms and propositions in first order logic. We assume a first order language (function and predicate symbols) is given. Provability is defined over sequents $\Gamma \Rightarrow C$ by the usual



The conclusion is red on the right, the two hypotheses blue on the left. The gray dotted arrows have been added to show the two possible actions.

Figure 1.1: A partial screenshot showing a goal in the Actema prototype

logical rules of natural deduction (NJ) and/or sequent calculus (LJ), as defined in Chapter ??.

Equality is treated in a common way: $=$ is a binary predicate symbol written in the usual infix notation, together with the reflexivity axiom $\forall x.x = x$ and the Leibniz scheme, stating that for any proposition A one has

$$\forall x.\forall y.x = y \wedge A \supset A\{x/y\}.$$

We will not consider, on paper, the details of variable renaming in substitutions, implicitly applying the so-called Barendregt convention, that bound and free variables are distinct and that a variable is bound at most once.

Extending this work to simple extensions of FOL, like multi-sorted predicate calculus is straightforward (and actually done in the Actema prototype). Some interesting points may show up when considering how to apply this work to more complex formalisms like type theories. We will not explore these questions here.

1.2 A first example

Layout

One advantage of the proof-by-action paradigm, is that it allows a very lean visual layout of the proof state. There is no need to name hypotheses. In the prototype we also dispense with a text buffer, since proofs are solely built through graphical actions.

Figure ?? shows the layout of the system using the ancient example from Aristotle. A goal appears as a set of *items* whose nature is defined by their respective colors¹:

- A *red item* which is the proposition to be proved, that is the *conclusion*,

1: We are well aware that, in later implementations, this color-based distinction ought to be complemented by some other visual distinction, at least for users with impaired color vision. But in the present description we stick to the red/blue denomination, as it is conveniently concise.

- *blue items*, which are the local *hypotheses*.

The items are what the user can act upon: either by *clicking* on them, or by *moving* them. Each item can be positioned freely on a so-called *proof canvas*, which is depicted by the white background in Figure ??.

Finally, note that each goal is displayed on a tab.

Two Kinds of Actions

In this example, there are two possible actions.

- A first one is to bring together, by drag-and-drop, the red conclusion $\text{Mortal}(\text{Socrates})$ with the succedant of the first hypothesis $\text{Mortal}(x)$. This will transform the goal by changing the conclusion to $\text{Human}(\text{Socrates})$.
- A second possibility is to combine the two hypotheses; more precisely to bring together the item $\text{Human}(\text{Socrates})$ with the premise $\text{Human}(x)$ of the first hypothesis. This will yield a new hypothesis $\text{Mortal}(\text{Socrates})$.

The first case is what we call a *backward step* where the conclusion is modified by using a hypothesis. The second case is a *forward step* where two known facts are combined to deduce a new fact, that is an additional blue item.

In both cases, the proof can then be finished invoking the logical axiom rule. In practice this means bringing together the blue hypothesis $\text{Human}(\text{Socrates})$ (resp. the new blue fact $\text{Mortal}(\text{Socrates})$) with the identical red conclusion.

Modelling the Mechanism

A backward step involves a hypothesis, here $\forall x. \text{Human}(x) \supset \text{Mortal}(x)$ and the conclusion, here $\text{Mortal}(\text{Socrates})$. Furthermore, the action actually links together two *subterms* of each of these items; this is written by squaring these subterms. The symbol \otimes , used as an operator, is meant to describe the result of the interaction. Internally, the behavior of this operator is defined by a set of rewrite rules given in Figure ?? and Figure ?. Here is the sequence of rewrites corresponding to the example²:

2: Note that \otimes has lower precedence than all logical connectives.

$$\begin{array}{lcl}
 \forall x. \text{Human}(x) \supset \boxed{\text{Mortal}(x)} \otimes \boxed{\text{Mortal}(\text{Socrates})} & & \\
 \rightarrow \text{Human}(\text{Socrates}) \supset \boxed{\text{Mortal}(\text{Socrates})} \otimes \boxed{\text{Mortal}(\text{Socrates})} & \text{L}\forall i & \\
 \rightarrow \text{Human}(\text{Socrates}) \wedge (\boxed{\text{Mortal}(\text{Socrates})} \otimes \boxed{\text{Mortal}(\text{Socrates})}) & \text{L}\supset_2 & \\
 \rightarrow \text{Human}(\text{Socrates}) \wedge \top & \text{id} & \\
 \rightarrow \text{Human}(\text{Socrates}) & \text{neur} &
 \end{array}$$

Notice that:

- These elementary rewrites are not visible for the user. What she sees is the final result of the action, that is the last expression of the rewrite sequence.

- The definitions of the rewrite rules in Figure ?? and Figure ?? do not involve squared subterms. The information of which subterms are squared is only used by the system to decide which rules to apply in which order.

In general, the action solves the goal when the interaction ends with the trivially true proposition \top . The base case being the action corresponding to the axiom/identity rule id : $A \odot A \rightarrow \top$.

A forward step, on the other hand, involves two (subterms of two) hypotheses. The interaction operator between two hypotheses is written \otimes . In the example above, the detail of the interaction is:

$$\begin{array}{ll}
 \forall x. \boxed{\text{Human}(x)} \supset \text{Mortal}(x) \otimes \boxed{\text{Human}(\text{Socrates})} & \\
 \rightarrow \boxed{\text{Human}(\text{Socrates})} \supset \text{Mortal}(\text{Socrates}) \otimes \boxed{\text{Human}(\text{Socrates})} & \text{F}\forall i \\
 \rightarrow (\boxed{\text{Human}(\text{Socrates})} \odot \boxed{\text{Human}(\text{Socrates})}) \supset \text{Mortal}(\text{Socrates}) & \text{F}\supset_1 \\
 \rightarrow \top \supset \text{Mortal}(\text{Socrates}) & \text{id} \\
 \rightarrow \text{Mortal}(\text{Socrates}) & \text{neul}
 \end{array}$$

The final result is the new hypothesis. We come back to the study of the rewrite rules of \odot and \otimes in Chapter ??.

1.3 Proof steps through clicks

Drag-and-drop actions involve two items. Some proof steps involve only one item; they can be associated to the action of clicking on this item. The general scheme is that clicking on a connective or quantifier allows to “break” or destruct this connective. The results of clicks are not very surprising, but this feature is necessary to complement drag-and-drop actions.

- Clicking on a blue conjunction $A \wedge B$ transforms the item into two separate blue items A and B .
- Clicking on a red conjunction $A \wedge B$ splits the goal into two subgoals, whose conclusions are respectively A and B .
- Clicking on a blue disjunction $A \vee B$ splits the goal into two subgoals of same conclusion, with A (resp. B) added as a new hypothesis.
- Clicking on the left (resp. right)-hand subterm of a red disjunction $A \vee B$ replaces this red conclusion by A (resp. B).
- Clicking on a red implication $A \supset B$ breaks it into a new red conclusion B and a new blue hypothesis A .
- Clicking on a red universal quantifier $\forall x.A$ introduces a new object x and the conclusion becomes A .
- Clicking on a blue existential $\exists x.A$ introduces a new object x together with a blue hypothesis A .
- Clicking on a red equality $t = t$ solves the goal immediately.

One can see that these actions correspond essentially to the (right) introduction rules of the head connective for the conclusion, and either the elimination rule from NJ or the left introduction rule from LJ for hypotheses. The exact mapping between click actions and inference rules is given in Table ?? . A few remarks are in order:

- ▶ In the current implementation of Actema, clicking on a blue item $A \supset B$ will work only if the conclusion is B . An alternative is to use the $\supset L$ rule from sequent calculus, which is applicable in every context.
- ▶ There is no action mapped to red \perp items, simply because \perp does not have any introduction rule.
- ▶ There is currently no action mapped to blue \forall and red \exists items. The reason is that one needs additional information about the *witness* to be used when instantiating with the $\forall L$ or $\exists R$ rule. This could be provided with further input (e.g. from a dialog box), but this would need a change in the communication protocol between the frontend and backend of Actema. Instead we decompose this in two steps: first the user can add the witness as a new object by using the +expr button (see Section ??); then she can drag the corresponding green item and drop it on the quantified item to instantiate it. It is also possible to select with the mouse an arbitrary subexpression occurring in any item of the current goal, and then drag-and-drop the item holding the selected subexpression instead.

Remark 1.3.1 (Click completeness) From the previous remarks and the completeness of the cut-free sequent calculus LJ, it follows that click actions, when combined with new object declarations and DnD instantiations, provide a sufficient set of interactions to prove any true formula of (intuitionistic) first-order logic.

Head connective	Red item	Blue item
\top	$\top R$	$\top L$
\perp	\emptyset	$\perp L$
\wedge	$\wedge R$	$\wedge L$
\vee	$\vee R_1, \vee R_2$	$\vee L$
\supset	$\supset R$	$\supset E$
\forall	$\forall R$	\emptyset
\exists	\emptyset	$\exists L$

Table 1.1: Mapping of click actions to inference rules

It is possible to associate some more complex effects to click actions performed on locations deeper under connectives. This is the essence of proof-by-pointing, and [13] provides ample description. Since we here focus more on drag-and-drop actions, we do not detail further more advanced PbP features. However we stress that these features are essentially compatible with what we describe in this work. In fact the version of Actema presented in Chapter ?? provides an implementation of proof-by-pointing available as a contextual menu action.

[13]: Bertot et al. (1994), ‘Proof by pointing’

1.4 Adding new items

Often in the course of a proof, one will want to add new items: either a new conjecture (blue item), or a new object (green item) that would be helpful to solve the current goal. These can be done respectively with the blue `+hyp` and the green `+expr` buttons, which appear in the screenshot of Figure ?? . When clicked, they prompt the user for the statement of the conjecture, or the name and expression defining the object. The `+hyp` button will also create a new subgoal requiring to prove the conjecture within the current context.

For now we ask the user to input textual data, in an idiosyncratic syntax specific to the logic of Actema. A desirable, but highly non-trivial feature would be to provide some elaborate input mechanism tailored to the type of object the user wants to create. This would obviously require some extensibility to new domain-specific input interfaces: typically one could imagine plugging a tool like GeoGebra to construct geometrical figures [72], or a categorical diagram editor like YADE. We will not explore the design of such features in this thesis, since we focus on finding a universal interface for logical reasoning rather than domain-specific interfaces for particular types of mathematical reasoning³. Note however that it is a necessary feature if one wants to achieve a fully graphical theorem proving environment which is accessible to non-expert users.

[72]: GmbH (2023), *GeoGebra Geometry*

add citation/link to Ambroise Lafont's work

3: For a related work that tackles this problem in the context of functional programming, see [140].

1.5 A simple example involving equality

Most interactive theorem provers expose a *rewrite* tactic that allows the use of equality hypotheses, that is known equations of the form $t = u$, in order to replace some occurrences of t by u (or symmetrically, occurrences of u by t). This substitution can be performed in the conclusion or in hypotheses. Specifying the occurrences to be replaced with textual commands can be quite tedious, since it involves either dealing with some form of naming/numbering to designate locations of subterms, or writing manually patterns which duplicate parts of the structure of terms.

In our setting we can provide this replacement operation through drag-and-drop. The user points at the occurrence(s) of t to be replaced, and then brings them to the corresponding side of the equality.

Figure ?? shows a very elementary example where one wants to prove $1 + 1 = 2$ in the setting of Peano arithmetic. For any number n , we write $S(n)$ to denote the application of the successor function to n ; closed terms are directly written in decimal notation. The proof goes as follows:

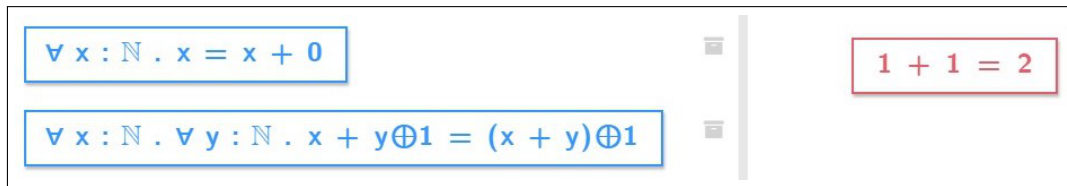


Figure 1.2: Proving $1 + 1 = 2$ in Peano arithmetic

- We link the left-hand side $x + S(y)$ of the second addition axiom with $1 + 1$ in the conclusion, which has the effect of rewriting $1 + 1$ into $S((1 + 0))$:

$$\begin{aligned}
& \forall x. \forall y. \boxed{x + S(y)} = S((x + y)) \otimes \boxed{1 + 1} = 2 \\
\rightarrow & \forall y. \boxed{1 + S(y)} = S((1 + y)) \otimes \boxed{1 + 1} = 2 & \text{L}\forall i \\
\rightarrow & \boxed{1 + S(0)} = S((1 + 0)) \otimes \boxed{1 + 1} = 2 & \text{L}\forall i \\
\equiv & \boxed{1 + 1} = S((1 + 0)) \otimes \boxed{1 + 1} = 2 \\
\rightarrow & S((1 + 0)) = 2 & \text{L}=_1
\end{aligned}$$

- We link the right-hand side $x + 0$ of the first addition axiom with $1 + 0$ in the conclusion, which rewrites $1 + 0$ into 1:

$$\begin{aligned}
& \forall x. x = \boxed{x + 0} \otimes S(\boxed{1 + 0}) = 2 \\
\rightarrow & 1 = \boxed{1 + 0} \otimes S(\boxed{1 + 0}) = 2 & \text{L}\forall i \\
\rightarrow & S(1) = 2 & \text{L}=_2 \\
\equiv & 2 = 2
\end{aligned}$$

We end up with the conclusion $2 = 2$, which is provable by a simple click. Notice how the orientation of the two rewritings is determined by which side of the equality is selected. Also, in this case, the rewritings correspond to backward proof steps, because the rewriting is performed in the conclusion. Similar rules ($F=_1$ and $F=_2$) are used to perform rewritings in hypotheses.

1.6 Drag-and-dropping through connectives

We mentioned in Section ?? that it is possible to destruct logical connectives through click actions. In many cases however, this will not be necessary: because a drag-and-drop involves subterms of the items involved, one can often directly use (resp. act on) the part of the hypothesis (resp. conclusion) which is of interest.

Conjunction and Disjunction

The conjunction is an easy to explain case. A hypothesis of the form $A \wedge B$ can be used directly both as evidence for A and as evidence for B . This is modeled by the rules $L\wedge_1$ and $L\wedge_2$. A very simple action is thus:

$$\begin{aligned}
\boxed{A} \wedge B \otimes \boxed{A} & \rightarrow \boxed{A} \otimes \boxed{A} & \text{L}\wedge_1 \\
& \rightarrow \top & \text{id}
\end{aligned}$$

On the other hand, considering a conjunctive goal $A \wedge B$, one can simplify or solve one of the branches by a DnD action. This involves rules $R\wedge_1$ and $R\wedge_2$. For instance:

$$\begin{aligned}
\boxed{A} \otimes \boxed{A} \wedge B & \rightarrow (\boxed{A} \otimes \boxed{A}) \wedge B & \text{R}\wedge_1 \\
& \rightarrow \top \wedge B & \text{id} \\
& \rightarrow B & \text{neul}
\end{aligned}$$

Red disjunctions work similarly to conjunctive goals, except that solving one branch will solve the entire goal. A nice consequence of this, which is hard to simulate with textual tactics, is that one can just simplify one branch of a disjunction without committing to proving it entirely:

$$\begin{aligned}
 \boxed{A} \otimes (B \wedge \boxed{A}) \vee C &\rightarrow (\boxed{A} \otimes B \wedge \boxed{A}) \vee C && \text{R}\vee_1 \\
 &\rightarrow (B \wedge (\boxed{A} \otimes \boxed{A})) \vee C && \text{R}\wedge_2 \\
 &\rightarrow (B \wedge \top) \vee C && \text{id} \\
 &\rightarrow B \vee C && \text{neur}
 \end{aligned}$$

Disjunctive hypotheses also have a backward behavior defined by the rules $\text{L}\vee_1$ and $\text{L}\vee_2$, although in most cases one will prefer the usual subgoal semantics associated with click actions. More interesting is their forward behavior with the rules $\text{F}\vee_1$ and $\text{F}\vee_2$, in particular when they interact with negated hypotheses. For instance:

$$\begin{aligned}
 \boxed{A} \vee B \otimes \neg \boxed{A} &\rightarrow (\boxed{A} \otimes \neg \boxed{A}) \vee B && \text{F}\vee_1 \\
 &\rightarrow \neg(\boxed{A} \otimes \boxed{A}) \vee B && \text{F}\supset_1 \\
 &\rightarrow \neg\top \vee B && \text{id} \\
 &\rightarrow \perp \vee B && \text{neul} \\
 &\rightarrow B && \text{neul}
 \end{aligned}$$

We have noticed that on some examples, such actions could provide a significant speed-up with respect to traditional textual command provers. We give a more concrete example in Section ??.

Notice that we used rules associated with implication, since negation can be defined by $\neg A \triangleq A \supset \perp$.

Implication

The implication connective is crucial, because it is not monotone. More precisely, the roles of hypotheses and conclusions are reversed on the left of an implication. We start with some very basic examples for the various elementary cases.

Using the right hand part of a hypothesis $A \supset B$ turns a conclusion B into A .

$$\begin{aligned}
 A \supset \boxed{B} \otimes \boxed{B} &\rightarrow A \wedge (\boxed{B} \otimes \boxed{B}) && \text{L}\supset_2 \\
 &\rightarrow A \wedge \top && \text{id} \\
 &\rightarrow A && \text{neul}
 \end{aligned}$$

This can also be done under conjunctions and/or disjunctions:

$$A \supset \boxed{B} \otimes C \wedge (D \vee \boxed{B}) \rightarrow^* C \wedge (D \vee A)$$

An interesting point is what happens when using implications with several premisses. The curried and uncurried versions of the implication will behave exactly the same way:

$$A \supset B \supset \boxed{C} \otimes D \vee \boxed{C} \rightarrow^* D \vee (A \wedge B)$$

and:

$$A \wedge B \supset \boxed{C} \otimes D \vee \boxed{C} \rightarrow^* D \vee (A \wedge B)$$

As we have seen in Aristotle's example (Section ??), blue implications can also be used in forward steps, where another hypothesis matches one of their premisses.

A first nice feature is the ability to strengthen a hypothesis by providing evidence for any of its premisses:

$$B \supset \boxed{A} \supset C \otimes \boxed{A} \rightarrow^* B \supset C$$

and again the same can be done for the uncurried version:

$$B \wedge \boxed{A} \supset C \otimes \boxed{A} \rightarrow^* B \supset C.$$

The two aspects of the implication can be combined:

$$B \supset \boxed{A} \supset C \otimes D \supset \boxed{A} \rightarrow^* B \supset D \supset C$$

or:

$$B \wedge \boxed{A} \supset C \otimes D \supset \boxed{A} \rightarrow^* B \wedge D \supset C.$$

Note that there is almost no difference in the way one uses different versions of a hypothesis $A \supset B \supset C$, $A \wedge B \supset C$, but also $B \supset A \supset C$, in forward as well as in backward steps⁴. This underlines, we hope, that our proposal makes the proof construction process much less dependent on arbitrary syntactical details, like the order of hypotheses or whether they come in curried form or not.

Also, the rules for implication combined with the rules for equality $L=$ or $F=$, naturally give access to *conditional rewriting*; we detail this in combination with quantifiers in the next section.

As for red implications, they also have a backward semantics with the rules $R\supset_1$ and $R\supset_2$, but most of the time one will want to destruct them immediately by click. An exception could be if one wants to simplify some part of an implicative, inductive goal before starting the induction.

Quantifiers

As the first example of this chapter shows, drag-and-drop actions work through quantifiers and can trigger instantiations of quantified variables. This is made possible by the rules $L\forall$ and $F\forall$, which allow the instantiation of a variable universally quantified in a hypothesis.

Symmetrically, a variable quantified existentially in a conclusion can also be instantiated. For instance:

$$\begin{array}{ccc} \boxed{A(t)} \otimes \exists x. \boxed{A(x)} & \rightarrow & \boxed{A(t)} \otimes \boxed{A(t)} \quad L\forall \\ & \rightarrow & \top \quad \text{id} \end{array}$$

4: When viewed as types through the Curry-Howard isomorphism, $A \supset B \supset C$, $A \wedge B \supset C$, $B \wedge A \supset C$ and $B \supset A \supset C$ are *isomorphic types*; and Roberto di Cosmo [43] has also precisely underlined that type isomorphisms should help to free the programmer from arbitrary syntactical choices.

An interesting feature is the possibility to modify propositions under quantifiers. Consider the following possible goal:

$$\forall a.\exists b.A(f(a) + g(b))$$

where A , f and g can be complex expressions. Suppose we have a lemma allowing us to prove:

$$\forall a.\exists b.A(g(b) + f(a)).$$

Switching from one formulation to the other, involves one use of the commutativity property $\forall x.\forall y.x + y = y + x$. In our setting, the equality can be used under quantifiers in one single action:

$$\begin{aligned} \forall x.\forall y.\boxed{x + y} &= y + x \odot \forall a.\exists b.A(\boxed{f(a) + g(b)}) \\ \rightarrow^* \quad \forall a.\exists b.A(g(b) + f(a)) \end{aligned}$$

Note also that it is possible to instantiate only some of the universally quantified variables in the items involved. In general, a universally quantified variable can be instantiated when the quantifier is in a negative position; for instance:

$$\forall x.\forall y.\boxed{P(y)} \supset R(x, y) \otimes \boxed{P(a)} \rightarrow^* \forall x.R(x, a)$$

This last example illustrates how partial instantiation abstracts away the order in which quantifiers are declared, very much like the partial application presented earlier for implication⁵.

Again, in some cases, only some existential quantifiers may be instantiated following a linkage:

$$\boxed{P(a)} \odot \exists x.\exists y.\boxed{P(y)} \wedge R(x, y) \rightarrow^* \exists x.R(x, a)$$

When using an existential assumption, one can either destruct it through a click, or use or transform it through a DnD; for instance:

$$\exists x.\boxed{P(x)} \otimes \forall y.\boxed{P(y)} \supset Q(y) \rightarrow^* \exists x.Q(x)$$

Dependency between Variables

Some more advanced examples yield simultaneous instantiations of existentially and universally quantified variables. In such cases, the system needs to check some dependency conditions. For instance, the following linkage is valid and solves the goal through one action:

$$\begin{aligned} &\exists y.\forall x.\boxed{R(x, y)} \odot \forall x'.\exists y'.\boxed{R(x', y')} \\ \rightarrow &\forall y.(\forall x.\boxed{R(x, y)} \odot \forall x'.\exists y'.\boxed{R(x', y')}) && \text{L}\exists\text{s} \\ \rightarrow &\forall y.\forall x'.(\forall x.\boxed{R(x, y)} \odot \exists y'.\boxed{R(x', y')}) && \text{R}\forall\text{s} \\ \rightarrow &\forall y.\forall x'.(\forall x.\boxed{R(x, y)} \odot \boxed{R(x', y)}) && \text{R}\exists\text{i} \\ \rightarrow &\forall y.\forall x'.(\boxed{R(x', y)} \odot \boxed{R(x', y)}) && \text{L}\forall\text{i} \\ \rightarrow &\forall y.\forall x'.\top && \text{id} \\ \rightarrow^* &\top \end{aligned}$$

5: This fact should not be too surprising to the reader familiar with dependent type theory, where implication is usually defined as a special case of universal quantification.

But the converse situation is not provable; the system will refuse the following linkage:

$$\forall x.\exists y.\boxed{R(x, y)} \otimes \exists y'.\forall x'.\boxed{R(x', y')}$$

Indeed, there is no reduction path starting from this linkage ending with the id rule. This can be detected by the system because the unification of $R(x, y)$ and $R(x', y')$ here results in a cycle in the instantiations of variables⁶. The system thus refuses this action.

6: We will come back to this in Section ?? . Also notice that this example requires to use full (first-order) unification, not only matching.

Conditional Rewriting

The example given in Section ??, although very simple, already combines the rules for equality and for quantifiers. When also using implication, one obtains naturally some form of conditional rewriting. To take another simple example, suppose we have a hypothesis of the form:

$$\forall x.x \neq 0 \supset f(x) = g(x)$$

We can use this hypothesis for replacing a subterm $f(t)$ by $g(t)$, which will generate a side-condition $t \neq 0$:

$$\begin{aligned} & \forall x.x \neq 0 \supset \boxed{f(x)} = g(x) \otimes A(\boxed{f(t)}) \\ \rightarrow & t \neq 0 \supset \boxed{f(t)} = g(t) \otimes A(\boxed{f(t)}) & \text{L}\forall i \\ \rightarrow & t \neq 0 \wedge (\boxed{f(t)} = g(t) \otimes A(\boxed{f(t)})) & \text{L}\supset_2 \\ \rightarrow & t \neq 0 \wedge A(g(t)) & \text{L}=_1 \end{aligned}$$

One could similarly do such a rewrite in a hypothesis. Furthermore, the conditional rewrite can also be performed under quantifiers; for instance:

$$\begin{aligned} & \forall x.x \neq 0 \supset \boxed{f(x)} = g(x) \otimes \exists y.A(\boxed{f(y)}) & \text{R}\exists s \\ \rightarrow & \exists y.(\forall x.x \neq 0 \supset \boxed{f(x)} = g(x) \otimes A(\boxed{f(y)})) & \text{L}\forall i \\ \rightarrow & \exists y.(y \neq 0 \wedge (\boxed{f(y)} = g(y) \otimes A(\boxed{f(y)}))) & \text{L}\supset_2 \\ \rightarrow & \exists y.(y \neq 0 \wedge A(g(t))) & \text{L}=_1 \end{aligned}$$

BACKWARD			
$A \otimes A \rightarrow \top$	id		
$t = u \otimes A\{t/x\} \rightarrow A\{u/x\}$	$L=1$		
$t = u \otimes A\{u/x\} \rightarrow A\{t/x\}$	$L=2$		
$(B \wedge C) \otimes A \rightarrow B \otimes A$	$L\wedge_1$		
$(C \wedge B) \otimes A \rightarrow B \otimes A$	$L\wedge_2$		
$A \otimes (B \wedge C) \rightarrow (A \otimes B) \wedge C$	$R\wedge_1$		
$A \otimes (C \wedge B) \rightarrow C \wedge (A \otimes B)$	$R\wedge_2$		
$(B \vee C) \otimes A \rightarrow (B \otimes A) \wedge (C \supset A)$	$L\vee_1^*$		
$(C \vee B) \otimes A \rightarrow (C \supset A) \wedge (B \otimes A)$	$L\vee_2^*$		
$A \otimes (B \vee C) \rightarrow (A \otimes B) \vee C$	$R\vee_1$		
$A \otimes (C \vee B) \rightarrow C \vee (A \otimes B)$	$R\vee_2$		
$(C \supset B) \otimes A \rightarrow C \wedge (B \otimes A)$	$L\supset_2$		
$A \otimes (B \supset C) \rightarrow (A \otimes B) \supset C$	$R\supset_1^*$		
$A \otimes (C \supset B) \rightarrow C \supset (A \otimes B)$	$R\supset_2^*$		
$(\forall x.B) \otimes A \rightarrow B\{x/t\} \otimes A$	$L\forall i$		
$(\forall x.B) \otimes A \rightarrow \exists x.(B \otimes A)$	$L\forall s$		
$A \otimes (\forall x.B) \rightarrow \forall x.(A \otimes B)$	$R\forall s^*$		
$(\exists x.B) \otimes A \rightarrow \forall x.(B \otimes A)$	$L\exists s^*$		
$A \otimes (\exists x.B) \rightarrow A \otimes B\{x/t\}$	$R\exists i$		
$A \otimes (\exists x.B) \rightarrow \exists x.(A \otimes B)$	$R\exists s$		
FORWARD			
$A\{t/x\} \otimes (t = u) \rightarrow A\{u/x\}$	$F=1$		
$A\{u/x\} \otimes (t = u) \rightarrow A\{t/x\}$	$F=2$		
$A \otimes (B \wedge C) \rightarrow A \otimes B$	$F\wedge_1$		
$A \otimes (C \wedge B) \rightarrow A \otimes B$	$F\wedge_2$		
$A \otimes (B \vee C) \rightarrow (A \otimes B) \vee C$	$F\vee_1$		
$A \otimes (C \vee B) \rightarrow C \vee (A \otimes B)$	$F\vee_2$		
$A \otimes (B \supset C) \rightarrow (A \otimes B) \supset C$	$F\supset_1$		
$A \otimes (C \supset B) \rightarrow C \supset (A \otimes B)$	$F\supset_2$		
$A \otimes (\forall x.B) \rightarrow A \otimes B\{x/t\}$	$F\forall i$		
$A \otimes (\forall x.B) \rightarrow \forall x.(A \otimes B)$	$F\forall s$		
$A \otimes (\exists x.B) \rightarrow \exists x.(A \otimes B)$	$F\exists s^*$		
$B \otimes A \rightarrow A \otimes B$	$Fcomm$		

In the rules $\{L\forall s, L\exists s, R\forall s, R\exists s, F\forall s, F\exists s\}$, x is not free in A .

Figure 1.3: Linking rules

UNITS			
$\langle \circ, \dagger \rangle \in \{\langle \wedge, \top \rangle, \langle \vee, \perp \rangle, \langle \supset, \top \rangle\}$	$\dagger \circ A \rightarrow A$	neul	
$\langle \circ, \dagger \rangle \in \{\langle \wedge, \top \rangle, \langle \vee, \perp \rangle\}$	$A \circ \dagger \rightarrow A$	neur	
$\langle \circ, \dagger \rangle \in \{\langle \wedge, \perp \rangle, \langle \vee, \top \rangle\}$	$\dagger \circ A \rightarrow \dagger$	absl	
$\langle \circ, \dagger \rangle \in \{\langle \wedge, \perp \rangle, \langle \vee, \top \rangle, \langle \supset, \top \rangle\}$	$A \circ \dagger \rightarrow \dagger$	absr	
$\langle \diamond, \dagger \rangle \in \{\langle \forall, \top \rangle, \langle \exists, \perp \rangle\}$	$\diamond x. \dagger \rightarrow \dagger$	absq	
	$\perp \supset A \rightarrow \top$	efq	

Figure 1.4: Unit elimination rules

1.7 Related works

Window Inference

We have already mentioned Proof-by-Pointing, which was part of the CtCoq and Pcoq efforts [4] to design a graphical user interface for the Coq proof assistant. Another contemporary line of work was the one based on *window inference*, initially pioneered by P.J. Robinson and J. Staples. In [163], window inference is described as a general proof-theoretical framework, which aims to accomodate for the pervasive use of *equivalence transformations* throughout mathematics and computer science.

Window inference has been used both for general-purpose logics like HOL [79], and in more specialized settings like program refinement [80]. It naturally lends itself to integration in a graphical user interface ([109], [116]), where the user can *focus* on a subexpression by clicking on it. One is then presented with a new *graphical* window, holding the selected expression as well as an extended set of hypotheses exposing information inferrable from the context of the expression. The user can pick from a list of valid transformations to be applied to the expression, before closing the window. This propagates the transformations to the parent window by replacing the old subexpression by the new one, without modifying the surrounding context.

This process is quite reminiscent of the rewriting produced by our DnD actions. One key difference is that window inference rules can be applied stepwise, while we choose to hide the sequence of rules that justifies a DnD. The window inference approach gives to the user a precise control of the transformations to be performed and thus could inspire interesting extensions of our work.

Other Gestural Proof Systems

There are other proof systems which include drag-and-drop features. Two of them are the KeY Prover [3] and TAS [116]. TAS is a window inference system tailored for program refinement, and uses DnD actions between an expression and a transformation, in order to apply the latter to the former. As for the KeY Prover, its usage of DnD overlaps only a very small portion of usecases that we hinted at in Section ??, namely the instantiation of quantifiers with objects.

We can also mention the recent work of Zhan et al. [200]. They share with us the vision of a proof assistant mainly driven by gestural actions, which requires far less textual inputs from the user. However, they only consider point-and-click actions, and rely on a text-heavy presentation at two levels:

1. the proof state, which is a structured proof text in the style of Isar [136];
2. the proof commands, which can only be performed through choices in textual menus.

[4]: Amerkad et al. (2001), *Mathematics and Proof Presentation in Pcoq*

[163]: Robinson et al. (1993), ‘Formalizing a Hierarchical Structure of Practical Mathematical Reasoning’

[79]: Grundy (1991), ‘Window Inference In The HOL System’

[80]: Grundy (1992), ‘A Window Inference Tool for Refinement’

[109]: Långbacka et al. (1995), ‘TkWin-HOL’

[116]: Lüth et al. (2000), ‘TAS — A Generic Window Inference System’

[3]: Ahrendt et al. (2016), ‘Using the KeY Prover’

[116]: Lüth et al. (2000), ‘TAS — A Generic Window Inference System’

[200]: Zhan et al. (2019), ‘Design of Point-and-Click User Interfaces for Proof Assistants’

[136]: Nipkow (2002), ‘Structured Proofs in Isar/HOL’

Explicit Proof Objects

Finally let us mention various recent implementations proposing various ways to construct proofs graphically: Building Blocks [112], the Incredible Proof Machine [18], Logitext⁷ and Click & coLLecT [24]. In particular, Logitext and Click & coLLecT exploit the same idea of associating click actions on head connectives to inference rules in sequent calculus. But these systems focus more on explicating the proof object than on making its construction easier.

[112]: Lerner et al. (2015), ‘Polymorphic Blocks: Formalism-Inspired UI for Structured Connectors’

[18]: Breitner (2016), ‘Visual Theorem Proving with the Incredible Proof Machine’

7: <http://logitext.mit.edu/main>

In this chapter, we engage in a thorough analysis of the logical semantics of DnD actions, which were introduced informally through examples in Chapter ???. We do this mainly from the formal perspective of deep inference proof theory, following the original work of K. Chaudhuri on his *subformula linking* paradigm [26]. But we always keep in mind the intended application to proof assistants, by motivating various design choices – actual or prospective – as ways to improve the UX of interactive proof building.

The chapter is organized as follows: Section ?? introduces the notions of context and polarity, and explains how DnD actions are specified by the user interactively through schemas called *linkages*. Section ?? explains how one can identify a subset of linkages that guarantees a *productivity* property on DnD actions. Section ?? describes the overall structure of how linkages translate into logical steps, and Section ?? discusses some subtleties of this translation that are related to the concept of *focusing* in automated proof search. Section ?? shows that the logical steps are sound, and Section ?? states and proves formally the productivity property. Finally, Section ?? shows how DnD actions can be turned into a complete deductive system without any need for click actions.

2.1 Linkages

Like most rewriting systems on terms (that is, tree-shaped data), the rewrite rules of Figure ?? and Figure ?? apply at any depth inside formulas. However logically, the shape of the *context* in which this rewriting occurs can provide important information, either to ensure soundness of the performed transformation (Section ??, Section ??), or to understand the status of quantified variables (Section ??).

As is standard in term rewriting, our notion of context will correspond to that of a (formula) tree with a distinguished leaf called its *hole*.

Definition 2.1.1 (Formula context) A formula context, written $A\Box$, is a proposition containing exactly one occurrence of a specific propositional variable \Box which is not used elsewhere.

Given another proposition B , we write $A\Box[B]$ for the proposition obtained by replacing \Box in $A\Box$ by B . Note that this replacement is not a substitution because it allows variable capture. For instance $\forall x. \Box[P(x)]$ is the proposition $\forall x. P(x)$.

Definition 2.1.2 (Path) A path is a proposition where one subformula has been selected. Formally, a path is a pair $(A\Box, B)$ formed by one context and one proposition:

- $A\Box$ is called the context of the path,

► B is called the *selection of the path*.

The path $(A\Box, B)$ can be viewed as the proposition $A\Box B$. For readability, we will generally also write $A\Box B$ for the path $(A\Box, B)$.

Definition 2.1.3 (Inversions) *Given a context $A\Box$, the number of inversions in $A\Box$, written $\text{inv}(A\Box)$, is the number of subterms of $A\Box$ which are of the form $C\Box \supset D$; that is the number of times the hole is on the left-hand side of an implication.*

For instance:

$$\begin{aligned}\text{inv}(D \wedge \Box) &= 0 \\ \text{inv}((D \wedge \Box) \supset E) &= 1 \\ \text{inv}((\Box \supset C) \supset D) &= 2\end{aligned}$$

Definition 2.1.4 (Polarity of a context) *We will write $A^+\Box$ to specify that a context is positive, meaning that $\text{inv}(A^+\Box)$ is even. Symmetrically, $A^-\Box$ will be used for negative contexts, meaning that $\text{inv}(A^-\Box)$ is odd.*

In addition to the items involved, every DnD action specifies the *selection* of a subterm in each item, which can be expressed formally as a path (Definition ??). We call *linkage* the combined data of the two items together with the selection, since the intent is to *link* the subterms to make them interact in some way.

Remark 2.1.1 In this thesis we only consider linkages between two subterms, but as noted in Section ??, rewriting is an example of action that can benefit from allowing multiple selections¹.

Each kind of DnD action is mapped in the system to a specific form of linkage, which is designed to hold all the information necessary for the correct execution of the action. In this way the system can automatically search for linkages of a certain form, and propose to the user all well-defined actions associated to these linkages.

Remark 2.1.2 In the future, one can imagine several DnD actions associated to a given linkage. In this case, the user could be queried to choose the action to be performed (typically with a pop-up menu). However with the actions considered in this thesis, such ambiguities never arise.

On the “items axis”, we already distinguished between backward and forward linkages, written respectively $A \oslash B$ and $A \otimes B$. If the items are unspecified, we will write $A @ B$.

Using the “selection axis”, we can specify a further distinction that was informal up to now: that of *logical* action and *rewrite* action.

- *Logical* linkages link two subformulas. Thus they have the form $B\Box A @ C\Box A'$.
- *Rewrite* linkages link one side of an equality with a first-order term. Using liberally the notations from Definitions ?? and ??, they thus

have the form

$$B \boxed{t} = u @ C \boxed{t'} \text{ (or symmetrically } B \boxed{u} = \boxed{t} @ C \boxed{t'})$$

By forgetting the information on which subterms are selected, one can see any linkage as a formula whose topmost connective is a linking operator $@ \in \{\otimes, \odot\}$. Then it is natural to view linkages as the redexes of the rewrite rules of Figure ??, although from the user's standpoint linkages only happen at the top level².

2.2 Validity

In the original formulation of subformula linking [26], a semantics is associated to every logical linkage, even when the selected subformulas A and A' are not unifiable. This is made possible by the addition of so-called *release* rules³, which simply turn linking operators into their associated logical connective. In our setting this would give the rewrite rules of Figure ?. However in this work we opt for a different approach: instead we define a *validity criterion* on linkages, which guarantees that they give rise to the behaviors described in the previous sections. The criterion tackles two issues:

- **Polarity:** the selected subterms must have opposite *polarities*, so that the *negative* subterm justifies the *positive* one;
- **Identity:** the selected subterms must be *unifiable*, so that after instantiating some quantifiers in their context they can interact through the id rule or the equality rules $L=$, $F=$.

One benefit of using this criterion is that it filters out all linkages whose semantics relies on release rules, capturing intuitively a notion of *productivity*: instead of just moving around subformulas, we know for sure that some simplification occurs, either a justification with the id rule on logical linkages, or a rewriting with the equality rules on rewrite linkages. This will be stated more formally in Section ?.

Validity is very useful to support the *suggestion* mechanism implemented in Actema. The idea is that when the user starts dragging an item, this indicates to the system that she wants to perform a DnD action involving subterms of this item. Then the system can suggest such possible actions by highlighting subterms in the goal which form a valid linkage with the dragged item. Typically in the example of Figure ?, dragging the hypothesis $\forall x. \text{Human}(x) \supset \text{Mortal}(x)$ will have the effect of highlighting exactly $\text{Mortal}(\text{Socrates})$ in the conclusion and $\text{Human}(\text{Socrates})$ in the other hypothesis as possible drop targets. In this case this corresponds to all subterms in the goal which are not contained in the dragged item. But if one were to drag the $\text{Human}(\text{Socrates})$ hypothesis, then only the subterm $\text{Human}(x)$ in the other hypothesis would be suggested as a drop target. This could not work with the “release” semantics mentioned earlier, since then all subterms would again be highlighted, providing no useful information to the user.

2: In fact this is more of a limitation of Actema's current interface: one cannot link two subterms that live in the same item, because dragging actions can only be performed on *entire* items. But in the original formulation and implementation of subformula linking [26], linkages can be created between arbitrary subformulas. We come back to this issue in Section ?.

$$\begin{aligned} A \odot B &\rightarrow A \supset B && \text{Brel} \\ A \otimes B &\rightarrow A \wedge B && \text{Frel} \end{aligned}$$

Figure 2.1: Release rules

[26]: Chaudhuri (2013), ‘Subformula Linking as an Interaction Method’

3: A terminology coming from the line of works on *focusing* in proof theory [5], see also Section ?.

We believe that in more complex situations, this filtering can be quite helpful to guide the user towards the right path to follow in their reasoning. Although non-trivial arguments are often based on “guessing” the right value or lemma to be used, a large part of mathematical reasoning also consists in “connecting the dots” with information already at hand. Our DnD actions capture this metaphor quite directly, and thus shall be especially useful to beginners unfamiliar with proving, who often show difficulties in understanding how to build a proof from scratch. More generally, proof assistants have the potential to provide a well-defined and rigorous methodology in the art of crafting proofs, in the same way that we have been teaching precise algorithms for solving equations in calculus classes for centuries. Having a graphical interface that makes this methodology more intuitive and discoverable is the main goal of this work, and (valid) DnD actions seem to be a good candidate as a core principle for such a methodology.

Polarity

The restrictions on polarities are captured formally by the following condition:

Condition 2.2.1 (Polarity) The following must be true for a logical linkage $B \boxed{A} @ D \boxed{A'}$ to be valid:

1. the parity of $\text{inv}(B \boxed{})$ is:
 - a) the same as $\text{inv}(D \boxed{})$ if $@ = \ominus$
 - b) the opposite of $\text{inv}(D \boxed{})$ if $@ = \otimes$
2. if $@$ is \ominus and $\text{inv}(D \boxed{}) = 0$, then $\text{inv}(B \boxed{}) = 0$.

The following must be true for a rewrite linkage $B \boxed{t} @ D \boxed{t'}$ to be valid:

1. if $B \boxed{}$ holds the equality, then it must be:
 - a) positive if $@ = \ominus$;
 - b) positive if $@ = \otimes$;
2. if $D \boxed{}$ holds the equality, then it must be:
 - a) negative if $@ = \ominus$;
 - b) positive if $@ = \otimes$.

One understands that for rewrite linkages, this simply guarantees that the equality is in negative position. For logical linkages, Clause ?? ensures that the selected subformulas have opposite polarities, and Clause ?? ensures that the linkage makes sense in our *intuitionistic* setting.

Indeed one could imagine the following behavior in classical logic:

$$(\boxed{A} \supset B) \supset C \otimes \boxed{A} \rightarrow^* C \supset A$$

which gives a proof of Peirce’s law when replacing C with A . We will come back to this example in Chapter ??, but for now we can just remark that there is no way to handle it with the rules of Figure ?? because we lack a rule for redexes of the form $B \boxed{A} \supset C \otimes D \boxed{A'}$.

Identity

A context binds variables in the selected proposition. These variables will be unifiable or not depending upon: (1) the nature of the quantifier (\forall or \exists), (2) whether they occur in a hypothesis or a conclusion, and (3) whether they occur on the left-hand of an (odd number of) implication(s). Therefore, we start by splitting the list of variables bound by a context in two parts.

Definition 2.2.1 (Positive and negative variables) *Given a context $A\Box$ seen as a tree, one can always start from the root and traverse the branch of $A\Box$ that leads to its hole \Box . We write $l(A\Box)$ the list of all variables quantified along the way. This list is ordered, the variables closer to the root coming first.*

$l(A\Box)$ can be seen as the interleaving of two sublists $l^+(A\Box)$ and $l^-(A\Box)$ of positively and negatively unifiable variables, in the following precise sense: $x \in l^+(A\Box)$ (resp. $x \in l^-(A\Box)$) iff there are contexts $B\Box$, $C^+\Box$ and $D^-\Box$ such that $A\Box$ is either $C^+[\exists x.B\Box]$ or $D^-[\forall x.B\Box]$ (resp. $D^-[\exists x.B\Box]$ or $C^+[\forall x.B\Box]$).

For instance, if $A\Box \equiv \forall x.\exists y.(B \wedge ((\exists x'.\forall y'.\Box) \supset \forall z.C))$, then we have:

$$l(A\Box) = [x, y, x', y'] \quad l^+(A\Box) = [y, y'] \quad l^-(A\Box) = [x, x']$$

Definition 2.2.2 (Unifiable variables) *The set $U(\mathcal{L})$ of unifiable variables of a linkage $\mathcal{L} \equiv B[A] @ C[A']$ is:*

- ▶ $l^-(B\Box) \cup l^+(C\Box)$ if $@$ is \otimes , and
- ▶ $l^-(B\Box) \cup l^-(C\Box)$ if $@$ is \otimes .

The following notions of substitution and unification are the usual ones and we do not go into details:

Definition 2.2.3 (Substitution) *A substitution is a mapping from variables to terms such that $\{x \mid \sigma(x) \neq x\}$ is finite; we call this set the domain of σ .*

When $\sigma(x) \equiv x$ we say that x is not instantiated by σ .

Given a proposition A and a substitution σ , we write $\sigma(A)$ for the application of σ to A in the usual way.

Definition 2.2.4 (Unification) *Given two propositions A and A' and a list of variables l , we say that a substitution σ unifies A and A' over l when $\sigma(A) \equiv \sigma(A')$ and the domain of σ is a subset of l .*

If such a substitution exists, we say that A and A' are unifiable over l .

Given A , A' and l , the well-known unification algorithm decides whether A and A' are unifiable over l and constructs the substitution when it exists [119].

[119]: Martelli et al. (1982), 'An Efficient Unification Algorithm'

Condition 2.2.2 (Identity) For a linkage $B \boxed{A} @ C \boxed{A'}$ to be valid, the following must be true:

1. There exists a substitution σ which unifies A and A' over the unifiable variables of the linkage.
2. Furthermore, the unification respects the order over the variables. More precisely, we request that there exists a list l which is an interleaving of $l(B\Box)$ and $l(C\Box)$ such that, given a unifiable variable x in the domain of σ , all variables occurring in $\sigma(x)$ are placed before x in l :

$$\forall y \in \text{fv}(\sigma(x)) \cap (l(B\Box) \cup l(C\Box)), y <_l x.$$

The last condition ensures acyclicity and will prohibit invalid linkages as described in Section ?? . More precisely, the list l specifies the order in which the quantifiers will be treated in the proof construction.

Finally we can state the full validity criterion for linkages:

Definition 2.2.5 (Valid linkage) *We say that a linkage \mathcal{L} is valid if it satisfies Conditions ?? and ??.*

One can check that all the examples given up to here were based on valid linkages.

2.3 Describing DnD actions

We are now equipped to specify how logical and rewrite linkages translate deterministically to the backward and forward proof steps shown in all examples.

First some remarks can be made about the rewrite rules of Figure ??:

- The set of rewrite rules is obviously non-confluent.
- It is also terminating, because the number of connectives or quantifiers under \otimes or \oslash decreases⁴.

As for the rules of Figure ??, they are both terminating *and* confluent. Indeed they define a function that eliminates redundant occurrences of the units \top and \perp .

Here is a high-level overview of the complete procedure followed to generate a proof step:

1. **Selection:** the user selects two subterms in two items of the current goal;
2. **Linkage:** this either gives rise to a logical linkage $B \boxed{A} @ C \boxed{A'}$ (resp. a rewrite linkage $B \boxed{t = u} @ C \boxed{t'}$), or does not correspond to a known form of linkage. In this case the procedure stops here, and the system does not propose any action to the user;
3. **Validity:** the system verifies that the linkage is *valid*, by performing successively the following checks:

4: Except for the Fcomm rule which is just meant to make the \otimes operator commutative; formally, the only infinite reduction paths end with an infinite iteration of Fcomm.

- a) **Polarity:** the linkage must satisfy Condition ??;
- b) **Unification:** the selected subterms A and A' (resp. t and t') must be unifiable, yielding a substitution σ ;
- c) **Dependencies:** the substitution σ must satisfy Condition ??.

The procedure stops if it fails at any of the above checks;

- 4. **Linking:** the system then chooses a rewriting starting from the linkage. Thanks to Theorem ??, this rewriting always ends with a proposition of the form $D \boxed{\sigma(A) \otimes \sigma(A')}$

$$(\text{resp. } D \boxed{\boxed{\sigma(t)} = u @ C_0 \boxed{\sigma(t')}});$$

- 5. **Interaction:** thus one can apply the id rule (resp. an equality rule in $\{L=1, L=2, F=1, F=2\}$);
- 6. **Unit elimination:** in the case of a logical action, this creates an occurrence of \top , which is eliminated using the rules of Figure ??;
- 7. **Goal modification:** the two previous steps produced a formula E . In the case of a forward linkage, a hypothesis E is added to the goal; in the case of a backward linkage, the goal's conclusion becomes E . In both cases, the logical soundness is guaranteed by Property ??.

2.4 Soundness

All examples up to now followed the scheme for DnD actions sketched in Section ??:

- Given a blue item A and a red item B , backward proof steps produce a new conclusion C by applying a sequence of rewrite rules $A \otimes B \rightarrow^* C$.
- Given two blue items A and B , forward proof steps produce a new hypothesis C by applying a sequence of rewrite rules $A \oplus B \rightarrow^* C$.

Thus for such actions to be logically sound, we have to make sure that our rewriting system satisfies the following property:

Theorem 2.4.1 (Soundness)

- If $A \otimes B \rightarrow^* C$, then $A, C \Rightarrow B$.
- If $A \oplus B \rightarrow^* C$, then $A, B \Rightarrow C$.

The following simple covariance and contravariance property will be used extensively later on:

Lemma 2.4.2 (Variance) If $\Gamma, A \Rightarrow B$, then $\Gamma, C^+ \boxed{A} \Rightarrow C^+ \boxed{B}$ and $\Gamma, D^- \boxed{B} \Rightarrow D^- \boxed{A}$.

Proof. By induction on the depths of $C^+ \square$ and $D^- \square$. □

For each rule, interpreting \otimes as \supset and \oplus as \wedge is enough to show that the rule satisfies Property ?? locally. Formally, we can define a mapping from

formulas containing linking operators to usual formulas where they have been replaced by their interpretation:

Definition 2.4.1 (Interpretation of linking operators) *The mapping $[\cdot]$ is defined inductively as follows:*

$$\begin{aligned}
 [A \oslash B] &= [A] \supset [B] \\
 [A \otimes B] &= [A] \wedge [B] \\
 [A \circ B] &= [A] \circ [B] && \text{for } \circ \in \{\wedge, \vee, \supset\} \\
 [\diamond x.A] &= \diamond x.[A] && \text{for } \diamond \in \{\forall, \exists\} \\
 [\dagger] &= \dagger && \text{for } \dagger \in \{\top, \perp\} \\
 [a] &= a && \text{for } a \text{ atomic}
 \end{aligned}$$

For rewritings taking place deeper inside a proposition however, we need to consider the polarity of their context.

Lemma 2.4.3 (Local soundness)

- ▶ If $C^+ \boxed{A \oslash B} \rightarrow D$ then $[D] \Rightarrow C^+ \boxed{A \supset B}$.
- ▶ If $C^- \boxed{A \oslash B} \rightarrow D$ then $C^- \boxed{A \supset B} \Rightarrow [D]$.
- ▶ If $C^+ \boxed{A \otimes B} \rightarrow D$ then $C^+ \boxed{A \wedge B} \Rightarrow [D]$.
- ▶ If $C^- \boxed{A \otimes B} \rightarrow D$ then $[D] \Rightarrow C^- \boxed{A \wedge B}$.

Proof. First notice that D is necessarily of the form $C \boxed{D_0}$ where $A @ B \rightarrow D_0$ ⁵. Then by careful analysis of each rule, it is straightforward to show that $[D_0] \Rightarrow A @ B$ if $@ = \oslash$ or $A \wedge B \Rightarrow [D_0]$ if $@ = \otimes$. We can conclude in each case by applying Lemma ?? with $C \square$ accordingly. \square

5: Indeed an implicit assumption in this section, which is preserved by all the rules, is that a formula contains at most one linking operator. Thus if $C \boxed{A @ B} \rightarrow D$, the only possible redex is $A @ B$.

Remark 2.4.1 For some rules, like $R_{\supset,1}$, the left-hand and right-hand propositions are equivalent:

$$A \supset B \supset C \iff A \wedge B \supset C$$

Such rules are called *invertible* and their names are tagged by *. This point will be relevant in Section ??.

An easy but important technical point is that rewrite rules preserve the polarity of contexts around redexes, in the following precise sense:

Fact 2.4.1 (Polarity preservation)

- ▶ If $C \boxed{A \oslash B} \rightarrow C' \boxed{A' \oslash B'}$ (resp. $C \boxed{A \otimes B} \rightarrow C' \boxed{A' \otimes B'}$) then $C \square$ and $C' \square$ have the same polarity.
- ▶ If $C \boxed{A \oslash B} \rightarrow C' \boxed{A' \otimes B'}$ (resp. $C \boxed{A \otimes B} \rightarrow C' \boxed{A' \oslash B'}$) then $C \square$ and $C' \square$ have opposite polarities.

Combining Lemma ?? and Fact ??, we obtain the central soundness result about the rewrite rules:

Lemma 2.4.4 (Contextual soundness)

- ▶ If $C^+ \boxed{A \otimes B} \rightarrow^* D$ then $[D] \Rightarrow C^+ \boxed{A \supset B}$.
- ▶ If $C^- \boxed{A \otimes B} \rightarrow^* D$ then $C^- \boxed{A \supset B} \Rightarrow [D]$.
- ▶ If $C^+ \boxed{A \otimes B} \rightarrow^* D$ then $C^+ \boxed{A \wedge B} \Rightarrow [D]$.
- ▶ If $C^- \boxed{A \otimes B} \rightarrow^* D$ then $[D] \Rightarrow C^- \boxed{A \wedge B}$.

Proof. By induction on the length of the derivation. The base case is trivial by reflexivity of entailment. We give the proof for the first statement in the list, other cases work similarly. We can assume without loss of generality that the derivation has the following shape:

$$C^+ \boxed{A \otimes B} \rightarrow C' \boxed{A' @ B'} \rightarrow^* D$$

Then we reason by case on the linking operator @ :

- ▶ @ = \otimes : by Fact ??, C' must be positive. Therefore by induction hypothesis $[D] \Rightarrow C' \boxed{A' \supset B'}$. By Lemma ?? we have $C' \boxed{A' \supset B'} \Rightarrow C^+ \boxed{A \supset B}$. Thus by transitivity $[D] \Rightarrow C^+ \boxed{A \supset B}$.
- ▶ @ = \otimes : by Fact ??, C' must be negative. Therefore by induction hypothesis $[D] \Rightarrow C' \boxed{A' \wedge B'}$. By Lemma ?? we have $C' \boxed{A' \wedge B'} \Rightarrow C^+ \boxed{A \supset B}$. Thus by transitivity $[D] \Rightarrow C^+ \boxed{A \supset B}$.

□

Finally, soundness (Theorem ??) is obtained as the special case where the rewriting starts in the (positive) empty context.

2.5 Productivity

An important property of the linking step ?? is that there is always a rewriting sequence that brings together the selected subterms, which ensures that we can proceed to the interaction step ??.

Because the rewrite rules are terminating, the important point is to show that one can always apply a rule until one reaches an interaction rule on the selected subterms. In other words, it is possible to find at least one rule which preserves Conditions ?? and ?? on linkages:

Lemma 2.5.1 (Valid Progress) *If a linkage $\mathcal{L} \equiv C \boxed{A} @ C' \boxed{A'}$ (resp. $C \boxed{t} @ C' \boxed{t'}$) is valid, then either:*

1. $\mathcal{L} \equiv \boxed{A} \otimes \boxed{A}$ (resp. $C \square \in \{\square = u, u = \square\}$ for some u and $t \equiv t'$);
2. or $\mathcal{L} \rightarrow E \boxed{\mathcal{L}'}$ for some $E \square, \mathcal{L}'$ with \mathcal{L}' valid.

A detailed proof is given hereafter for the case of logical linkages. It is not fundamentally difficult, but understandably verbose. The two main points are:

- ▶ The rules involving a connective always preserve validity.

- When one can apply a rule involving a quantifier $\forall x$ (resp. $\exists x$), one checks whether the substitution instantiates x or not. In the first case one performs the instantiation rule $L\forall i$ or $F\forall i$ (resp. $R\exists i$); in the second case the corresponding switch rule in $\{L\forall s, R\forall s, F\forall s\}$ (resp. $\{L\exists s, R\exists s, F\exists s\}$).

Proof. Let $\mathcal{L} \equiv B \boxed{A} @ C \boxed{A'}$ be a valid linkage.

1. Suppose $B\Box \equiv C\Box \equiv \Box$. By Condition ??, we know that a forward linkage cannot verify $(\text{inv}(B\Box), \text{inv}(C\Box)) = (0, 0)$, thus \mathcal{L} must be a backward linkage. Also $l(B\Box)$ and $l(C\Box)$ are empty, hence by Condition ?? A and A' are unified by an empty substitution, which entails that $A \equiv A'$. Therefore we are in the first case where $\mathcal{L} \equiv \boxed{A} \otimes \boxed{A}$.

2. Otherwise, either $B\Box$ or $C\Box$ is non-empty. In the following, we show that we can always apply a rewrite rule that produces a new, valid linkage $\mathcal{L}' \equiv B' @' C'$.

Let σ and l be respectively the substitution and interleaving of the quantified variables of $B\Box$ and $C\Box$ given by Condition ??, with l decomposed as $x :: l'$.

- If x is quantified at the head of either $B\Box$ or $C\Box$, then we apply the associated quantifier rule:

Switch rule ($L\forall s, L\exists s, R\forall s, R\exists s, F\forall s, F\exists s$) Only if x is not in the domain of σ . In forward mode and when $B\Box$ binds x , one must first apply the rule $F\text{comm}$ to put $B \boxed{A}$ on the right of \otimes , so that the switch rule is applicable. Now we show that \mathcal{L}' is valid:

1. \mathcal{L}' satisfies Condition ?? trivially since none of the switch rules changes the number of inversions.
2. For each switch rule we can show, using the fact that x is not in the domain of σ , that $U(\mathcal{L}') = U(\mathcal{L})$. Since the selected formulas A and A' stay untouched by the rule, we can choose σ as a valid unifier that ranges over $U(\mathcal{L}')$.
3. In all switch rules, we have $l(\mathcal{L}') = l'$ because the quantifier of x is moved in the outer context of the linkage. Thus we can just take l' as interleaving, and Condition ?? will still be verified because l' is a sublist of l .

Instantiation rule ($L\forall i, R\exists i, F\forall i$) Only if x is instantiated by σ , using $\sigma(x)$ as witness. Again one might need to apply $F\text{comm}$ first. Then we check the validity of \mathcal{L}' :

1. \mathcal{L}' satisfies Condition ?? trivially since none of the instantiation rules changes the number of inversions.
2. For each instantiation rule we can show, using the fact that x is instantiated by σ , that $U(\mathcal{L}') = U(\mathcal{L}) \setminus \{x\}$. Then we take as unifier σ where the binding for x is removed, written $\sigma \setminus x$.

Now we need to make sure that $\sigma \setminus x$ is indeed a unifier for the selected formulas. We consider only the case where $B\Box$ binds x , the proof being exactly symmetric when $C\Box$ binds x . Let $B_0\Box$ be the direct subcontext of $B\Box$, that is $B\Box$ without the head quantifier binding x .

First we can assert that $B_0\Box\{A\{\sigma(x)/x\} \equiv B_0\{\sigma(x)/x\}\Box\{A\{\sigma(x)/x\}\}$. Indeed, Clause ?? of Condition ?? guarantees that for any free variable y of $\sigma(x)$, $y \notin l(B_0\Box)$, and thus the above instantiation can propagate safely to A without capture. To convince yourself that $y \notin l(B_0\Box)$, suppose the contrary. Then $y \in l(B\Box)$, and by Clause ?? y must be placed before x in l . But this is impossible since x is the first element of l !

So we know that the selected formula on the left of \mathcal{L}' is $A\{\sigma(x)/x\}$, while it is still A' on the right. Thus it only remains to show that

$$A\{\sigma(x)/x\}[\sigma \setminus x] \equiv A'[\sigma \setminus x].$$

On the left we have by definition that $A\{\sigma(x)/x\}[\sigma \setminus x] \equiv A[\sigma]$, and on the right we have $A'[\sigma \setminus x] \equiv A'[\sigma]$ because x cannot occur in A' since it is bound in $B_0\Box$ (here we rely on the Barendregt convention).

3. In all instantiation rules, we have $l(\mathcal{L}') = l'$ because the quantifier of x is removed by the instantiation. Thus we can again take l' as interleaving.
- If x is not quantified at the head of $B\Box$ or $C\Box$, then either both heads are propositional connectives, or one is a propositional connective and the other is empty. In both cases we can choose either a rule of the form $L_{\circ i}$, $R_{\circ i}$ or $F_{\circ i}$, where \circ is the connective and i the index of the direct subcontext where A or A' occurs, or the F_{comm} rule. Again we check the conditions of Definition ??:
1. In most rules the number of inversions stays unchanged. The only exceptions are $R_{\supset i}$ and $F_{\supset i}$, which decrease the number of inversions of the right context $C\Box$ by 1. But since they are also the only rules that change the linking operator, the truth of Clause ?? is preserved: if the parities were opposite (resp. identical) in \mathcal{L} , then \mathcal{L} must be forward (resp. backward). Thus \mathcal{L}' is necessarily backward (resp. forward), and so the parities in \mathcal{L}' must be identical (resp. opposite), which is the case thanks to the inversion decrement.
- For Clause ??, we can distinguish two cases:
- If \mathcal{L} is backward, then either we apply the $R_{\supset i}$ rule and \mathcal{L}' is forward, and thus satisfies Clause ?? trivially; or we apply another backward rule and \mathcal{L}' is backward. Now suppose $\text{inv}(C'\Box) = 0$. Then we must have $\text{inv}(C\Box) = \text{inv}(C'\Box) = 0$ and $\text{inv}(B\Box) = \text{inv}(B'\Box)$ since all backward rules other than $R_{\supset i}$ preserve the number of inversions. And because \mathcal{L} satisfies Clause

?? by validity, we can deduce that $\text{inv}(B\Box) = 0$, and thus $\text{inv}(B'\Box) = 0$.

- If \mathcal{L} is forward, then either we apply a forward rule that is neither $F\supset_1$ nor $F\text{comm}$ and \mathcal{L}' is forward, and thus satisfies Clause ?? trivially; or we consider applying either $F\supset_1$ or $F\text{comm}$. There are three cases:
 - * If $\text{inv}(C\Box) > 1$, then we can safely apply $F\supset_1$ since we have $\text{inv}(C'\Box) = \text{inv}(C\Box) - 1 > 0$;
 - * If $\text{inv}(C\Box) = 0$, then $C\Box$ is empty and we are forced to apply $F\text{comm}$ so that we can apply the forward rule corresponding to the head connective of $B\Box$. Then $C\Box$ ends up on the left of \otimes , thus if we apply $F\supset_1$ for $B\Box$ Clause ?? will be satisfied trivially;
 - * If $\text{inv}(C\Box) = 1$, then either $\text{inv}(B\Box) = 0$ and we can safely apply $F\supset_1$ since $\text{inv}(B'\Box) = \text{inv}(B\Box)$; or $\text{inv}(B\Box) > 0$, and we cannot apply $F\supset_1$ because we would end up with $\text{inv}(C'\Box) = 0$ and $\text{inv}(B'\Box) > 0$, thus violating Clause ?. Hence as in the previous case, we need to apply $F\text{comm}$ first. Then it cannot be the case that $\text{inv}(B\Box) = 1$ because we would have $\text{inv}(B\Box) = \text{inv}(C\Box)$, which violates Clause ? from the validity of \mathcal{L} . Thus $\text{inv}(B\Box) > 1$, which entails that we can safely apply $F\supset_1$ on $B\Box$ as in the first case.

Notice that whenever we apply the $F\text{comm}$ rule, it is to apply the rule corresponding to the head connective of $B\Box$ immediately afterwards: we never enter a loop by applying $F\text{comm}$ twice in a row. Thus technically there are two reduction steps, but we treat them as one.

2. Since we do not deal with quantifiers, we can just take the same unifier σ .
3. Idem here, we take the same interleaving l .

□

Then we can state the following *productivity theorem*, which is a direct consequence of the previous lemma and the fact that the rewrite rules terminate:

Theorem 2.5.2 (Productivity) *If \mathcal{L} is a valid linkage, then there is a sequence of reductions with one of the following forms:*

$$\mathcal{L} \rightarrow^* D^+ \boxed{A \otimes A}$$

$$\mathcal{L} \rightarrow^* D \boxed{t = u @ A[t]} \quad \mathcal{L} \rightarrow^* D \boxed{u = t @ A[t]}$$

This is the formal counterpart to the notion of productivity mentioned in Section ?. Intuitively, this theorem ensures non-trivial progress in the reasoning: we managed to connect some dots in the problem and actually

solve a subgoal. That is, either the conclusion is *strictly* weakened after a backward DnD, or the assumptions are *strictly* strengthened after a forward DnD, instead of having just an equivalent goal written in a different way⁶. This again contrasts with the release semantics of subformula linking which do not provide this guarantee of productivity, or with the logical reasoning tactics of proof assistants based on natural deduction rules.

2.6 Focusing

A last point to deal with is non-confluence and in particular choosing between first simplifying the head connective on the right or the left of \otimes or \odot . For instance in $\boxed{A} \vee B \odot B \vee \boxed{A}$ one can apply either L_{\vee_1} or R_{\vee_2} .

Interestingly, an answer is provided by *focusing*. It has been noticed by Andreoli [5] that, in bottom-up proof search, one should apply the invertible logical rules first since they preserve provability. In our framework, this translates into first applying the invertible rewrite rules (the ones marked by a *). In the case of the example above, this means performing L_{\vee_1} first, which leads to the following behavior:

$$\boxed{A} \vee B \odot B \vee \boxed{A} \rightarrow^* B \supset B \vee A.$$

This is indeed the “right” choice, since applying R_{\vee_2} first would lead to a dead-end⁷:

$$\boxed{A} \vee B \odot B \vee \boxed{A} \rightarrow^* B \vee (B \supset A).$$

The general scheme for choosing a rule to apply to a redex $C\boxed{A} @ D\boxed{B}$ is the following⁸:

1. If $C\Box \equiv D\Box \equiv \Box$, we just apply the id rule (assuming $A \equiv B$ by Lemma ??).
2. If only one context is non-empty, say $C\Box$, we look at its head connective as well as the side where its hole resides:
 - ▶ either $C\Box \equiv C_0\Box \circ E$ for some binary connective \circ , and we choose the rule L_{\circ_1} (resp. F_{\circ_1}) if $@ = \odot$ (resp. $@ = \otimes$);
 - ▶ or $C\Box \equiv E \circ C_0\Box$ and we choose the rule L_{\circ_2} (resp. F_{\circ_2}) if $@ = \odot$ (resp. $@ = \otimes$).

In the case where it is $D\Box$ which is non-empty, we apply the same logic but with the right rules R_{\circ_i} instead of the left rules L_{\circ_i} .

3. If both contexts are non-empty, then the previous logic determines one rule for $C\Box$ and one rule for $D\Box$, giving rise to the ambiguity described in the above example.

There are three possibilities when analysing invertibility of the two rules in the third case:

1. if both are invertible, then the order of application does not matter since we preserve provability in the end;
2. if only one is invertible, we apply it first following the focusing discipline;

6: This remark only applies to logical linkages however, since rewriting equalities can only produce equivalent statements. Some proof assistants provide facilities to rewrite arbitrary relations in subterms of arbitrary depth, such as Coq with its *generalized rewriting* mechanism [171]. This includes non-symmetric relations that can produce non-equivalent statements, and there is no reason in principle it could not be integrated in our paradigm, in the form of generalized substitution rules in place of $L_{=}$ and $F_{=}$.

[5]: Andreoli (1992), ‘Logic Programming with Focusing Proofs in Linear Logic’

7: Interestingly in this case it creates a dead-end only in intuitionistic logic: in classical logic both results are provable.

8: A less deterministic version of this scheme is already present implicitly in the proof of Lemma ??.

3. if neither are invertible, we want to choose the order that maximizes the preservation of provability. It turns out that in almost all cases the two rules commute, that is the formulas obtained in the two orderings are equivalent. The only exceptions are the critical pairs $Fv_i / F\supset_2$ for $i \in \{1, 2\}$, as was noted independently in [28]. In this case, one should rely on information given by the user to choose the right ordering, which can be done by exploiting the *orientation* of the associated DnD action, that is distinguishing between the source path and the destination path⁹.

Currently we do not have detailed proofs of permutability for all pairs of rules. The reason is mostly pragmatic: given the great number of rules, this would take a lot of time to perform a full case analysis. Actually our claim of permutability comes from [28] which uses a subformula linking system almost identical to ours. We hope we will be able to provide rigorous proofs in annex when time permits.

2.7 Completeness

To enable a fully graphical approach to theorem proving that does not rely on a textual proof language, it is important to show that (a subset of) the set of actions exposed to the user is *complete* with respect to provability. That is, any formula A which is *true* in our logic — here intuitionistic FOL — can be proved by executing a sequence of graphical actions that reduces it to the empty goal. We noticed in Remark ?? that click actions are a sufficient basis for completeness. While we believe that a combination of both click and DnD actions is more comfortable to handle a variety of proof situations, it is still interesting to consider the question of completeness for DnD actions alone. It turns out that the answer is positive: the mechanism of *subformula linking* underlying DnD actions is powerful enough to capture provability in FOL. This has already been shown by Chaudhuri in [26] for linear logic, and [28] for intuitionistic logic. Here we give a completeness proof for a system based on a slight extension of our rewrite rules, following ideas from these works.

Remark 2.7.1 What we prove in this section is a *weak* form of completeness: we show that for any true formula, there always exists a derivation in our subformula linking system, but this derivation might not be constructible by the deterministic procedure outlined in Section ?. There are two aspects that make the stronger version hard to prove in practice:

- To show that the choices performed by the focusing procedure always allow to find a proof when there exists one, it would be necessary to formulate and prove a *focusing theorem* based on the permutability of rules mentioned at the end of Section ?.
- Even then, some additional rules of our subformula linking system are not simulated in any way by the DnD procedure of Section ?. We will come back to this point soon.

To the rewrite rules of Figure ?? and Figure ??, we add *linkage formation* rules (Figure ??), which are a deep generalization of linkage creation

[28]: Chaudhuri (2021), ‘Subformula Linking for Intuitionistic Logic with Application to Type Theory’

9: Note that in the current implementation of Actema, we instead rely on an arbitrary prioritizing fixed in the system, which can hinder in some cases the ability to prove a goal through DnD actions. In practice, one rarely encounters such cases in real examples.

$$\begin{array}{lcl} C^+ \boxed{A \supset B} & \rightarrow & C^+ \boxed{A \otimes B} \quad B \\ C^- \boxed{A \wedge B} & \rightarrow & C^- \boxed{A \otimes B} \quad F \end{array}$$

Figure 2.2: Linkage formation rules

between two formulas of a sequent. Rule B creates a *backward* linkage between \supset -linked formulas in any positive context $C^+\square$, and dually rule F creates a *forward* linkage between \wedge -linked formulas in any negative context $C^-\square$ ¹⁰. Note that contrary to the rules considered up to now, linkage formation rules are not closed under arbitrary contexts: indeed the polarity restrictions are necessary to ensure soundness, as reviewed in Section ?? . A backward linkage in a sequent $\Gamma, D[A] \Rightarrow E[B]$ would be encoded by the instance

$$C^+ [D[A] \supset E[B]] \rightarrow C^+ [D[A] \otimes E[B]]$$

of B where $C^+\square \equiv \bigwedge \Gamma \supset \square$, while a forward linkage in a sequent $\Gamma, D[A], E[B] \Rightarrow F$ would be encoded by the instance

$$C^- [D[A] \wedge E[B]] \rightarrow C^- [D[A] \otimes E[B]]$$

of F where $C^-\square \equiv \bigwedge \Gamma \wedge \square \supset F$.

Another necessary ingredient is the addition of a deep version of the *structural rules* of sequent calculus. We already have the Fcomm rule to handle commutativity of the \otimes operator, which acts as a kind of *exchange* rule. Then we add the equivalent of *contraction* and *weakening* with the rules conn and weak (Figure ??). These allow to erase and duplicate hypotheses at will, by identifying any subformula occurring in a negative context as a hypothesis. Thus once again we need to be careful about polarity, and cannot close these rules under arbitrary contexts.

An alternative to the full contraction rule conn is to systematically duplicate negative formulas in the linkage formation rules, giving the rules Bconn and Fconn of Figure ?? . This models more closely what we do in Actema, where hypotheses involved in a DnD action are always preserved in the new goal. This is important from a usability standpoint, because this ensures the user needs not fret with manual duplication of hypotheses in order to complete a proof. The downside is that the context always grows bigger, but this can be balanced by exposing the weakening rule in the interface. In Actema it is mapped to a “delete” button placed next to every hypothesis (the little gray trashbin icons in Figure ??). In our completeness proof we will use all the rules in {conn, weak, B, F, Bconn, Fconn}, in order to make derivations more concise.

Because linkages created by rules B and F are not necessarily valid, one needs to add the so-called *release* rules already mentioned in Section ?? (Figure ??). In fact these rules are crucial in order to simulate rules from sequent calculus, which will be the backbone of our completeness proof as in [26]. It is interesting to consider the question of completeness without release rules, especially since we do not use them in the semantics of DnD actions. We conjecture that it should hold but would require a completely different argument, maybe of a more semantic nature like the original proof of Gödel with Tarski models¹¹. Another possibility might be to use a more canonical representation of proofs that is in-between syntax and semantics, like the combinatorial proofs of Hughes [97] which are known to be closely related to deep inference proofs.

Lastly, a trivial but necessary addition is the rule refl of Figure ?? stating the reflexivity of $=$. It was not introduced before because it is already

10: This is reminiscent of the adjunction between the product and the exponential in *cartesian closed categories*, which respectively interpret conjunction and implication in the Curry-Howard-Lambek correspondence for intuitionistic logic.

$$\begin{array}{lcl} C^- [A] & \rightarrow & C^- [A \wedge A] \quad \text{conn} \\ C^- [A] & \rightarrow & C^- [\top] \quad \text{weak} \end{array}$$

Figure 2.3: Resource rules

$$\begin{array}{lcl} C^+ [A \supset B] & \rightarrow & C^+ [A \supset (A \otimes B)] \quad \text{Bconn} \\ C^- [A \wedge B] & \rightarrow & C^- [A \wedge (A \otimes B) \wedge B] \quad \text{Fconn} \end{array}$$

Figure 2.4: Duplicating linkage formation rules

11: Or Kripke models in an intuitionistic setting.

[97]: Hughes (2006), ‘Proofs without syntax’

$$t = t \rightarrow \top \quad \text{refl}$$

Figure 2.5: Reflexivity rule for $=$

handled by click actions on red items in Actema (Section ??), but here we want a self-contained system that models as closely as possible the space of proofs that can be built through DnD actions only. In this context, one could imagine restricting the usage of the refl rule to the unit elimination phase (Section ??), where it would play the same role as the rules of Figure ??. Thus adding this rule does not correspond morally to modelling a click action, nor to a modification of the semantics of DnD actions as for release rules.

Then we simply rely on the completeness of sequent calculus by performing a proof by simulation. There are many variants of sequent calculi for intuitionistic first-order logic described in the literature. In our case the choice mostly does not matter: all we need is that it is *analytic*, i.e. satisfies the subformula property. Indeed the very idea of subformula linking is based on analyticity: one should be able to prove a statement by the sole act of linking sub-sentences already present in the statement.

We chose the calculus G3i from [134] as our basis, because all structural rules are admissible in it (but they would be straightforward to simulate apart from the cut rule). The first modification we do is that we model hypotheses in sequents as lists instead of multisets, to make the translation from sequents to formulas completely deterministic. Thus we need to add the exchange rule exch , which is simulated straightforwardly with the Fcomm rule as mentioned earlier. The second modification we do is adding introduction rules $=R$ and $=L$ for equality. The left introduction rule $=L$ captures Leibniz's elimination scheme, and is in fact the rule Repl from [134] (modulo the fact that we use single-succedant instead of multi-succedant sequents). The right introduction rule $=R$ is an axiomatic reflexivity rule, instead of the Ref rule from [134] (Figure ??). The reason is that we cannot simulate the latter directly without adding its equivalent rule ref to our calculus (Figure ??), which we do not want to do because it would break the subformula property. We conjecture that using $=R$ instead of Ref does not break the cut admissibility theorem from [134].

Theorem 2.7.1 (Completeness of subformula linking) *If $\Gamma \Rightarrow A$ is provable in $\text{G3i} + \{\text{exch}, =R, =L\}$, then $\bigwedge \Gamma \supset A \rightarrow^* \top$.*

Proof. By induction on the derivation of $\Gamma \Rightarrow A$. The base case simulates the rules ax , $\top R$, $\perp L$ and $=R$. Other rules are simulated as usual by composing the derivations obtained from the induction hypotheses, making a crucial use of the release rules Brel and Frel . The full mapping from sequent calculus rules to derivations in our subformula linking calculus is given in the following table. Note that we treat conjunctive formulas modulo associativity to avoid bureaucratic details.

$$\frac{}{\Gamma, A \Rightarrow A} \text{ax} \quad \mapsto \quad \begin{array}{ll} \Gamma \wedge A \supset A & \\ \rightarrow \Gamma \wedge A \otimes A & \text{B} \\ \rightarrow A \otimes A & \text{L}_{\wedge_2} \\ \rightarrow \top & \text{id} \end{array}$$

It seems that the question of admissibility of the release rules is very similar to the question of admissibility of the fence rule in the flower calculus. Both serve the same purpose of enabling a local simulation of sequent calculus rules, but do not appear in real proofs because of the arbitrary deep/global power of link formation/iteration rules.

$$\frac{\Gamma, t = t \Rightarrow C}{\Gamma \Rightarrow C} \text{Ref}$$

$$\top \rightarrow t = t \text{ ref}$$

Figure 2.6: Non-analytic reflexivity rules

$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma, B, A, \Gamma' \Rightarrow C \end{array}}{\Gamma, A, B, \Gamma' \Rightarrow C} \text{exch}$	\mapsto	$\begin{array}{l} \Gamma \wedge A \wedge B \wedge \Gamma' \supset C \\ \rightarrow \Gamma \wedge (A \otimes B) \wedge \Gamma' \supset C \quad \mathbf{F} \\ \rightarrow \Gamma \wedge (B \otimes A) \wedge \Gamma' \supset C \quad \mathbf{Fcomm} \\ \rightarrow \Gamma \wedge B \wedge A \wedge \Gamma' \supset C \quad \mathbf{Frel} \\ \rightarrow^* \top \quad \mathbf{IH}(\pi_1) \end{array}$
$\frac{}{\Gamma \Rightarrow \top} \top R$	\mapsto	$\begin{array}{l} \Gamma \supset \top \\ \rightarrow \top \quad \mathbf{absr} \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \quad \vdots \pi_2 \\ \Gamma \Rightarrow A \quad \Gamma \Rightarrow B \end{array}}{\Gamma \Rightarrow A \wedge B} \wedge R$	\mapsto	$\begin{array}{l} \Gamma \supset A \wedge B \\ \rightarrow \Gamma \supset (\Gamma \otimes A \wedge B) \quad \mathbf{Bconn} \\ \rightarrow \Gamma \supset (\Gamma \otimes A) \wedge B \quad \mathbf{R\wedge_1} \\ \rightarrow \Gamma \supset (\Gamma \supset A) \wedge B \quad \mathbf{Brel} \\ \rightarrow^* \Gamma \supset \top \wedge B \quad \mathbf{IH}(\pi_1) \\ \rightarrow \Gamma \supset B \quad \mathbf{neul} \\ \rightarrow^* \top \quad \mathbf{IH}(\pi_2) \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma \Rightarrow A_i \end{array}}{\Gamma \Rightarrow A_0 \vee A_1} \vee R_i$	\mapsto	$\begin{array}{l} \Gamma \supset A_0 \vee A_1 \\ \rightarrow \Gamma \otimes A_0 \vee A_1 \quad \mathbf{B} \\ \rightarrow (\Gamma \otimes A_i) \vee A_{1-i} \quad \mathbf{R\vee_i} \\ \rightarrow (\Gamma \supset A_i) \vee A_{1-i} \quad \mathbf{Brel} \\ \rightarrow^* \top \vee A_{1-i} \quad \mathbf{IH}(\pi_1) \\ \rightarrow \top \quad \mathbf{absl} \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma, A \Rightarrow B \end{array}}{\Gamma \Rightarrow A \supset B} \supset R$	\mapsto	$\begin{array}{l} \Gamma \supset A \supset B \\ \rightarrow \Gamma \otimes A \supset B \quad \mathbf{B} \\ \rightarrow (\Gamma \otimes A) \supset B \quad \mathbf{R\supset_1} \\ \rightarrow \Gamma \wedge A \supset B \quad \mathbf{Frel} \\ \rightarrow^* \top \quad \mathbf{IH}(\pi_1) \end{array}$
$x \notin \text{fv}(\Gamma) \frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma \Rightarrow A \end{array}}{\Gamma \Rightarrow \forall x.A} \forall R$	\mapsto	$\begin{array}{l} \Gamma \supset \forall x.A \\ \rightarrow \Gamma \otimes \forall x.A \quad \mathbf{B} \\ \rightarrow \forall x.(\Gamma \otimes A) \quad \mathbf{R\forall s} \\ \rightarrow \forall x.\Gamma \supset A \quad \mathbf{Brel} \\ \rightarrow^* \forall x.\top \quad \mathbf{IH}(\pi_1) \\ \rightarrow \top \quad \mathbf{absq} \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma \Rightarrow A\{t/x\} \end{array}}{\Gamma \Rightarrow \exists x.A} \exists R$	\mapsto	$\begin{array}{l} \Gamma \supset \exists x.A \\ \rightarrow \Gamma \otimes \exists x.A \quad \mathbf{B} \\ \rightarrow \Gamma \otimes A\{t/x\} \quad \mathbf{R\exists i} \\ \rightarrow \Gamma \supset A\{t/x\} \quad \mathbf{Brel} \\ \rightarrow^* \top \quad \mathbf{IH}(\pi_1) \end{array}$

$\frac{}{\Gamma \Rightarrow t = t} =R$	\mapsto	$\begin{array}{l} \Gamma \supset t = t \\ \rightarrow \Gamma \supset \top \quad \text{refl} \\ \rightarrow \top \quad \text{absr} \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma \Rightarrow C \end{array}}{\Gamma, \top \Rightarrow C} \top L$	\mapsto	$\begin{array}{l} \Gamma \wedge \top \supset C \\ \rightarrow \Gamma \supset C \quad \text{neur} \\ \rightarrow^* \top \quad IH(\pi_1) \end{array}$
$\frac{}{\Gamma, \perp \Rightarrow C} \perp L$	\mapsto	$\begin{array}{l} \Gamma \wedge \perp \supset C \\ \rightarrow \Gamma \wedge \perp \otimes C \quad B \\ \rightarrow \perp \otimes C \quad L\wedge_2 \\ \rightarrow \perp \supset C \quad \text{Brel} \\ \rightarrow \top \quad \text{efq} \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma, A, B \Rightarrow C \end{array}}{\Gamma, A \wedge B \Rightarrow C} \wedge L$	\mapsto	$\begin{array}{l} \Gamma \wedge A \wedge B \supset C \\ \rightarrow^* \top \quad IH(\pi_1) \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma, A \Rightarrow C \end{array} \quad \begin{array}{c} \vdots \pi_2 \\ \Gamma, B \Rightarrow C \end{array}}{\Gamma, A \vee B \Rightarrow C} \vee L$	\mapsto	$\begin{array}{l} \Gamma \wedge (A \vee B) \supset C \\ \rightarrow \Gamma \wedge (A \vee B) \supset (\Gamma \wedge (A \vee B) \otimes C) \quad \text{Bconn} \\ \rightarrow \Gamma \wedge \top \supset (\Gamma \wedge (A \vee B) \otimes C) \quad \text{weak} \\ \rightarrow \Gamma \supset (\Gamma \wedge (A \vee B) \otimes C) \quad \text{neur} \\ \rightarrow \Gamma \supset (A \vee B \otimes C) \quad L\wedge_2 \\ \rightarrow \Gamma \supset (A \otimes C) \wedge (B \supset C) \quad L\vee_1 \\ \rightarrow \Gamma \supset (A \supset C) \wedge (B \supset C) \quad \text{Brel} \\ \rightarrow \Gamma \supset (\Gamma \otimes (A \supset C) \wedge (B \supset C)) \quad \text{Bconn} \\ \rightarrow \Gamma \supset (\Gamma \otimes A \supset C) \wedge (B \supset C) \quad R\wedge_1 \\ \rightarrow \Gamma \supset ((\Gamma \otimes A) \supset C) \wedge (B \supset C) \quad R\supset_1 \\ \rightarrow \Gamma \supset (\Gamma \wedge A \supset C) \wedge (B \supset C) \quad \text{Frel} \\ \rightarrow^* \Gamma \supset \top \wedge (B \supset C) \quad IH(\pi_1) \\ \rightarrow \Gamma \supset B \supset C \quad \text{neul} \\ \rightarrow \Gamma \otimes B \supset C \quad B \\ \rightarrow (\Gamma \otimes B) \supset C \quad R\supset_1 \\ \rightarrow \Gamma \wedge B \supset C \quad \text{Frel} \\ \rightarrow^* \top \quad IH(\pi_2) \end{array}$
$\frac{\begin{array}{c} \vdots \pi_1 \\ \Gamma, A \supset B \Rightarrow A \end{array} \quad \begin{array}{c} \vdots \pi_2 \\ \Gamma, B \Rightarrow C \end{array}}{\Gamma, A \supset B \Rightarrow C} \supset L$	\mapsto	$\begin{array}{l} \Gamma \wedge (A \supset B) \supset C \\ \rightarrow \Gamma \wedge \Gamma \wedge (A \supset B) \supset C \quad \text{conn} \\ \rightarrow \Gamma \wedge (\Gamma \otimes A \supset B) \supset C \quad F \\ \rightarrow \Gamma \wedge ((\Gamma \otimes A) \supset B) \supset C \quad F\supset_1 \\ \rightarrow \Gamma \wedge ((\Gamma \supset A) \supset B) \supset C \quad \text{Brel} \\ \rightarrow^* \Gamma \wedge (\top \supset B) \supset C \quad IH(\pi_1) \\ \rightarrow \Gamma \wedge B \supset C \quad \text{neul} \\ \rightarrow^* \top \quad IH(\pi_2) \end{array}$

$$\begin{array}{c}
\vdots \pi_1 \\
\hline
\Gamma, A\{t/x\} \Rightarrow C \\
\hline
\Gamma, \forall x.A \Rightarrow C \quad \forall L
\end{array}
\mapsto
\begin{array}{l}
\Gamma \wedge (\forall x.A) \supset C \\
\rightarrow \Gamma \wedge (\forall x.A) \supset (\Gamma \wedge (\forall x.A) \otimes C) \quad \text{Bconn} \\
\rightarrow \Gamma \wedge (\forall x.A) \supset (\forall x.A \otimes C) \quad \text{L}\wedge_2 \\
\rightarrow \Gamma \wedge \top \supset (\forall x.A \otimes C) \quad \text{weak} \\
\rightarrow \Gamma \supset (\forall x.A \otimes C) \quad \text{neur} \\
\rightarrow \Gamma \supset (A\{t/x\} \otimes C) \quad \text{L}\forall i \\
\rightarrow \Gamma \supset (A\{t/x\} \supset C) \quad \text{Brel} \\
\rightarrow \Gamma \otimes (A\{t/x\} \supset C) \quad \text{B} \\
\rightarrow (\Gamma \otimes A\{t/x\}) \supset C \quad \text{R}\supset_1 \\
\rightarrow \Gamma \wedge A\{t/x\} \supset C \quad \text{Frel} \\
\rightarrow^* \top \quad \text{IH}(\pi_1)
\end{array}$$

$$\begin{array}{c}
\vdots \pi_1 \\
\hline
\Gamma, A \Rightarrow C \\
\hline
\Gamma, \exists x.A \Rightarrow C \quad \exists L
\end{array}
\mapsto
\begin{array}{l}
\Gamma \wedge (\exists x.A) \supset C \\
\rightarrow \Gamma \wedge (\exists x.A) \supset (\Gamma \wedge (\exists x.A) \otimes C) \quad \text{Bconn} \\
\rightarrow \Gamma \wedge (\exists x.A) \supset (\exists x.A \otimes C) \quad \text{L}\wedge_2 \\
\rightarrow \Gamma \wedge \top \supset (\exists x.A \otimes C) \quad \text{weak} \\
\rightarrow \Gamma \supset (\exists x.A \otimes C) \quad \text{neur} \\
\rightarrow \Gamma \supset \forall x.(A \otimes C) \quad \text{L}\exists s \\
\rightarrow \Gamma \supset \forall x.A \supset C \quad \text{Brel} \\
\rightarrow \Gamma \otimes \forall x.A \supset C \quad \text{B} \\
\rightarrow \forall x.(\Gamma \otimes A \supset C) \quad \text{R}\forall s \\
\rightarrow \forall x.(\Gamma \otimes A) \supset C \quad \text{R}\supset_1 \\
\rightarrow \forall x.\Gamma \wedge A \supset C \quad \text{Frel} \\
\rightarrow^* \forall x.\top \quad \text{IH}(\pi_1) \\
\rightarrow \top \quad \text{absq}
\end{array}$$

$$\begin{array}{c}
\vdots \pi_1 \\
\hline
\Gamma, t = u, A\{u/x\}, A\{t/x\} \Rightarrow C \\
\hline
\Gamma, t = u, A\{t/x\} \Rightarrow C \quad =L
\end{array}
\mapsto
\begin{array}{l}
\Gamma \wedge t = u \wedge A\{t/x\} \supset C \\
\rightarrow \Gamma \wedge t = u \wedge (t = u \otimes A\{t/x\}) \wedge A\{t/x\} \supset C \quad \text{Fconn} \\
\rightarrow \Gamma \wedge t = u \wedge A\{u/x\} \wedge A\{t/x\} \supset C \quad \text{F}=_1 \\
\rightarrow^* \top \quad \text{IH}(\pi_1)
\end{array}$$

□

2.8 Related works

Canonical Proofs The idea of reducing a proof to a collection of links between its dual formulas is not new, and can be traced back to the *matings* of Andrews [6] in the context of automated deduction. Matings are *sets* of links covering all *atomic* occurrences, and proofs are matings satisfying certain conditions. Our work differs in that we are interested in *interactive* deduction, and thus consider links as a mechanism of inference rather than a syntactic criterion to discriminate proofs. Then a proof is better understood as a *list* of links, and the atomicity constraint is relaxed to gain expressivity, since the creation of links is offloaded to the user instead of the search procedure.

[6]: Andrews (1976), ‘Refutations by Matings’

Another line of work, starting with the *proof nets* of Girard [66], is con-

[66]: Girard (1987), ‘Linear logic’

cerned with the more fundamental problem of *proof identity*, which requires a canonical notion of proof object [177]. In the case of unit-free multiplicative linear logic, the absence of any form of duplication/sharing/removal mechanism allows to completely characterize a proof net by the set of its *axiom* links¹², because of the absence of duplication. This is because adding additives or exponentials, which can encode intuitionistic and classical logic, requires additional structure to represent uses of weakening and contraction. The *combinatorial proofs* of Hughes [97][90] are examples of polynomially-checkable proof objects exhibiting such structure, and have recently been extended to handle first-order classical quantifiers [98] (intuitionistic quantifiers are still an open problem). This compartmentalization of axiom links and structural rules resembles the distinction between interaction phases and manual applications of *conn* and *weak* (Figure ??), which is itself inspired by the *decomposition theorem* of the calculus of structures [185, Theorem 4.1.3].

There is also an analogy between the correctness criterions of proof nets, and the validity criterion of linkages:

- ▶ they both identify a subset of valid objects among a larger set of structures characterized by links on formulas;
- ▶ they both allow many different *sequential* readings, that is sequent calculus proofs for proof nets, and CoS proofs for linkages¹³.

Hence, our approach to subformula linking seems to exhibit some properties of canonical proofs, but at the level of *partial proofs*: valid linkages make for *compact-parallel-spatial* representations of inferences, whose operational meaning is given by their *detailed-sequential-temporal* CoS derivations.

Tangible Functional Programming We noticed an interesting connection with the work of Conal Elliott on tangible functional programming [54]. His concept of *deep application* of λ -terms seems related to the notion of subformula linking, when viewing function and product types as implications and conjunctions through the formulae-as-types interpretation. He also devised a system of basic combinators which are composed sequentially to compute the result of a DnD, though it follows a more complex dynamic than our rewrite rules. Even if the mapping between proofs and programs is not exact in this case, it suggests a possible interesting field of application for the Curry-Howard correspondence, in the realm of graphical proving/programming environments.

[177]: Straßburger (2019), ‘The problem of proof identity, and why computer scientists should care about Hilbert’s 24th problem’

12: The difference with matings is that correctness of a proof structure can be checked in *polynomial* instead of exponential time.

[97]: Hughes (2006), ‘Proofs without syntax’

[90]: Heijltjes et al. (2019), ‘Intuitionistic proofs without syntax’

[98]: Hughes (2019), *First-order proofs without syntax*

[185]: Tubella et al. (2019), ‘Introduction to Deep Inference’

13: Note that invalid linkages still give rise to CoS-style *derivations*, but not *proofs* since they do not end with \top . The incorrect proof structures of Girard are in a sense more parallel as they cannot always be mapped to correct sequent calculus derivations.

[54]: Elliott (2007), ‘Tangible Functional Programming’

In the previous chapters, we explained the core principles of our so-called Proof-by-Action paradigm and especially its drag-and-drop actions, first through basic and abstract examples in Chapter ??, and then from a proof-theoretical perspective in Chapter ?. The goal of this chapter is to provide a better sense of what proofs by action/DnD look like in practice, and how they compare to more traditional approaches to interactive theorem proving. To that effect, we perform a case study of a few select examples, unrolling and commenting in details one or many of their proofs. Although still basic, they are fully fledged, concrete logical riddles or mathematical problems that one might give as exercise to an undergraduate student learning formal proofs. Note that our analysis will stay quite informal and opinionated: a more systematic approach such as a user study would allow for a better evaluation of our paradigm, but at the time of writing of this thesis the Actema prototype is not mature enough to conduct a project of this scale.

The chapter is organized as follows: Section ?? studies a proof of a small logical riddle in Actema, highlighting some benefits of our approach compared to textual systems. Section ?? explores how basic properties about functions between sets can be proved graphically, introducing the use of definitions in addition to logical reasoning steps. In Section ?? we prove equations in Peano arithmetic, showing how one can incorporate additional actions into the paradigm to deal with more specialized forms of reasoning: *induction* and *automatic computation*.

3.1 Forward reasoning

Our first example is a small logical riddle, which we borrow from a textual educational system, Edukera [164]. One considers a population of people, with at least one individual h , together with a single function `mother` and one predicate `Rich`. The aim is to show that the two following assumptions are incompatible:

- (1) $\forall x. \neg \text{Rich}(x) \vee \neg \text{Rich}(\text{mother}(\text{mother}(x)))$,
- (2) $\forall x. \neg \text{Rich}(x) \supset \text{Rich}(\text{mother}(x))$.

The original goal thus corresponds to the illustration of Figure ??.

It is quite natural to approach this problem in a forward manner, by starting from the hypotheses to establish new facts. And a first point illustrated by this example is that DnD actions allow to do this in a smooth and precise manner. A possible first step is to bring h to the first hypothesis, to obtain a new fact:

- (3) $\neg \text{Rich}(h) \vee \neg \text{Rich}(\text{mother}(\text{mother}(h)))$.

Double clicking on this new fact yields two cases:

- (4) $\neg \text{Rich}(h)$,

Explain that for all examples, we provide a Coq proof script that tries to follow the structure of the graphical proof, for the sake of comparison with a more standard text-based interface. But this would obviously compare differently with other textual approaches, e.g. Isar which is more declarative, and thus farther from the Proof-by-Action paradigm.

Maybe advise the reader to reproduce the examples herself? Supposes an easy way to setup and use coq-actema: nix seems like a good option, but maybe JsCoq could be doable with some efforts, and would provide an even more out-of-the-box experience.

[164]: Rognier et al. (2016), ‘Présentation de la plateforme edukera’

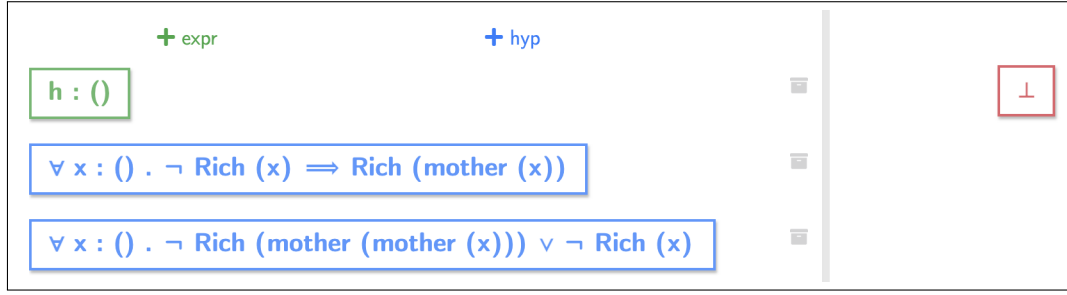


Figure 3.1: The beginning of an example due to Edukera

(4') $\neg \text{Rich}(\text{mother}(\text{mother}(h)))$.

Let us detail how one solves the second one.

By bringing $\neg \text{Rich}(\text{mother}(\text{mother}(h)))$ on the premise of $\forall x. \boxed{\neg \text{Rich}(x)} \supset \text{Rich}(\text{mother}(x))$ one obtains

(6) $\text{Rich}(\text{mother}(\text{mother}(\text{mother}(h))))$.

The next step is a good example where DnD actions are useful. By bringing this new fact to the right-hand part of

(1) $\forall x. \neg \text{Rich}(x) \vee \neg \boxed{\text{Rich}(\text{mother}(\text{mother}(x)))}$

one immediately obtains a new fact

(7) $\neg \text{Rich}(\text{mother}(h))$.

In other proof systems, this last step requires a somewhat intricate tactic line and/or writing down at least the statement of the new fact.

One can then finish the case by combining (7) and (2) which yields

$$\text{Rich}(\text{mother}(\text{mother}(h)))$$

contradicting (4'). These two last steps each correspond to a simple DnD. The other case, $\neg \text{Rich}(h)$, is quite similar.

Note that once a user has understood the proof, the riddle is routinely solved in less than a minute in Actema, which seems out of reach for about any user in a tactic based prover. At least as important is the fact that the proof can be performed without typing any text, especially no intermediate statement.

To conclude this example, we propose in Figure ?? a complete proof of the riddle formalized in the Coq proof assistant, which follows very closely the structure of the graphical proof just outlined. To make the correspondence more visible and ease the comparison, we interspersed the proof script with comments of the form `(** [actions] *)`, where `[actions]` is a sentence describing a sequence of actions in Actema that produces the same goal transformation as the tactics preceding the comment. There are a few interesting things to note:

- We chose to name manually all the hypotheses introduced in the course of the proof. This is generally considered good practice in the Coq community, because it makes proof scripts easier to maintain. In our case it also has the advantage of expliciting which hypotheses are used exactly in the reasoning, something that an Actema user does with her pointing device when designating the blue items involved in an action. It appears clearly in Figure ?? that in a moderately long proof like this based mostly on forward reasoning, one needs to keep track of *a lot* of names, which can be overwhelming for many users. This is especially true for beginners discovering Coq, because the syntax for assigning names, based on patterns like $[H \mid H]$ that reproduce the subgoal structure, can induce a steep learning curve. Of course this problem is mitigated trivially in Actema, since names are not needed.
- There is no exact correspondence between the tactics of Coq and the actions of Actema: some tactics are simulated by multiple actions, and often a complex sequence of tactics can be simulated by a single action¹.

For instance, line 23 does at the same time a specialization of the hypothesis $H_2 : \forall x. \neg \text{Rich}(\text{mother}(\text{mother}(x))) \vee \neg \text{Rich}(x)$ to the individual h with the application ($H_2 \ h$), and a case analysis with the `destruct` tactic. In Actema this is performed in two steps, first by drag-and-dropping h on H_2 , and then by clicking on the resulting hypothesis².

In the other direction, a pattern of reasoning that occurs multiple times in the proof is the combination of H_2 with another hypothesis which contradicts one of the two cases, in order to deduce the truth of the other case. While it is captured straightforwardly in Actema with a single DnD between the contradictory statements, it requires in Coq a decomposition into many administrative steps:

1. first a case analysis with `destruct`, where the expression instantiating H_2 (e.g. $\text{mother}(\text{mother}(h))$) needs to be written down explicitly, instead of being inferred automatically from unification;
 2. optionally focusing on the subgoal corresponding to the contradictory case if it is the right disjunct (line 56), which requires to know a somewhat idiosyncratic and infrequently used syntax of the tactic language;
 3. and finally expliciting the contradiction with `apply` and `exact`.
- More generally, the actions of Actema are more *versatile* and *context-dependent* than the tactics of Coq. For instance, click actions have a different effect depending on the main connective of the formula being clicked, but provide a unique interface for applying rules of natural deduction/sequent calculus. On the contrary, there is almost one tactic for dealing with each logical connective in Coq, e.g. `intros` for \supset and \forall , `split` for \wedge , `left` and `right` for \vee , `exists` for \exists , etc. The same remark applies to DnD actions, whose functionalities are provided in Coq by many different tactics: `apply` $_$, `apply` $_ \text{ in } _$, `pose proof`, `specialize`, etc.

1: This was already noticed in [13], where clicking on a subformula can simulate a sequence of introduction rules of arbitrary length.

2: This could also be achieved in two steps in Coq, by using the `specialize` tactic instead of the inlined application.

From this detailed comparison, it appears that the interface offered by the Proof-by-Action paradigm might be more suited to forward reasoning

```

1
2 (* Declaration of constants used in the statement of the riddle *)
3
4 Context (i : Type).
5
6 Context (Rich : i -> Prop).
7 Context (mother : i -> i).
8 Context (h : i).
9
10 (* Statement of the riddle *)
11
12 Theorem rich_mothers :
13   (forall x, ~Rich(x) -> Rich(mother(x))) ->
14   (forall x, ~Rich(mother(mother(x))) \ / ~Rich(x)) ->
15   False.
16
17 (* Proof of the riddle *)
18
19 Proof.
20   intros H1 H2.
21
22   (** 2 clicks on the conclusion *)
23
24   destruct (H2 h) as [H | H'].
25
26   (** DnD of [h] onto [H2], then click on the resulting hypothesis *)
27
28   * pose proof (H1 _ H) as H'.
29
30   (* If one naively uses [apply _ in], then one loses [H] although
31      it is needed later! Hence the use of [pose proof]. *)
32
33   (** DnD of [H1] onto [H] *)
34
35   destruct (H2 (mother h)) as [H2' | H2'].
36   apply H2'. exact H'.
37
38   (** DnD of [H'] onto [H2]. Could also be performed stepwise:
39      - Selection of [mother(h)] in [H']
40      - DnD of [H'] onto [H2]
41      - Click on the resulting hypothesis
42      - DnD of [H2'] onto [H'] *)
43
44   apply H1 in H2'.
45
46   (** DnD of [H1] onto [H2'] *)
47
48   apply H. exact H2'.
49
50   (** DnD of [H] onto [H2'] *)
51
52   * pose proof (H1 _ H) as H'.
53
54   (** DnD of [H1] onto [H] *)
55
56   destruct (H2 (mother h)) as [H2' | H2'].
57   2: { apply H2'. exact H'. }
58
59   (** DnD of [H'] onto [H2] *)
60
61   pose proof (H1 _ H2') as H2''.
62
63   (** DnD of [H1] onto [H2'] *)
64
65   destruct (H2 (mother (mother h))) as [H2''' | H2'''].
66   apply H2'''. exact H2''.
67
68   (** DnD of [H2''] onto [H2] *)
69
70   apply H1 in H2'''.
71
72   (** DnD of [H1] onto [H2'''] *)
73
74   apply H2'. exact H2'''.
75
76   (** DnD of [H2'] onto [H2'''] *)
77 Qed.
78

```

Figure 3.2: Coq proof script formalizing Edukera's riddle

than the tactic language of Coq, at least in some respects. It makes the flow of argumentation more straightforward to express with DnD actions, and avoids the overheads of name management and syntax memorization. This altogether shall prove to be particularly helpful to beginners and learners of the proof assistant.

3.2 Sets and functions

Our second example comes from a preprint of Bartzia et al. [11], where it is chosen specifically for a case study aiming to compare the features of different proof assistants' interfaces in an educational setting. It is “a typical exercise about sets, relations and functions, as commonly found in introductory courses about reasoning and proof.” (p. 6):

Exercise 3.2.1 Given three sets A , B and C such that $C \subseteq A$ and a function $f : A \rightarrow B$, show that:

1. $C \subseteq f^{-1}(f(C))$.
2. If f is injective then $f^{-1}(f(C)) \subseteq C$.

where $f(D)$ and $f^{-1}(E)$ denote respectively the direct and inverse image (or preimage) of sets $D \subseteq A$ and $E \subseteq B$ by f .

Compared to our previous example, this exercise has the particularity of involving multiple *definitions*, here about sets and functions between them. There are many possible ways to handle definitions in a formal proof system. A common one is to decompose the definition into a new function or predicate symbol, the definition's *head*, and a universally parametrized equality or equivalence between the head and the *body* of the definition. For instance, the concept of injectivity can be encoded as a unary predicate $\text{injective}(\cdot)$ on functions, satisfying the following equivalence:

$$\forall A. \forall B. \forall f: A \rightarrow B. \text{injective}(f) \Leftrightarrow \forall x \in A. \forall y \in A. f(x) = f(y) \supset x = y$$

Notice that $\text{injective}(\cdot)$ is a *higher-order* predicate, since it takes any function as argument. Depending on the underlying logical framework, this might have an impact on the exact way the definition is encoded. Here we do not want to bother with such implementation details, and simply assume that higher-order definitions are possible, even though Actema is currently limited to first-order logic. In practice this does not affect the semantics of graphical actions, and we can imagine having a first-order set theory such as ZF to make everything work behind the scenes³.

Let us now describe how to prove the second question of the exercise in the Proof-by-Action paradigm. The first thing we want to do is to unfold the definition of set inclusion in the conclusion $f^{-1}(f(C)) \subseteq C$, so that we can see how to prove logically such an inclusion. One might imagine multiple kinds of graphical actions for doing this. In Actema we implemented a general *subterm selection* mechanism, where the user can successively point at different subterms appearing in the goal — either in the context or the conclusion — and then choose from a list of available

3: See also Section ?? for a discussion on a higher-order extension of Actema.

actions taking the selection as argument. In our case we can select the whole conclusion, and then choose to apply the Unfold action:

$$\boxed{f^{-1}(f(C)) \subseteq C} \quad (\text{Unfold})$$

The system will be able to tell that we selected an instance of the two-place inclusion predicate $\cdot \subseteq \cdot$, and thus will replace the head of this definition by its body, instantiating parameters accordingly. This gives us a new conclusion

$$\forall x. x \in f^{-1}(f(C)) \supset x \in C$$

on which we can click twice to introduce a new variable x in the context, together with the hypothesis:

$$(1) \quad x \in f^{-1}(f(C))$$

Now there is no available action on the conclusion $x \in C$, because set membership is a *primitive* predicate in set theory: it does not have any associated definition in the sense mentioned above⁴. But we can still unfold some definitions in the context, which might suggest further possible interactions. First we can unfold the definition of preimage used in (1) by selecting the precise corresponding subterm:

$$x \in \boxed{f^{-1}(f(C))} \quad (\text{Unfold})$$

which, assuming a definition based on set comprehension, gives:

$$(1) \quad x \in \{a \in A \mid f(a) \in f(C)\}$$

At this stage, we would like to make the set comprehension in (1) disappear, by simply deducing $f(x) \in f(C)$ from it. But depending on the underlying logical framework, the way to perform this deduction step in Proof-by-Action will vary:

In ZF set theory We would need to invoke explicitly the *axiom of comprehension*, which states the following:

$$\forall \phi. \forall D. \forall y. y \in \{d \in D \mid \phi\} \Leftrightarrow (y \in D \wedge \phi\{y/d\})$$

Note that this is again a higher-order statement, but this time because it quantifies over every formula ϕ ⁵. Thus we assume that the underlying proof engine can handle such higher-order statements, and in particular that the axiom of comprehension is available in its database of lemmas.

In Actema, one can freely search in this database by typing text in a search bar, typically in this case the keyword “comprehension”. Then the system will show a list of lemmas whose names match the keywords, and the user can click on the lemma she is interested in, in order to add it as a blue item in the current context. An alternative and more precise way of retrieving a lemma is to search by *content* of the statement instead of searching by name. State-of-the-art proof assistants usually provide facilities for this: for instance Coq has a Search command which can take *patterns*, i.e. terms with holes or so-called *metavariables*, in order to filter out results that do not match the given pattern. In Actema, we implemented a novel feature which replaces patterns by a selection of subterms in the

4: Formally, the meaning of \in in a set theory such as ZF comes from the various axioms involving it. One might call such a definition *behavioral*, since the meaning of the symbol emerges from the way it can be used in proofs through axioms. In contrast, the usual notion of mathematical definition we tackle in this chapter might be called *nominal*, because it essentially amounts to giving a name (the head) to a reoccurring pattern of statement (the body). Note that the syntax of first-order logic is unaware of this distinction, since in both cases the defined concepts are encoded as *atomic* predicates. This is usually not the case of logical frameworks found in proof assistants: for instance, the duality between *judgmental* (nominal) and *propositional* (behavioral) equality is at the heart of Martin-Löf’s type theory, and it is used extensively in Coq to perform automation, both in the computation of expressions and the matching of statements modulo definitions.

5: Traditionnally, logicians preferred to speak of *axiom schemas*, that is denumerable sets of axioms, rather than higher-order axioms, in order to stay purely in a first-order setting. But this does not make much sense from an implementation point of view, as a proof engine will only be able to manipulate a finite amount of axioms.

current goal, similarly to what is given as argument to contextual actions like `Unfold`. Then the system will only look for lemmas which can be used in a DnD action involving precisely the current selection of subterms. In this case, selecting the full statement of (1) and searching:

$$\boxed{x \in \{a \in A \mid f(a) \in f(C)\}} \quad (\text{Search})$$

should return the comprehension axiom among other lemmas, because this axiom and (1) can interact through the following forward DnD:

$$\boxed{x \in \{a \in A \mid f(a) \in f(C)\}} \otimes \forall \phi. \forall D. \forall y. \boxed{y \in \{d \in D \mid \phi\}} \Leftrightarrow (y \in D \wedge \phi\{y/d\})$$

by substituting D with A , d with a , y with x and ϕ with $f(a) \in f(C)$. Performing this DnD will finally result in a new hypothesis corresponding to the intended unfolding of the definition of set comprehension⁶:

$$(2) \quad x \in A \wedge f(x) \in f(C)$$

6: Here in the sense of a *behavioral* definition.

In higher-order type theory In type theory, every mathematical object or statement is ultimately encoded as a function, in the sense of the λ -calculus. It is Alonzo Church who first got the idea of representing a set by its *characteristic function* in his higher-order logic, as a λ -term of type $\iota \rightarrow o$ where ι is the type of individuals, and o the type of propositions. With this encoding, the only way to construct a set is by comprehension, and set membership corresponds to function application; that is, $\{x \in A \mid \phi\}$ is identified with the characteristic function $\lambda x: A. \phi$, and $x \in t$ is the application $t \ x$ ⁷. Then if we consider λ -terms modulo β -equivalence, unfolding the “definition” of set comprehension just amounts to performing one step of β -reduction⁸: hypothesis (1) becomes

$$(\lambda a: A. f(C) \ f(a)) \ x$$

which β -reduces to

$$f(C) \ f(x)$$

which we can translate back as $f(x) \in f(C)$. This encoding has now found its way in the libraries of many proof assistants based on type theory, and is the one used in the Coq solution to the exercise provided in annex of [11]. To perform β -reduction in Coq, there is a tactic called `simpl` as in “simplify”⁹. Coming back to Proof-by-Action, one can easily imagine a corresponding `Simplify` or `Compute` contextual action, which performs β -reduction inside of the selected subterm. Then the previous transformation is achieved by applying this action on hypothesis (1):

$$\boxed{x \in \{a \in A \mid f(a) \in f(C)\}} \quad (\text{Simplify})$$

From a user perspective, the two styles of actions induced by the two types of logical frameworks differ mainly in one aspect: while the definition of set comprehension is *implicit* in the type-theoretical encoding, it must be manipulated *explicitly* when using the axiom of comprehen-

add citation

7: Note that this induces a strict hierarchical notion of set as in Russell’s type theory, where sets containing other sets have a higher-order type, i.e. they correspond to functions taking other functions as arguments.

8: One can consider this as a third kind of definition qualified of *computational*. In Martin-Löf’s type theory, it is merged with nominal definitions in the concept of judgmental equality. In Coq they are distinguished: computational and nominal definitions correspond respectively to β -reduction and δ -reduction.

9: There are also `simp` tactics available in Isabelle and Lean, although they are not restricted to β -reduction and can perform rewriting of arbitrary equalities and equivalences present in the lemma database, as long as they are flagged as simplification rules.

sion¹⁰. Depending on the user's background and context of usage, one might prefer one style over the other. Typically in an educational setting, having to manipulate explicitly the axiomatic definition might be more instructive, but also more confusing when carrying formal proofs for the first time.

Going back to the proof, we now have the following context of hypotheses:

- (0) $\text{injective}(f)$
- (2) $f(x) \in f(C)$

We can unfold the definition of direct image in (2) the same way we did for the inverse image in (1): first perform the contextual action

$$f(x) \in \boxed{f(C)} \quad (\text{Unfold})$$

which gives us

- (2) $f(x) \in \{b \in B \mid \exists a \in A. a \in C \wedge b = f(a)\}$

Then we can simplify the set comprehension with

$$\boxed{f(x) \in \{b \in B \mid \exists a \in A. a \in C \wedge b = f(a)\}} \quad (\text{Simplify})$$

which gives us

- (3) $\exists a \in A. a \in C \wedge f(x) = f(a)$

Now since f is injective, we should be able to deduce that $x = a$. First we unfold the definition of injectivity in (0):

$$\boxed{\text{injective}(f)} \quad (\text{Unfold})$$

which gives us

- (0) $\forall y \in A. \forall z \in A. f(y) = f(z) \supset y = z$

Then we can use injectivity with the following forward DnD between (0) and (3):

$$\forall y \in A. \forall z \in A. \boxed{f(y) = f(z)} \supset y = z \quad \otimes \quad \exists a \in A. a \in C \wedge \boxed{f(x) = f(a)}$$

which gives us immediately that $x = a$ in

- (4) $\exists a \in A. a \in C \wedge x = a$

The last steps consist in clicking twice on (4) to introduce a in the context together with

- (5) $a \in C \wedge x = a$

doing a backward DnD with (5) to rewrite x in the conclusion into a :

$$a \in C \wedge \boxed{x} = a \quad \otimes \quad \boxed{x} \in C$$

and finally a backward DnD with (5) to conclude the proof:

$$\boxed{a \in C} \wedge x = a \quad \otimes \quad \boxed{a \in C}$$

10: In fact one could also use the axiom of comprehension implicitly by relying on stronger automation. For example in Isabelle/Isar, one would write explicitly the desired goal $f(x) \in f(C)$, refer to the axiom by its name in the library, and then let the engine find the details of how to apply it. But writing statements manually goes against the philosophy of Proof-by-Action, which explores to what extent proofs can be carried by pure manipulation of the proof state. Of course there is still an escape hatch for doing this when strictly necessary or more convenient.

```

1  Definition Ens {A : Type} := A -> Prop.
2
3
4  Definition subset {A : Type} (C D : Ens) :=
5    forall (x : A), C x -> D x.
6
7  Infix "<=" := subset (at level 30).
8
9  Definition image {A B : Type} (f : A -> B) (C : Ens) : Ens :=
10    fun y => exists x, C x /\ y = f x.
11
12  Definition preimage {A B : Type} (f : A -> B) (C : Ens) : Ens :=
13    fun x => C (f x).
14
15  Definition injective {A B : Type} (f : A -> B) :=
16    forall x x', f x = f x' -> x = x'.
17
18  Context (A B : Type).
19

```

Figure 3.3: Preliminary definitions in Coq of an exercise on abstract functions

For the sake of completeness, we included in Figure ??, Figure ?? and Figure ?? a Coq formalization of the definitions, solution to the first question, and solution to the second question of the exercise, respectively. We simply took the data provided in [11], and added corresponding Actema actions below tactic invocations, as in the previous section. It is quite close to the graphical proof just outlined for the second question, hence we do not add further commentary.

```

1
2 Theorem subset_preimage_image (f : A -> B) :
3   forall C, C  $\subseteq$  preimage f (image f C).
4 Proof.
5   intros C.
6   (** Click on conclusion *)
7
8   unfold subset.
9   (** Select conclusion, then apply Unfold from contextual action menu *)
10  intros a H.
11  (** Two clicks on conclusion *)
12
13  unfold preimage.
14  (** Select conclusion, then apply Unfold from contextual action menu *)
15  unfold image.
16  (** Select conclusion, then apply Unfold from contextual action menu *)
17  exists a.
18  split.
19  apply H.
20  (** DnD of [H] on [C(x)] in conclusion *)
21  reflexivity.
22  (** Click on conclusion *)
23 Qed.
24

```

Figure 3.4: Solution in Coq to the first question of an exercise on abstract functions

```

1
2 Theorem preimage_image_subset (f : A -> B) :
3   injective f -> forall C, preimage f (image f C)  $\subseteq$  C.
4 Proof.
5   intros Hinj C.
6   (** 2 clicks on conclusion *)
7
8   unfold subset.
9   (** Select conclusion, then apply Unfold from contextual action menu *)
10  intros x H.
11  (** 2 clicks on conclusion *)
12
13  unfold preimage in H.
14  (** Select [H], then apply Unfold from contextual action menu *)
15  unfold image in H.
16  (** Select [H], then apply Unfold from contextual action menu *)
17  destruct H as [x' [H1 H2]].
18  apply Hinj in H2.
19  (** Here we need to unfold [injective] so that Actema detects a possible DnD action:
20    1. Select [Hinj], then apply Unfold from contextual action menu
21    2. Click on [H]
22    3. DnD of [H] on [f x = f x'] in [Hinj] *)
23  rewrite <- H2 in H1.
24  (** DnD of last hypothesis on the leftmost [x] in [H] *)
25  apply H1.
26  (** DnD of last hypothesis on conclusion *)
27 Qed.
28

```

Figure 3.5: Solution in Coq to the second question of an exercise on abstract functions

3.3 Peano arithmetic

In our last example, we will analyse a common proof often taught in logic courses: the commutativity of addition in Peano arithmetic. The novelty compared to previous examples is that it involves reasoning by *induction*, which usually has special support in mainstream proof assistants. In the Proof-by-Action paradigm, it seems natural to map it to a special contextual action *Induction*, whose availability and effect will depend on the selected subterm. One could also imagine manipulating explicitly induction schemes as blue items, in the same way we did for the axiom of comprehension in the previous section. In this section we focus on describing features of the more convenient contextual action.

First and foremost, it only makes sense to apply induction to a variable which is quantified *universally*, either because it appears in the context, or because it is bound by a \forall in the conclusion. In the first case, one can access the contextual action in Actema by selecting the green item corresponding to the variable; in the latter case, by selecting the subterm of the conclusion whose head connective is the binding \forall ¹¹. This could also work by selecting any occurrence of the variable regardless of its binding point, since the system can always infer it. The only condition is that if the variable is bound by a \forall , it must occur in a *strictly positive* location, i.e. in the conclusion and not on the left of an implication \supset . Obviously the variable should also be of an *inductive* type, i.e. one which is mapped to an induction scheme in the system¹². Then the *Induction* action will simply apply the associated induction scheme. In our commutativity example, we can thus start the proof like so:

$$\boxed{\forall n \in \mathbb{N}. \forall m \in \mathbb{N}. n + m = m + n} \quad (\text{Induction})$$

which performs an induction on n , generating the two following subgoals:

$$\forall m \in \mathbb{N}. 0 + m = m + 0 \quad \text{and} \quad \forall m \in \mathbb{N}. S(n) + m = m + S(n)$$

where $S(n)$ denotes the successor of n , and the second subgoal has a new variable $n \in \mathbb{N}$ in its context, together with the induction hypothesis

$$(1) \quad \forall x \in \mathbb{N}. n + x = x + n$$

The proofs of the two subgoals can be done by induction on m . We focus on the second one, which is a bit more involved. As mentioned above, an alternative way of performing induction is to first introduce m in the context by clicking on the conclusion, and then selecting it to access the contextual action:

$$\boxed{m \in \mathbb{N}} \quad (\text{Induction})$$

which generates again two new subgoals:

$$S(n) + 0 = 0 + S(n) \quad \text{and} \quad S(n) + S(m) = S(m) + S(n)$$

where the second subgoal has a new variable $m \in \mathbb{N}$ in its context, together with the induction hypothesis

$$(2) \quad S(n) + m = m + S(n)$$

11: In the standalone version of Actema, induction is performed by clicking directly on green items, rather than through a contextual action.

12: The standalone version of Actema only supports induction on natural numbers, but in a proof assistant like Coq or Lean one can easily check if a given type is inductive.

Let us now focus on the first subgoal. Once again, as with set comprehension in the previous section, the addition operation may have a more *axiomatic* or more *computational* definition, depending on the underlying logical framework and library used. For instance in Coq's standard library, it is implemented as a *program* built by recursion on the left-hand argument. Thus in this setting, if one performs computation in the whole conclusion like so:

$$\boxed{S(n) + 0 = 0 + S(n)} \quad \text{Simplify}$$

this will give a new conclusion

$$S(n + 0) = S(n)$$

where the addition program was able to automatically evaluate $S(n) + 0$ to $S(n + 0)$ on the left-hand side of the equality, and $0 + S(n)$ to $S(n)$ on the right-hand side. If the proof engine does not offer such a level of automation, one can always fallback to using Peano axioms manually, provided they are available in the lemma database. As we have already seen, the most convenient way to do this in the Proof-by-Action paradigm is to perform a Search action. For example to evaluate $S(n) + 0$, one might first select it in the conclusion and then make a search query:

$$\boxed{S(n) + 0} = 0 + S(n) \quad (\text{Search})$$

Among the results which are Peano axioms, one will only find the following ones:

- (a) $\forall x. 0 \neq S(x)$
- (b) $\forall x. \forall y. S(x) = S(y) \supset x = y$
- (c) $\forall x. \forall y. S(x) + y = S(x + y)$

because the other axioms do not contain any subterm that could form a *valid* backward linkage with the selection¹³. Of course we are interested in axiom (c), which we can use through the following backward DnD:

$$\forall x. \forall y. \boxed{S(x) + y} = S(x + y) \quad \ominus \quad \boxed{S(n) + 0} = 0 + S(n)$$

in order to rewrite $S(n) + 0$ into $S(n + 0)$ in the conclusion.

Now notice that the addition program earlier was not able to evaluate $n + 0$ to n . This is because 0 occurs on the right-hand side of +, and the program is not aware of the commutativity of addition, which is precisely what we are trying to prove. Fortunately, we can apply our induction hypothesis on n (1), with the following backward DnD:

$$\forall x \in \mathbb{N}. \boxed{n + x} = x + n \quad \ominus \quad S(\boxed{n + 0}) = S(n)$$

which rewrites $n + 0$ into $0 + n$ in the conclusion:

$$S(0 + n) = S(n)$$

Now we can continue the computation:

$$S(\boxed{0 + n}) = S(n) \quad (\text{Simplify})$$

13: See Section ?? for the notion of validity of a linkage.

and conclude the base case of the induction on m by reflexivity, by clicking on the conclusion $S(n) = S(n)$.

The inductive case of the induction on m works similarly, but obviously we will also need to use the induction hypothesis on m (2). First we compute everywhere we can in the conclusion:

$$\boxed{S(n) + S(m) = S(m) + S(n)} \quad \text{Simplify}$$

Then we can apply the induction hypothesis on n (1):

$$\forall x. \boxed{n + x} = x + n \quad \otimes \quad S(\boxed{n + S(m)}) = S(m + S(n))$$

and also the induction hypothesis on m (2):

$$S(n) + m = \boxed{m + S(n)} \quad \otimes \quad S(S(m) + n) = S(\boxed{m + S(n)})$$

Again we compute everywhere:

$$\boxed{S(S(m) + n) = S(S(n) + m)} \quad (\text{Simplify})$$

apply the induction hypothesis on n (1) once again:

$$\forall x. n + x = \boxed{x + n} \quad \otimes \quad S(S(\boxed{m + n})) = S(S(n + m))$$

and conclude by reflexivity on $S(S(n + m)) = S(S(n + m))$.

As in previous sections, the interested reader can find a complete Coq formalization in Figure ??, which follows the same structure as the graphical proof just outlined. In this case the correspondence between Coq tactics and graphical actions is almost exact. This suggests that designing a compiler from proofs-by-action to Coq proof scripts might be a reasonable endeavor. It will indeed be one of the subjects of Chapter ??.

```

1
2 Theorem add_comm :
3   forall (n m : nat), n + m = m + n.
4 Proof.
5   induction n as [|n IHn|.
6     (** Select conclusion, then apply Induction from contextual action menu *)
7
8   * induction m as [|m IHm|.
9     (** Select conclusion, then apply Induction from contextual action menu *)
10    - reflexivity.
11      (** Click on conclusion *)
12    - simpl.
13      (** Select conclusion, then apply Simplify from contextual action menu *)
14      rewrite <- IHm.
15      (** DnD of [IHm] on conclusion *)
16      reflexivity.
17      (** Click on conclusion *)
18
19  * induction m as [|m IHm|.
20    (** Select conclusion, then apply Induction from contextual action menu *)
21    - simpl.
22      (** Select conclusion, then apply Simplify from contextual action menu *)
23      rewrite IHn.
24      (** DnD of [IHn] on conclusion *)
25      reflexivity.
26      (** Click on conclusion *)
27    - simpl.
28      (** Select conclusion, then apply Simplify from contextual action menu *)
29      rewrite IHn.
30      (** DnD of [IHn] on conclusion *)
31      rewrite <- IHm.
32      (** DnD of [IHm] on conclusion *)
33      simpl.
34      (** Select conclusion, then apply Simplify from contextual action menu *)
35      rewrite IHn.
36      (** DnD of [IHn] on conclusion *)
37      reflexivity.
38      (** Click on conclusion *)
39 Qed.
40

```

Figure 3.6: Proof of commutativity of addition on natural numbers in Coq

Parallel Conclusions and Classical Logic

4

In virtually every proof assistant, the goals the user is faced with are sequents of the form $\Gamma \Rightarrow C$, with a *single* conclusion C to be proved under many hypotheses in Γ . Historically, this form of sequent was introduced by Gentzen to formalize the rules of intuitionistic logic in his sequent calculus LJ. But his main interest was in classical logic, as intuitionistic logic was still in its infancy and almost all of mathematics had been developed in a classical setting. Interestingly, he found that the right syntax to develop a rich metatheory of his classical sequent calculus LK consisted in *multi-conclusion* sequents of the form $\Gamma \Rightarrow \Delta$, where Δ is a list of conclusions that should be read *disjunctively*. That is, a sequent

$$A_1, \dots, A_n \Rightarrow C_1, \dots, C_m$$

has the same meaning as the formula

$$\bigwedge_{i=1}^n A_i \supset \bigvee_{j=1}^m C_j$$

One way to get a multi-conclusion sequent in LK is to apply the “multiplicative”¹ introduction rule $\vee R$ (Figure ??). For instance, Figure ?? shows a proof of the law of excluded middle, where for each rule we squared the principal formula. One could imagine performing the same proof in Actema by successively clicking on these principal formulas, following a bottom-up reading of the sequent calculus derivation seen as the trace of a proof search process. First we decide to prove $A \vee \neg A$: this amounts to proving alternatively A or $\neg A$, which now appear as two separate red items in the same tab. Then we try to prove $\neg A$, with the usual method of supposing A to find a contradiction. However instead of a contradiction, we decide to backtrack and prove the alternative conclusion A , which is now trivial by assumption. We come back to these multi-conclusion click actions in Section ??.

It is clear in the proof that the negative occurrence of A in $\neg A$ is the one that becomes the assumption A that justifies the conclusion A in the last step. It would be natural to specify this causal relationship by linking directly the two occurrences of A , as we do with DnD actions in Actema. However for this to be possible, we need to introduce a new linking operator — let us note it \oplus — that works between two conclusions, where $A \oplus B$ is obviously interpreted as $A \vee B$. Then after clicking on $A \vee \neg A$ we can just finish the proof by connecting A and $\neg A$:

$$\boxed{A} \oplus \neg \boxed{A} \rightarrow^* \top$$

This would avoid the additional step of clicking on $\neg A$ to turn it into an hypothesis, and suggests the possibility of a more general behavior associated to this \oplus operator for arbitrary logical connectives. This is what we explore in Section ??.

$$\frac{\Gamma \Rightarrow A, B, \Delta}{\Gamma \Rightarrow A \vee B, \Delta} \vee R$$

Figure 4.1: Multiplicative right introduction rule for disjunction

$$\frac{\frac{\frac{}{A \Rightarrow \boxed{A}, \perp} ax}{\Rightarrow A, \boxed{\neg A}} \supset R}{\Rightarrow \boxed{A \vee \neg A}} \vee R$$

Figure 4.2: Proof of the excluded middle in LK

1: Terminology borrowed from linear logic, where $\vee R$ is exactly the right introduction rule for multiplicative disjunction \wp .

4.1 Backtracking

Interestingly, the classical aspect of the proof of $A \vee \neg A$ in Figure ?? comes exclusively from the *backtracking* operation during the last step, a phenomenon which is well known in the literature on constructive/computational properties of classical logic. Then one can see the introduction rules $\vee R_1$ and $\vee R_2$, and the restriction of intuitionistic sequents to one conclusion, as ways to prevent such backtracking by forcing the choice of disjunct to prove at an early stage.

In fact backtracking can still be performed in intuitionistic logic, but at the meta-level of the proof search process instead of the object-level of inference rules. In an interactive theorem prover, this corresponds to the ability for the user to *undo* an inference and go back to a previous proof state. However keeping track of the times we undo/redo inferences is very hard to do as humans, and the user interfaces of current proof assistants do not provide any mechanism for it either. This has already been noted by Ayers², and is a good motivation for trying to design proof systems where the need for meta-level backtracking is reduced, or even removed. One way to do this is to maximize the proportion of inference rules that are *invertible*, meaning that their premisses always follow from their conclusion. Indeed when looking at rules as tactics (see Section ??), it means that they will always reduce a provable goal to provable subgoals, and thus can never induce a backtracking point³. The $\vee R$ rule is an example of invertible rule, and in LK it can replace the other, non-invertible rules $\vee R_1$ and $\vee R_2$.

But $\vee R$ requires multi-conclusion sequents, and Gentzen restricted their use to classical logic. It turns out that logicians after Gentzen have proposed various multi-conclusion sequent calculi that work for intuitionistic logic, the most famous being GHCP from Dragalin [51], which uses $\vee R$. In the rest of this chapter, we will consider to what extent one can benefit from having multiple conclusions in an intuitionistic setting.

4.2 Implementation in theorem provers

Despite the aforementioned benefits of multi-conclusion sequents, we do not know of any proof assistant, whether classical or intuitionistic, that exposes them in its user interface. One reason is that most proof/-tactic languages are based on the rules of natural deduction, which use single-conclusion sequents. Another reason is that having one conclusion removes the need to designate it with an explicit name or number, as is the case with hypotheses⁴. And the explicit handling of names in tactic invocations is known to be tedious and time-consuming, to the point that some tactic languages like SSREFLECT have been designed around this problem [74]. Thus having multiple conclusions would only double the effort for no compelling reason.

However in our graphical paradigm based on direct manipulation, hypotheses and conclusions are designated by the act of *pointing* at them with a mouse, finger or any other pointing device⁵. This opens up the possibility of exposing multiple conclusions in the interface with associated graphical proof actions, as outlined in the introductory example on the

add references

2: Section 3.1.3 of his thesis [9].

3: Except of course if the user deems the subgoal too complex to prove in its current form, and explicitly wants to back-track to shape it differently.

[51]: Dragalin et al. (1990), 'Mathematical Intuitionism. Introduction to Proof Theory'

4: The current trend is to have user-chosen or automatically generated strings for names as in Coq and Lean, but some provers like HOL Light ask for the position in the list as an integer to designate a particular hypothesis.

[74]: Gonthier et al. (2016), *A Small Scale Reflection Extension for the Coq system*

5: With the recent advances in natural language processing and voice recognition, one could also imagine a system based on the selection of subterms by spelling their content. Then click and DnD actions could be triggered by voice commands once the subterms they apply to have been selected. This could be an important alternative for users with impaired vision and/or motricity.

excluded middle. While we did not implement such an extension, we explore in the following sections its design, and the theoretical foundations behind it.

4.3 Click actions

In Table ??, we showed how click actions in Actema are in direct correspondence with the rules of the single-conclusion sequent calculus LJ for intuitionistic logic. Following the literature mentioned earlier, we just need to replace two actions/introduction rules to get a multi-conclusion system capturing either intuitionistic or classical first-order logic:

- ▶ clicking on a red disjunction $A \vee B$ breaks it into two conclusions A and B . This is the dual behavior to click actions on blue conjunctions, and corresponds to the $\vee R$ rule of Figure ??, which is common to both the intuitionistic and classical variants;
- ▶ as before, clicking on a red implication $A \supset B$ breaks it into an hypothesis A and a conclusion B . Without further changes, this corresponds to the right introduction rule from the classical sequent calculus LK of Gentzen (named $\supset R * c$ in Figure ??), and our set of actions becomes a proof system for classical logic. To go back to intuitionistic logic, one needs the additional behavior that all the other conclusions of the goal are removed. This corresponds to the right introduction rule from the GHCP calculus of Dragalin (named $\supset R * i$ in Figure ??).

Remark 4.3.1 In the special case of intuitionistic sequents with one conclusion, the two variants $\supset R * c$ and $\supset R * i$ collapse into the usual $\supset R$ rule.

Note that we only modified the behavior of the disjunction \vee and implication \supset connectives; and for the latter, only in the case when there are at least two parallel conclusions, and thus implicitly a disjunction. Then it is interesting to notice that the classical behavior of the other connectives ($\perp, \wedge, \forall, \exists$) essentially arises from their interaction with (positive) disjunctive statements.

If we stick to intuitionistic logic, the benefits of having multiple conclusions are unclear. Indeed while the $\vee R$ rule is invertible, the $\supset R * i$ rule is not, and thus at some point the choice of which conclusion to prove must be made by the user irreversibly, even if the choice is delayed⁶. On the other hand the $\supset R * c$ rule is invertible: this is known to allow the formulation of sequent calculi for classical logic where *all* rules are invertible, like the G3c calculus of [134]. In the propositional case, this gives a constructive decision procedure for the question of provability: given a sequent $\Gamma \Rightarrow \Delta$, one just has to choose any formula in Γ or Δ and apply the introduction rule associated to its main connective, or the axiom rule whenever possible. In Actema, this would correspond to having the user click randomly on blue and red items until all goals are solved. The procedure ends because all introduction rules destroy the main connective, and none of them duplicate formulas: thus the total size of the sequent decreases strictly after each rule application.

$$\frac{\Gamma, A \Rightarrow B, \Delta}{\Gamma \Rightarrow A \supset B, \Delta} \supset R * c$$

$$\frac{\Gamma, A \Rightarrow B}{\Gamma \Rightarrow A \supset B, \Delta} \supset R * i$$

Figure 4.3: Multi-conclusion right introduction rules for implication

6: In Section ??, we will see how to overcome this limitation by using a *nested sequent* system.

[134]: Negri et al. (2001), *Structural Proof Theory*

$$\frac{\Gamma, \forall x.A, A\{t/x\} \Rightarrow \Delta}{\Gamma, \forall x.A \Rightarrow \Delta} \forall L*$$

$$\frac{\Gamma \Rightarrow A\{t/x\}, \exists x.A, \Delta}{\Gamma \Rightarrow \exists x.A, \Delta} \exists R*$$

Figure 4.4: Multi-conclusion instantiation rules for quantifiers

When dealing with quantifiers, the situation is not so simple: if one wants invertible introduction rules, it is necessary to duplicate the quantified formula being instantiated, which can be seen as the root cause of undecidability in predicate logic as noted by Girard[68, Section 3.3.2]. This is already what happens in Actema for the universal quantifier: dropping a term t on a blue item $\forall x.A$ will produce a new hypothesis $A\{t/x\}$, while keeping the original $\forall x.A$ item. This corresponds to the invertible left introduction rule of G3c ($\forall L^*$ in Figure ??). But in the single-conclusion framework, dropping a term t on a red item $\exists x.A$ necessarily replaces it by the instantiated conclusion $A\{t/x\}$. Allowing multiple conclusions circumvents this problem and restores the symmetry between \forall and \exists , since we can create a new conclusion for $A\{t/x\}$ while preserving the old one. This corresponds to the invertible right introduction rule of G3c ($\exists R^*$ in Figure ??).

4.4 DnD actions

Once we allow for more than one conclusion, it is natural to wonder whether it makes sense to also allow for DnD actions between two conclusions. But we already capture *backward* reasoning with the $A \otimes B$ operator between a hypothesis A and a conclusion B , and *forward* reasoning with the $A \oplus B$ operator between two hypotheses. There does not seem to be room for a third mode of reasoning, at least in the traditional way of building proofs we are used to, either on paper or with proof assistants. However from a purely formal point of view, there is nothing preventing us from trying to design rewrite rules for a new linking operator, by following the same recipe we used for \otimes and \oplus . Furthermore, we already saw earlier in the excluded middle example that such an operator did seem useful.

When looking for a proof of a sequent with multiple conclusions, unless we commit to proving one conclusion and give up on the others by applying the $\supset R^* i$ rule, we can switch freely our focus between the different conclusions. Thus in a way, we are looking for proofs of all the conclusions *in parallel*, and we stop as soon as we find one⁷. Hence we chose to call this third kind of interaction between two conclusions *parallel* reasoning. This justifies the choice of notation for the parallel linking operator \oplus , which is suggestive of the parallel composition $|$ from process calculi.

The rules governing \oplus are presented in Figure ?. A parallel linkage can be created either by drag-and-dropping two conclusions together, or through an instance of the new backward rule $L\supset_1$. It is important to note that this rule is only sound *classically*; indeed we can now come back to the example of Section ?? and give the following derivation of Peirce's law with it:

$$\begin{array}{ll}
 (\boxed{A} \supset B) \supset A \otimes \boxed{A} & \rightarrow (\boxed{A} \supset B \oplus \boxed{A}) \wedge (A \supset A) & L\supset_1 \\
 & \rightarrow ((\boxed{A} \otimes \boxed{A}) \vee B) \wedge (A \supset A) & P\supset_1 \\
 & \rightarrow (\top \vee B) \wedge (A \supset A) & \text{id} \\
 & \rightarrow \top \wedge (A \supset A) & \text{absl} \\
 & \rightarrow A \supset A & \text{neul}
 \end{array}$$

7: This is also related to the \wp connective of linear logic which uses the $\vee R$ rule of Figure ??, and whose spelling “par” is historically motivated by an understanding of the multiplicative fragment of LL as a logic of parallel computation [66].

The other rules of Figure ?? handle the rewriting of parallel linkages, and were conceived as the dual counterpart of forward rules. Indeed, while a forward linkage combines two negative subformulas in the same context to produce a new *hypothesis*, a parallel linkage combines two positive subformulas in the same context to produce a new *conclusion*. Backward linkages can then be seen as mediating between these two opposite modes of reasoning, by handling the interaction of a positive and a negative subformula in the same context. A schematic view of the back and forth between the different modes through the 4 rewriting rules that change linking operators is provided in Figure ?. Notice that the latter correspond exactly to the rules that handle interaction with the antecedent of an implication: this is because it is the only way to switch polarity when descending into a direct subformula, which is what triggers the change of mode.

4.5 Metatheory of parallel reasoning

Like backward rules, a parallel rule $A \rightarrow B$ will be logically sound if B entails A . Then if one wants to stick to an intuitionistic setting, one has to remove the rules $P\supset_1$, $P\supset_2$ and $P\forall s$ from the system, in addition to the $L\supset_1$ rule. Indeed those are all sound classically but not intuitionistically⁸.

Now if we look back at the schema from Figure ??, removing $L\supset_1$ and $P\supset_1$ in particular has the consequence of isolating completely parallel reasoning from the other modes. But remember from Section ?? that we are only interested in *valid* linkages, that is those linkages who satisfy productivity (Theorem ??) and thus will always terminate on an instance of either the id rule (backward mode) or the equality rules (backward/forward modes). Thus if there is no way to reach either forward or backward mode from a parallel linkage, it has no meaning in our paradigm. Then if we trust that rules $L\supset_1$ and $P\supset_1$ are necessary to get the intended semantics, it seems that parallel reasoning only makes sense in a classical setting. In the following, we only show that the rules of Figure ?? are sufficient for our purpose, by extending the results of Chapter ?? to the classical, multi-conclusion setting.

We start by updating the validity criterion on linkages, more specifically we drop Clause ?? of Condition ?? about the polarities of linked subformulas. Indeed it was introduced precisely to forbid behaviors which only make sense in classical logic, but are now given a semantics with the $L\supset_1$ rule. We also need to add a case for the \oplus operator in the other clauses of Condition ??, which gives the following updated condition:

Condition 4.5.1 (Classical Polarity) The following must be true for a logical linkage $B \boxed{A} @ D \boxed{A'}$ to be *classically valid*:

1. the parity of $\text{inv}(B\boxed{})$ is:
 - a) the same as $\text{inv}(D\boxed{})$ if $@ = \ominus$
 - b) the opposite of $\text{inv}(D\boxed{})$ if $@ = \otimes$
 - c) the opposite of $\text{inv}(D\boxed{})$ if $@ = \oplus$

The following must be true for a rewrite linkage $B \boxed{t} @ D \boxed{t'}$ to be *clas-*

BACKWARD

$$B \supset C \otimes A \rightarrow (B \oplus A) \wedge (C \supset A) \quad L\supset_1$$

PARALLEL

$$A \oplus (B \wedge C) \rightarrow (A \oplus B) \wedge C \quad P\wedge_1$$

$$A \oplus (C \wedge B) \rightarrow C \wedge (A \oplus B) \quad P\wedge_2$$

$$A \oplus (B \vee C) \rightarrow A \oplus B \quad P\vee_1$$

$$A \oplus (C \vee B) \rightarrow A \oplus B \quad P\vee_2$$

$$A \oplus (B \supset C) \rightarrow (B \otimes A) \vee C \quad P\supset_1^*$$

$$A \oplus (C \supset B) \rightarrow C \supset (A \oplus B) \quad P\supset_2^*$$

$$A \oplus (\forall x.B) \rightarrow \forall x.(A \oplus B) \quad P\forall s^*$$

$$A \oplus (\exists x.B) \rightarrow A \oplus B\{x/t\} \quad P\exists i$$

$$A \oplus (\exists x.B) \rightarrow \exists x.(A \oplus B) \quad P\exists s^*$$

$$B \oplus A \rightarrow A \oplus B \quad P\text{comm}$$

In the rules $\{P\forall s, P\exists s\}$, x is not free in A .

Figure 4.5: Parallel linking rules

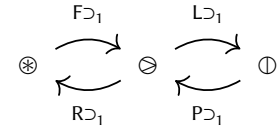


Figure 4.6: Alternating structure between reasoning modes

8: We do not prove this formally here, but this can be done by exhibiting intuitionistic counter-models in which the entailments are false, i.e. Kripke structures or Heyting algebras.

sically valid:

1. if $B \square$ holds the equality, then it must be:
 - a) positive if $@ = \ominus$;
 - b) positive if $@ = \otimes$;
 - c) negative if $@ = \oplus$;
2. if $D \square$ holds the equality, then it must be:
 - a) negative if $@ = \ominus$;
 - b) positive if $@ = \otimes$.
 - c) negative if $@ = \oplus$.

Then we add the following case to the statement of Theorem ??:

$$\text{If } A \oplus B \rightarrow^* C, \text{ then } C \Rightarrow A, B.$$

and we interpret \oplus as disjunction:

$$[A \oplus B] = [A] \vee [B]$$

We add the two following cases to Lemmas ?? and ??:

- If $C^+ [A \oplus B] \rightarrow D$ then $[D] \Rightarrow C^+ [A \vee B]$.
- If $C^- [A \oplus B] \rightarrow D$ then $C^- [A \vee B] \Rightarrow [D]$.

The proof of Lemma ?? is easily extended by inspecting each parallel rule, and we already mentioned that the backward rule \vdash_1 is sound classically. Note that now sequents have multiple conclusions, thus one needs to use rules from a multi-succedant calculus such as G3c [134].

Polarity preservation (Fact ??) is also true with \oplus , we just need to add the missing cases from Figure ??:

- If $C [A \oplus B] \rightarrow C' [A' \oplus B']$ then $C \square$ and $C' \square$ have the same polarity.
- If $C [A \otimes B] \rightarrow C' [A' \oplus B']$ (resp. $C [A \oplus B] \rightarrow C' [A' \otimes B']$) then $C \square$ and $C' \square$ have the same polarity.

The proof of Lemma ?? is also extended straightforwardly. We only write the added case for \oplus in the proof of the first statement:

- $@ = \oplus$: by Fact ??, C' must be positive. Therefore by induction hypothesis $[D] \Rightarrow C' [A' \vee B']$. By Lemma ?? we have $C' [A' \vee B'] \Rightarrow C^+ [A \supset B]$. Thus by transitivity $[D] \Rightarrow C^+ [A \supset B]$.

Regarding completeness (Theorem ??), we already noticed that our rules now allow us to prove Peirce's law, which is known to be sufficient to recover classical logic from intuitionistic logic.

The proof of productivity (Theorem ??) is again extended straightforwardly, by considering the additional case of parallel linkages and using arguments "dual" to those used for forward linkages. There is even less work to do regarding the preservation of Condition ?? since we dropped the intuitionistic restriction.

Finally about focusing (Section ??), we can just remark that some rules that were not invertible in intuitionistic logic become invertible in classical logic. Therefore the dynamics of focusing should be different, and it might

be interesting to compare the behaviors of intuitionistic and classical DnD actions on specific examples.

In the previous chapters, we introduced the Proof-by-Action paradigm (Chapter ??), and tried to convince the reader that it is both theoretically sound with its firm grounding in deep inference proof theory (Chapter ?? and Chapter ??), and practically useful by analysing proofs of mathematical problems expressed within it (Chapter ??). We also mentioned multiple times our prototype of interface implementing Proof-by-Action called Actema, and in particular the fact that it exists as a *standalone* web application with its own proof engine [48]. This is convenient for distributing it online as a publicly available website, so that people can immediately try it out without the hassles of installation procedures. However due to both historical choices in its design and lack of human resources for development, Actema’s proof engine is quite limited in its features:

- ▶ it can only handle goals expressed in many-sorted intuitionistic first-order logic (hereafter iFOL), whereas all state-of-the-art PAs support *higher-order logic* in one form or another; and higher-order features are crucial for formalizing many mathematical notions in a concise way, as witnessed by the example of Section ??;
- ▶ it does not implement a *certified logical kernel* for checking proof objects, which makes it hard to trust and interoperate with;
- ▶ it has no mechanism for adding new *mathematical notations*, only ad hoc support for arithmetical expressions; thus formulas become very quickly impossible to read and manipulate;
- ▶ it has poor support for managing *libraries* of definitions, lemmas and proofs, partly because of the previous items.

To address these limitations, and thus enable a confrontation of the Proof-by-Action paradigm to real mathematical developments, we decided to build `coq-actema`, a Coq plugin that directly connects Actema to a running instance of the Coq PA. The idea is that Actema should act as an enhanced graphical, interactive proof view that integrates in the usual text-based workflow of proof scripts. Thus instead of trying to turn Actema into a full-fledged PA, we exploit the over 30 years of effort that have been put in the development of Coq, and limit the role of Actema to that of a novel frontend for building proofs in Coq. This shall open the way to more advanced experimentations through the huge body of theories already developed in Coq, and make the Proof-by-Action paradigm visible to the large community of existing users of this popular PA.

Note that the same approach should be applicable in principle to any ITP that supports at least iFOL, and provides an interaction protocol for building proofs in a goal-directed manner. This includes other popular PAs such as Lean and Isabelle, but also more specialized software like the Why3 platform for deductive program verification, the Meta-F* framework in the F* programming language, or the EasyCrypt toolset for proving cryptographic protocols.

The chapter is organized as follows: we start in Section ?? by explaining the implementation design of the Actema web application, which follows

the standard conceptual separation between frontend and backend. In Section ??, we reflect on some considerations that led us to the specific choice of a Coq plugin, in order to integrate the Actema web app with Coq. Then in Section ?? we present the architecture of the coq-actema system, which structures all interactions between the user, Coq and Actema. Section ?? describes in more details the main usage scenario of coq-actema, following the flow of data and control between the different processes involved. Section ?? explains how the various graphical actions performed by the user in Actema are compiled into Coq tactics, ultimately producing certified proof terms. Finally in Section ??, we discuss possible avenues for extending the usability of coq-actema to a broader class of Coq goals, as well as prospective solutions to the problem of *proof evolution* in our graphical paradigm.

5.1 Actema

At its core, Actema is a web application made of two components: a *frontend* that implements the graphical interface with which the user interacts, written in HTML/CSS and JavaScript with the Vue.js framework [183]; and a *backend* that implements the proof engine, written in OCaml and compiled to JavaScript (JS hereafter) with js_of_ocaml [189]. The two components interact through an object-oriented API written in OCaml, which is loaded at runtime in the form of a JS object called *engine*, and whose methods can be called from the Vue components in the frontend.

The engine object provides various high-level methods for handling the current *proof state*. Common operations include getting the list of open subgoals, querying available proof actions on a subgoal, or applying a given proof action. Lower-level methods are also available in other objects to inspect the data of the proof state. For instance,

```
engine.subgoals[0].context[0]
```

will return an object representing the first hypothesis of the first subgoal; and this object itself exposes an `html` method, which returns a string holding the HTML code used to display the statement of the hypothesis.

In the standalone version of Actema, the proof engine takes care of computing the new subgoals stemming from actions performed by the user. It is thus responsible for defining the *semantics* of proof actions. It is also in charge of various other tasks that process the logical data of the proof state, typically checking the *validity* of linkages during a DnD action, which requires the use of a unification algorithm (see Section ??).

5.2 Why a plugin?

Usually, integrated development environments for Coq live in an independent process, and exchange data with Coq through a high-level communication protocol: either the command line interface provided by coqtop, Coq's default XML protocol, or its improved superset SerAPI [60]. In particular, SerAPI emerged from the development of jsCoq [7], an IDE that runs entirely in web browsers by embedding a version of

[183]: The Vue.js team (2022), *Vue.js*

[189]: Vouillon et al. (2014), 'From bytecode to JavaScript'

Add a little side figure illustrating an API call to the backend? Or we wait for the description of the sequence diagram of Section ??.

[60]: Gallego Arias (2016), 'SerAPI: Machine-Friendly, Data-Centric Serialization for COQ'

[7]: Arias et al. (2017), 'jsCoq: Towards Hybrid Theorem Proving Interfaces'

Coq compiled with `js_of_ocaml`. Since Actema is also web-based and uses `js_of_ocaml`, our first idea was essentially to fork `jsCoq` and replace its interface by that of Actema. However as noted by E. J. G. Arias, the SerAPI protocol — and in fact all the other protocols turn out to be too high-level for our purpose. Typically we need to (partially) translate Coq goals into iFOL goals, which can be done much more easily with a direct access to Coq’s low-level API for manipulating kernel terms.

Now, remember that Actema is not meant as a full-fledged IDE that can manage the edition and execution states of the proof script, but only as an enhanced proof view for manipulating already-parsed goals. One should think of Actema’s actions as just a graphical frontend for invoking a new set of tactics. And this is precisely what the plugin system of Coq has been designed for: extending Coq with new tactics. Thus the solution of a Coq plugin made a lot more sense, with the important benefit of ensuring compatibility with all existing IDEs. This would also entail easier adoption of Actema into existing Coq developments and workflows.

In this setting, it is now the Coq plugin which defines the semantics of proof actions as new tactics, instead of Actema’s backend. This allows us to leverage the facilities already provided by Coq to handle the proof state and generate proof terms in its own logical framework, the Calculus of Inductive Construction. This does not make the backend of Actema completely irrelevant however: we still need it so that Actema can maintain its own, first-order version of the proof state, with additional metadata used to display and interact graphically with objects and statements. Also tasks related to the querying of both display data and proof actions, like the `html` method and unification algorithm mentioned in the previous section, are at the time of writing of this thesis still performed in Actema’s backend. It is unclear to what extent this should rather be a responsibility of the Coq plugin, relegating Actema to a pure role of frontend to the PA¹.

1: For instance in the ProofWidgets framework of Lean [10], all these tasks are implemented in the meta-programming language of Lean itself, which makes it easily extensible by (expert) users of the PA.

5.3 The coq-actema system

Let us now give the full picture of the `coq-actema` system that integrates both Actema and the Coq plugin. A schematic view of its overall architecture, including the various components and their relationships, is provided in Figure ???. The different *processes/agents* involved are represented by shapes of different *colors*, and we add a directed *arrow* whenever two of

Add link to GitHub repository of `coq-actema` (which should thus become public)

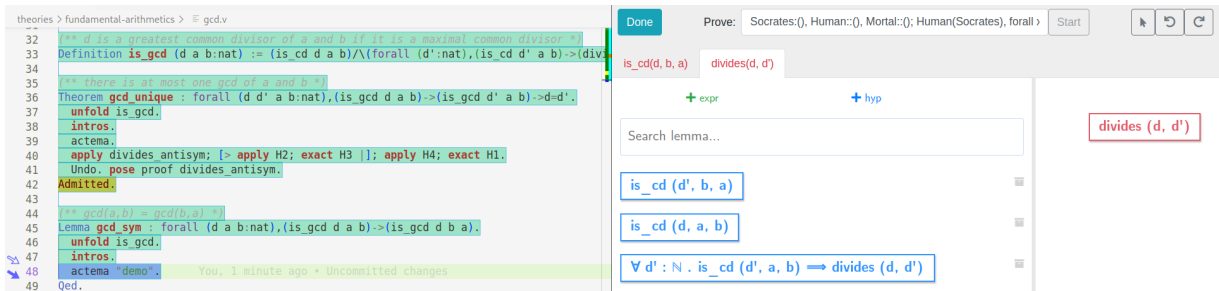


Figure 5.1: A possible graphical layout of the `coq-actema` system. On the left, the usual interactive view of the proof script, in the VsCoq IDE. On the right, the graphical proof view of Actema.

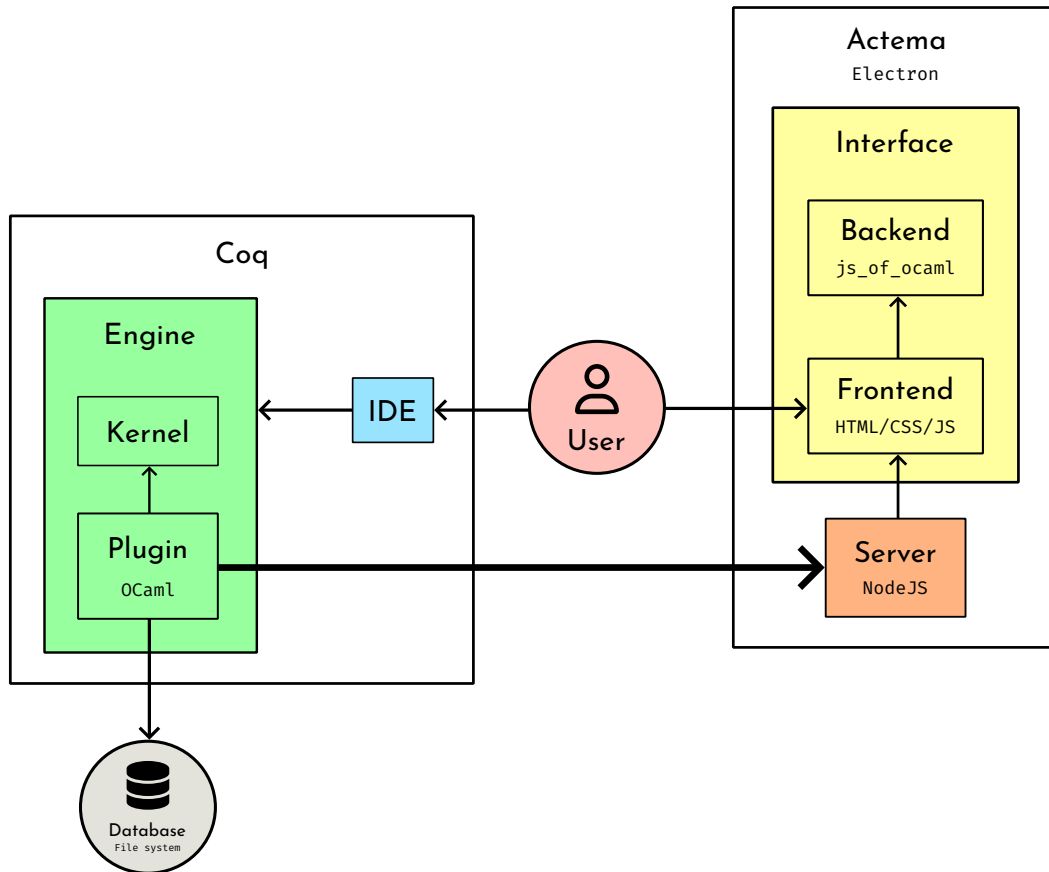


Figure 5.2: Architecture of the coq-actema system

them communicate with each other, where the *source* requests data from, or sends instructions to the *target*.

The User (pink circle) is the only human agent in the system, and drives all interactions. She interacts with the Coq and Actema subsystems (transparent rectangles), through the interfaces provided by her Coq IDE of choice (blue rectangle) and Actema's Frontend (yellow rectangle). This will typically take the form of a two-windows layout, as depicted by the screenshot of Figure ??.

Actema web app

The Actema web app runs in a process independent from Coq, represented by the yellow Interface rectangle. We add a third layer to the Frontend and Backend described in Section ??, namely a HTTP Server (orange rectangle) that handles requests from, and responses to the Coq Plugin. Thus we implement interprocess communication between Actema and Coq through the network layer of the operating system, rather than a more local mechanism such as Unix pipelines. There are a few reasons behind our choice of the HTTP protocol:

- it provides useful abstractions when working with a client/server architecture structured around requests;

- ▶ it is a widely spread standard, especially in web technologies. Thus we were able to reduce development time by reusing generic implementations of both client and server from standard libraries;
- ▶ more anecdotically, this makes it easy to run Coq and Actema on different machines connected on the same network. This could be used for instance to offload heavy computations in a proof to the machine running Coq, while still being able to interact with Coq through Actema on the weaker machine.

The Server runs in a process separate from the Interface, in order to avoid any delay in the latter. Then we bundle everything in an Electron application [144], so that Actema can easily be run locally on most operating systems. This also allows us to exploit the multi-process architecture of Electron [143], where the so-called *main* process runs the server and has the ability to issue system calls for networking through the Node.js HTTP library [145]; and the so-called *renderer* process runs the Interface in the Chromium browser.

[144]: OpenJS Foundation and Electron contributors (2022), *What is Electron?*

[143]: OpenJS Foundation and Electron contributors (2022), *Process Model*

[145]: OpenJS Foundation and Node.js contributors (2020), *Node.js HTTP library documentation*

Coq plugin

The Plugin is loaded dynamically in Coq's Engine (green rectangle) by executing the following command in a proof script:

```
From Actema Require Import Loader .
```

It essentially exposes a single tactic called `actema`, which can run in two distinct modes:

Interactive The Plugin sends the current subgoals to Actema, and the user applies a sequence of actions on them. Each time an action is performed, it is sent back to Coq, compiled into the appropriate tactic call, and then executed to generate new subgoals that are sent again to Actema. The `actema` tactic finishes its execution either when:

- ▶ all subgoals are proved (in Actema);
- ▶ the User decides to stop and give back control to the IDE;
- ▶ in some rare cases, an unrecoverable error occurs.

Non-interactive If the `actema` tactic has already been executed on the subgoal under focus, then the Plugin automatically saved the sequence of actions performed by the User in a Database (gray circle). Currently for ease of development, the Database is implemented as a simple directory on the local filesystem, where each file encodes an entry as follows:

- ▶ the filename is a hash code that uniquely identifies the goal by both its *content*, i.e. the statements of the hypotheses and conclusion, and an optional *identifier*, which can be given as argument to the tactic in the form of an arbitrary string;
- ▶ the contents of the file is essentially a Base64 encoding of the data specifying each action, whose format will be detailed in Section ??.

Then the tactic will load the sequence of actions from the appropriate file, recompile it into one big tactic, and execute it on the current subgoal.

One can also force the execution in interactive mode by using a variant of the tactic named `actema_force`. We provide details of the complete interaction protocol followed by the `actema` tactic in the following section.

Regarding the implementation of the Plugin, we chose to do it in the standard way by interfacing with the `coq-core` API in OCaml [182], although it has been encouraged in recent versions of Coq to interface with more stable APIs such as those provided by Coq-Elpi [179] and MetaCoq [172]². The main reason is that our plugin performs *side effects* by interacting with an external environment: the file system when saving and retrieving graphical proofs, and the network when issuing HTTP requests to Actema. Those cannot be implemented in the aforementioned frameworks.

[182]: The Coq Development Team (2022), *coq-core OCaml API documentation*

[179]: Tassi (2023), *Coq-Elpi GitHub repository*

[172]: Sozeau et al. (2020), ‘The MetaCoq Project’

2: Indeed breaking changes are frequently introduced in `coq-core` with newer versions of Coq, which requires more maintenance efforts from plugin developers.

5.4 Interaction protocol

We will now unroll the details of a complete interaction in `coq-actema`, starting from the User calling the `actema` tactic in her IDE, and ending with her viewing the new subgoals displayed in the IDE. We chose to represent this with a *sequence diagram*, as specified by the UML standard [192]. This kind of diagram is used to depict runtime behavior of a system, showing interactions between objects and the messages they exchange in the order they occur chronologically. In our case, the objects are the different processes described in the previous section, as well as the User. Since the full interaction is quite involved, we split the diagram in three parts: Figure ?? includes the beginning of the interaction, focusing on the non-interactive mode of the `actema` tactic where the Plugin communicates with Coq’s kernel and the Database. Figure ?? and Figure ?? tackle the interactive mode of the `actema` tactic: Figure ?? focuses on the conditions for breaking out of the interaction loop, and Figure ?? on the interactions at work when the User performs a proof action in Actema.

Translating goals

The first task performed by the Plugin when calling the `actema` tactic is to ask the kernel for the data of the subgoal G currently under focus. Then for the goal G to be understandable by the Backend of Actema, the Plugin will translate it into a new representation $\llbracket G \rrbracket$ in a custom datatype. In order to share the definition of this datatype across implementations of the Plugin and Backend, we decided to use the ATD data specification language [121]. It provides a set of tools to automatically generate idiomatic datatype definitions in a few target languages — including OCaml — along with (de)serialization and validation helpers. This is particularly fit for our usecase, where we need to serialize complex data like $\llbracket G \rrbracket$ in order to transmit it over HTTP messages. Since both the Plugin and Backend are written in OCaml, it also allows us to share across implementations our own domain-specific helpers for manipulating this data.

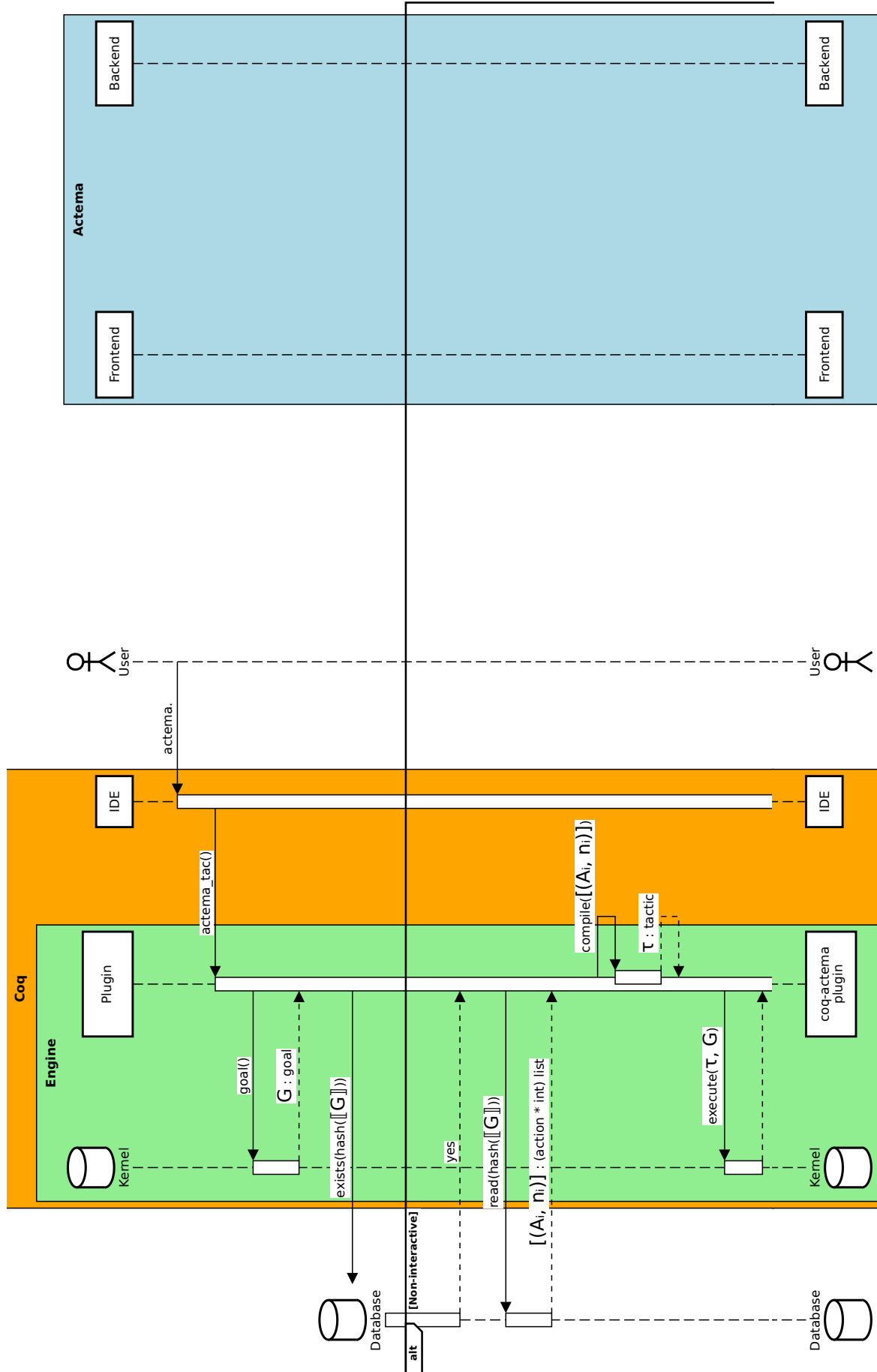


Figure 5.3: Sequence diagram of coq-actema's interaction protocol — non-interactive mode

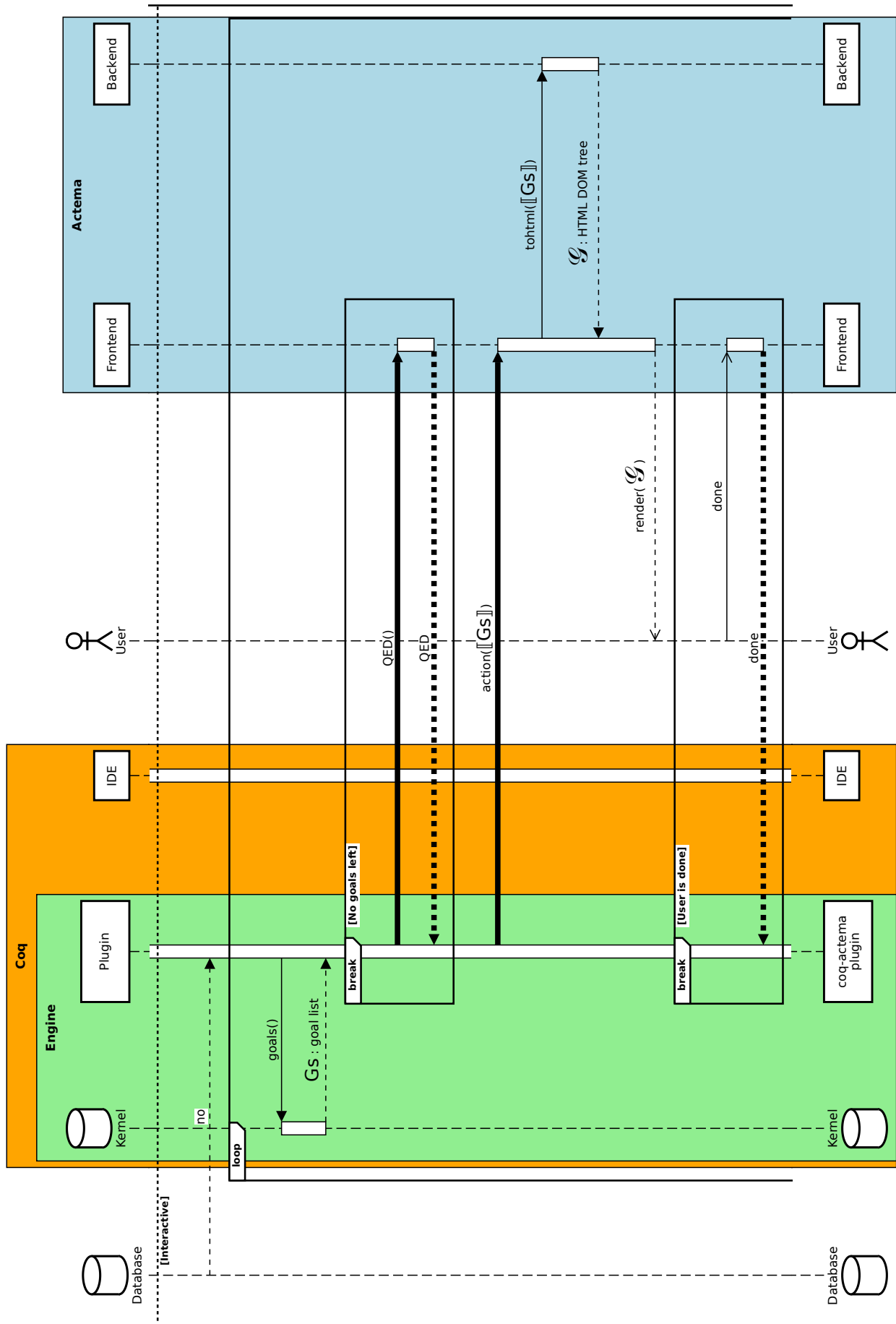


Figure 5.4: Sequence diagram of coq-actema's interaction protocol — breaking out of the interaction loop

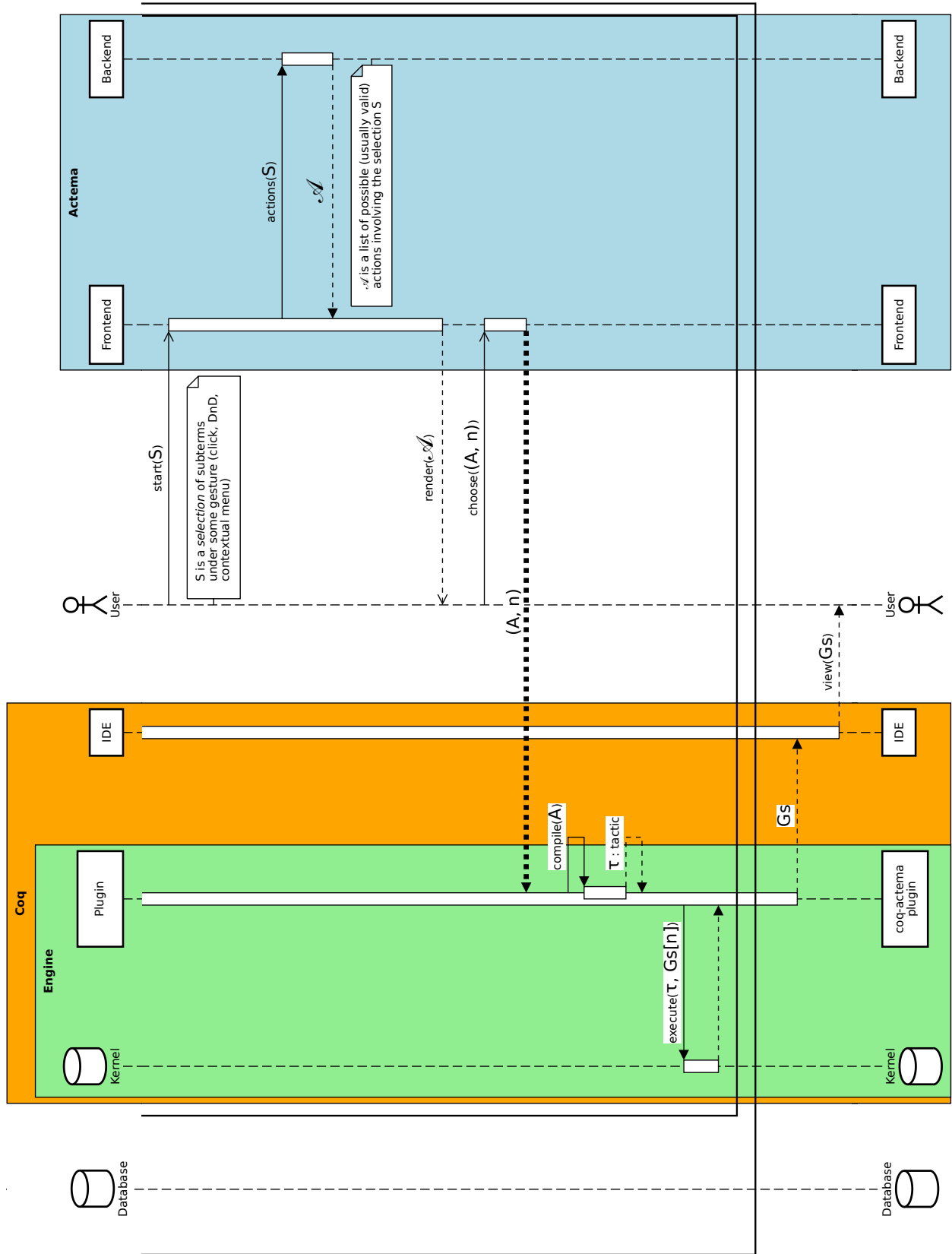


Figure 5.5: Sequence diagram of coq-actema's interaction protocol — applying an action

```

1
2 (* ----- *)
3 (** Identifiers *)
4
5 type name = string
6
7 (* ----- *)
8 (** Types *)
9
10 type type_ = [
11   | TVar of name
12 ]
13
14 type arity = type_ list
15 type sig_ = (arity * type_)
16
17 (* ----- *)
18 (** Expressions *)
19
20 type expr = [
21   | EVar of name
22   | EFun of (name * expr list)
23 ]
24
25 (* ----- *)
26 (** Formulas *)
27
28 type logcon = [ And | Or | Imp | Equiv | Not ]
29 type bkind = [ Forall | Exist ]
30
31 type form = [
32   | FTrue
33   | FFalse
34   | FPred of (name * expr list)
35   | FConn of (logcon * form list)
36   | FBind of (bkind * name * type_ * form)
37 ]
38
39 (* ----- *)
40 (** Terms = Formulas + Expressions *)
41
42 type term = [ F of form | E of expr ]
43
44 (* ----- *)
45 (** Environments *)
46
47 (* Body of a variable declaration, holding its type and eventually an expression
48    in the case of a local definition *)
49 type bvar = (type_ * expr option)
50
51 type varenv = (name * bvar) list
52
53 type env = {
54   env_sort      : name                list; (* Sorts, i.e. atomic types *)
55   env_prp       : (name * arity       ) list; (* Predicate symbols *)
56   env_fun       : (name * sig_        ) list; (* Function symbols *)
57   env_sort_name : (name * name       ) list;
58   env_prp_name  : (name * name       ) list;
59   env_fun_name  : (name * name       ) list;
60   env_var       : varenv;             (* Variable declarations *)
61 }
62
63 (* Local environment, only maps abstract variables to their type *)
64 type lenv = (name * type_) list
65

```

Figure 5.6: ATD definitions for first-order formulas and environments

```

1  (* ----- *)
2  (** Goals *)
3
4  (* Unique identifier *)
5  type uid = string
6
7  (* Hypothesis *)
8  type hyp = {
9    h_id : uid;
10   h_form : form;
11  }
12
13
14  (* Goal *)
15  type goal = {
16    g_env : env;
17    g_hyps : hyp list;
18    g_concl : form;
19  }
20
21  type goals = goal list
22
23  (* Abstract goal, without the signature *)
24  type agoal = {
25    a_vars : varenv;
26    a_hyps : hyp list;
27    a_concl : form;
28  }
29

```

Figure 5.7: ATD definitions for goals

The ATD definition of goals is given by the `goal` type in Figure ??³. It relies on the ATD types `form` of *formulas*, and `env` of *environments* of available constants and variables. In our setting, these correspond respectively to the formulas and *signatures* of many-sorted first-order logic, whose ATD definitions are given in Figure ?. But one could imagine using formulas and environments in higher-order logic instead, and this would not change the structure of the `goal` datatype. Note that hypotheses are encoded with a `h_id` attribute corresponding to their string identifier in the Coq goal, even though we do not display it in Actema’s interface. This is required later by the plugin to compile actions into tactics, because we need to identify which Coq hypotheses correspond to those designated graphically by the User.

3: The syntax is almost the same as that of OCaml datatypes, for the reader already acquainted with this language.

Retrieving actions

The next step for the Plugin is to check if there already exists a graphical proof associated to $\llbracket G \rrbracket$ in the Database. If so, then it retrieves it in the form of a list A of *actions*, whose data format will be precised in Section ?. There is also a positive integer n_i associated to each action A_i in the list, corresponding to the index of the goal to which A_i applies in the list of subgoals. Then each A_i is compiled into a tactic $\langle A_i \rangle$, and all the $\langle A_i \rangle$ are composed into a unique tactic τ , which is executed by the kernel on G to apply the full sequence of actions.

Remark 5.4.1 Currently the translation $\llbracket \cdot \rrbracket$ is not *injective*: it might map two different Coq goals to the same Actema goal, because strictly higher-order subterms are translated into a dummy atomic predicate.

Thus one might retrieve a proof from a different goal when calling the *actema* tactic. However this is not problematic, since the User cannot perform any actions involving the part of the two goals that make them distinct; they might as well be seen as the same goal from her point of view. It can thus be considered as a feature that maximizes proof reuse.

Otherwise the *actema* tactic has never been executed on $\llbracket G \rrbracket$, and thus we let the User provide a (partial) proof in Actema. First the Plugin retrieves the list G_s of all subgoals, instead of just the one under focus. If G_s is empty, which would happen after all subgoals have been solved from Actema, then it sends a QED request to Actema so that the latter can update its view accordingly, and the interaction loop with Actema stops here⁴.

Otherwise there is at least one subgoal, and we send an *action* HTTP request to Actema, whose body contains the translated subgoals $\llbracket G_s \rrbracket$. To do this, we chose to serialize $\llbracket G_s \rrbracket$ with the Biniou helpers autogenerated by *atdgen*, the OCaml backend of ATD. According to its authors: “Biniou is a binary format extensible like JSON but more compact and faster to process” [120]. This data is then deserialized and compiled into a set \mathcal{G} of HTML DOM nodes by the Backend, so that the goals can be rendered by the Frontend and exposed to the User. Then the User has two options:

- she can apply either a click, DnD or contextual action⁵. The precise protocol followed for applying an action is summarized in Table ?? . Let us focus on the more complex case of DnD actions. The **Start** column describes how the User *starts* the action, here by dragging some item I of the current subgoal. Then the Frontend asks the Backend for the set \mathcal{A} of all available DnD actions involving I . The **Selection** column describes how the computation of \mathcal{A} is impacted by the set S of subterms that are selected in the current subgoal. For DnD actions, we essentially filter out all linkages that do not match the selection. The **Render** column describes how \mathcal{A} is *rendered* to the User: here we highlight all valid drop targets, which correspond to subterms of the current goal located in other items⁶. Lastly, the **End** column describes how the user chooses a specific action $A \in \mathcal{A}$ to apply, here by dropping I on a given target. Then A is serialized and sent in the body of the response to the *action* request, together with the index n of the subgoal under focus in Actema. The Plugin can therefore compile A into a tactic $\langle A \rangle$ which is executed on the n^{th} Coq subgoal, giving a new list of subgoals which is sent again to Actema for another round of the interaction loop.
- or she can click on a Done button in Actema’s interface: this has the effect of answering the *action* request from the Plugin with a done response, and the interaction loop with Actema stops here. This will happen when the User wants to go back to editing the proof script, either because she is satisfied with the new subgoals obtained from previous actions, or because she is stuck and wants to try native Coq tactics instead. Indeed our protocol is *synchronous*: the IDE’s interface is stuck until the *actema* tactic has finished its execution, and thus one cannot edit the proof script *and* build a proof in Actema at the same time.

4: In Figure ?? and Figure ??, we depict requests as being sent to the Frontend of Actema. This is an imprecision for trading some readability, since as reviewed in Section ?? it is the Server which handles communication with the Plugin, and in particular forwards requests to the Frontend.

[120]: Martin Jambon (2023), *OCaml support – atdgen*

5: See Section ?? for an introductory example of contextual action with Unfold.

6: Highlighting is here understood in a *visual* sense: in the current implementation of Actema, subterms are indicated graphically by squaring them. But one could imagine other modalities for highlighting, typically *spelling* the subterms with a speech synthesis algorithm for users with impaired vision.

Table 5.1: Protocol for applying an action in Actema

Kind	Start	Selection S	Render	End
Click	Hover item I	Ignored	Highlight $P \subseteq [I]$	Click on some $p \in P$
DnD	Drag item I	If $\exists p \in S \cap [I]$ then match only $p @ q$ where $q \in \overline{[I]}$ If $\exists q \in S \cap \overline{[I]}$ then match only $p @ q$ where $p \in [I]$	Highlight $Q \subseteq \overline{[I]}$	Drop on some $q \in Q$
Contextual	Open menu	Populate menu only with actions applicable on S	Show menu	Choose an item in the menu

We introduced some notations for conciseness:

- ▶ p, q denote paths to subterms of the current goal
- ▶ P, Q and the selection S denote sets of paths
- ▶ $[I]$ denotes the set of paths within item I
- ▶ $\overline{[I]}$ denotes the complement of $[I]$, i.e. all paths in all items $J \neq I$
- ▶ $p@q$ is a linkage as introduced in Section ??

5.5 Compiling actions

Once it has received the actions to execute, either from the Database or the User, the Plugin will compile them with a function $\langle \cdot \rangle$ which translates any action A into a Coq tactic $\langle A \rangle$. This function actually has access to some other data used for interpreting actions: Coq's goal G , its Actema translation $\llbracket G \rrbracket$, and a bijective mapping Σ between Coq constants in the environment of G and the corresponding Actema symbols in the first-order signature of $\llbracket G \rrbracket$.

The action datatype

The action datatype is described thoroughly in the ATD specification provided in Figure ?? . It is a big algebraic datatype, where each constructor encodes a specific *type* of action. An action's type is equivalent to the *signature* of a tactic, i.e. its name and the types of its arguments. In particular, the translation function $\langle \cdot \rangle$ is defined as a big pattern-matching on the action's type⁷. The arguments in action types rely on most datatypes defined previously in Figure ?? and Figure ??, and on two new datatypes: the type `ipath` of *paths*, which is used pervasively to designate subterms of the current subgoal (that are typically indicated by the User through pointing); and the type `itrace` of *subformula linking traces*, which is used in the compilation of DnD actions that perform subformula linking, to be described soon.

Most click and contextual actions have a straightforward translation as Coq tactics. For instance, the `AIIntro` action that corresponds to a click on the conclusion C will be mapped to the Coq tactic that introduces the

7: Note that an action's type is orthogonal to what we referred to as its *kind* in Table ??, that is the interface mechanism through which it is accessible. One might for example want to map some action types to *vocal commands* instead of click or DnD gestures.

```

1  (* ----- *)
2  (** Actions *)
3
4
5  (* A path refers to a subterm in the current subgoal, through a [handle]
6     identifying an item of kind [kind], and a list of integers [sub] designating
7     the specific subterm of the item *)
8  type pkind = [Hyp | Concl | Var of [Head | Body]]
9  type ctxt = { kind : pkind; handle : uid }
10 type ipath = { ctxt : ctxt; sub : int list }
11
12 (* Trace of a subformula linking, from which the list of rewrite rules to apply
13    can be reconstructed *)
14 type choice = (int * (lenv * lenv * expr) option)
15 type itrace = choice list
16
17 type action = [
18   | AId (* The empty action which does nothing *)
19   | ADef of (name * type_ * expr) (* Introduction of a local definition *)
20   | AIntro of (int * (expr * type_) option) (* Click on a conclusion *)
21   | AExact of uid (* Proof by assumption *)
22   | AElim of (uid * int) (* Click on a hypothesis *)
23   | AInd of uid (* Click on a variable of inductive type *)
24   | ASimpl of ipath (* Simplify contextual action *)
25   | ARed of ipath (* Unfold contextual action *)
26   | AIndt of ipath (* Induction contextual action *)
27   | APbp of ipath (* Proof-by-Pointing contextual action *)
28   | ACase of ipath (* Case contextual action *)
29   | ACut of form (* Click on +hyp button *)
30   | AGeneralize of uid (* Generalization of a hypothesis *)
31   | AMove of (uid * uid option) (* Reordering of a hypothesis *)
32   | ADuplicate of uid (* Duplication of a hypothesis *)
33   | ALink of (ipath * ipath * itrace) (* DnD action for subformula linking *)
34   | AInstantiate of (expr * ipath) (* DnD action for instantiating a quantifier *)
35 ]
36
37 (* An action identifier is a pair of an abstract goal and an arbitrary string identifier *)
38 type aident = (string * agoal)
39

```

Figure 5.8: ATD definitions for actions

main connective of C , and is thus defined by case on the latter: `intro` for \supset and \forall , `split` for \wedge , etc. The actions `AInd`, `ASimpl` and `ARed` correspond respectively to the contextual actions `Induction`, `Simplify` and `Unfold` introduced in Chapter ??, and are mapped almost directly to the equivalent Coq tactics `induction`, `simpl` and `red`. The only difference is that they have a *deep inference* flavor, since they can all be applied on an arbitrary subterm selected by the User. This relies on our implementation of deep inference semantics directly in Coq, that we now briefly describe.

Deep inference semantics

In a deep inference setting, one can reason on subterms located arbitrarily *deep* inside statements, usually by applying some kind of rewriting rules on them. In particular, the semantics of DnD actions described in Chapter ?? are based on the rules of SFL (Figure ??). To implement them, we chose to do a *deep embedding* of first-order logic inside the logic of Coq, the Calculus of Inductive Constructions (CoIC hereafter). Here the word “deep” has a different meaning, related to the fact that we encode the statements of first-order logic with our own custom datatypes, instead of reusing the statements of CoIC. This makes it easier to define the SFL rewrite

```

1 Theorem b3_corr : forall p q T,
2   coerce p -> coerce (b3 p q T) -> coerce q.
3
4 Theorem f3_corr : forall p q T,
5   coerce p -> coerce q -> coerce (f3 p q T).
6
7

```

Figure 5.9: Soundness theorems of DnD fixpoints in Coq

rules, in particular because we need to manipulate *contexts* (Definition ??) explicitly, and those are not available for ColC propositions.

Then we use a technique called *computational reflection* in order to apply the embedded deep inference semantics to Coq goals. Originating from the *small scale reflection* methodology supported by the SSREFLECT framework [74], it consists in translating Coq objects into their equivalent formulation in the deep embedding with a `reify` function, reasoning on the deep embedding with Coq programs (also called *fixpoints*), and then translating objects back into Coq with a `reflect` function. It is easy to implement the `reflect` function because the datatypes in a deep embedding are almost always defined as *inductive* types, and thus one can easily do pattern-matching on them. It is a different story for the `reify` function, especially in our case: indeed we want to translate the statements of Coq goals into first-order propositions. But Coq statements are objects of type `Prop`, and thus cannot be pattern-matched on inside ColC⁸. Thus we need to have recourse to a *meta-programming* language in order to inspect the structure of Coq goals. Here we use the standard \mathcal{L}_{tac} language, which provides powerful constructs for pattern-matching on goals⁹.

The most complex tactics are those implementing backward and forward DnD actions, called respectively *backward* and *forward*. They rely on two Coq fixpoints `b3` and `f3` which respectively compute the new conclusion $b3(p, q, T)$ from a backward linkage $p \odot q$, and the new hypothesis $f3(p, q, T)$ from a forward linkage $p \otimes q$, where T is the so-called *subformula linking trace* mentioned earlier. Of course the paths p, q and the trace T are all expressed with custom Coq datatypes relying on our deep embedding of first-order logic. The role of the trace in particular is to provide the list of SFL rewrite rules to apply, including Coq terms instantiating quantifiers that were computed in Actema by unification of the two linked subformulas. Then we formulate in Coq two theorems that guarantee the logical *soundness* of `b3` and `f3` (Figure ??). Note that the theorems are formulated using the native implication connective `->` of Coq, thanks to the `reflect` function. The final tactics *backward* and *forward* can thus modify the goal by simply applying these theorems, first reifying the goal with the `reify` function, and then relying on the fact (also proved in Coq) that `reflect` is the inverse of `reify`.

8: For reasons of consistency of the logic, well-known in the literature on type theory.

9: A downside of \mathcal{L}_{tac} is that it is an *untyped* language, whose programs are notoriously hard to debug and maintain. One might consider a cleaner implementation with more recent alternatives in the Coq ecosystem, like the successor to \mathcal{L}_{tac} Ltac2 [181], or the MetaCoq project [172].

Remark 5.5.1 There exist a few other approaches to the computer implementation of deep inference systems. Ozan Kahramanoğlu has pioneered the field, by implementing various calculi of structures inside frameworks like Maude [106] and Tom [104], that are dedicated to the specification of rewriting systems. For an integration within modern proof assistants, we only know of Chaudhuri’s recent work [34] that explores different techniques in addition to reflection, like *combinators*

and some more powerful usages of *metaprogramming*. He also provides an effective implementation of the techniques in his Profint tool [28], that allows to export subformula linking derivations built with Profint's GUI as proof scripts directly executable in various proof assistants (Coq, Lean, Isabelle/HOL).

5.6 Future works

The coq-actema system described in this chapter has been successfully implemented and tested on various simple examples, including those of Section ?? and Section ??. But there are many Coq goals that cannot be properly handled in Actema, which still hinders the usability of the system in real mathematical developments, even in an educational setting. Typically, the example of Section ?? cannot be completely performed in Actema, in this case because of the lack of support for *higher-order* functions and predicates, but also because of the poor support for user-defined *notations*. Those are only a few of the current limitations of coq-actema, and we describe in the following pages how they could be overcome, both to widen the scope and improve the UX of the system.

Higher-order logic

The importance of being able to express and manipulate higher-order functions and predicates has been stressed multiple times before. The fact that Actema is limited to first-order logic is mostly a historical contingency, motivated by the fact that some algorithms like unification are more tractable in this setting. But now that we rely on Coq's proof engine, there is no fundamental reason for maintaining this choice. Because the language of statements is at the foundation of a logical framework, many other components of a proof assistant will depend on it. Thus the switch to higher-order logic should be done as soon as possible, to limit the amount of refactoring work to perform in the future. This will require changes to Actema's Backend and Frontend, but also to the Coq Plugin¹⁰ and the ATD datatype definitions enabling communication between the two.

One central question in the transition to higher-order logic is how unification of subterms will be handled. Algorithms in this setting are known to be incomplete because of undecidability [96], and their implementation can be very tricky. The most sensible option seems to rely on the implementation already provided by Coq, which is the fruit of years of development and improvements. But this would require changing the interaction protocol of coq-actema, by allowing the Backend of Actema to make unification requests to the Plugin. This might be doable without changing the current client-server architecture, but will probably involve some intricate design decisions.

A more radical solution would be to replace the actions request from the Frontend to the Backend by a start response from the Frontend to the Plugin, with the data of the selection in its body. Then we could completely delegate the computation of available actions to the Plugin, allowing us to freely use Coq's unification. This might not be too hard since we should be able to directly reuse OCaml code from the Backend,

10: The Coq theory implementing the tactics for deep inference-based actions already has partial support for higher-order goals, thus work remains mostly on the side of the translation module for Actema written in OCaml.

[96]: Huet (1973), 'The undecidability of unification in third order logic'

but is a deeper structural change to the interaction protocol, that makes the Plugin responsible for an important part of Actema's behavior. And this would induce a lot of unnecessary reimplementation efforts if we were to port the Plugin to other PAs.

Notations

Another big limitation already mentioned in the introduction of this chapter, is that we do not handle custom *notations* for displaying terms¹¹. It is however a crucial feature for making proofs in a specific domain tractable, especially in the Proof-by-Action paradigm where one needs to manipulate directly statements in the goal. Now that we are connected to Coq, we can in principle reuse the notation system already implemented within Coq. The `coq-core` OCaml API indeed exposes methods for pretty-printing Coq terms using their assigned notations. The problem is that these methods only return *strings*, but in order to manipulate terms interactively in Actema we also need access to *trees* mapping their subterm structure to the pretty-printed string. At the time of writing there is no support for the latter, but the Coq development team informed us that they plan to add it. The same problem was met by the developers of the ProofWidgets framework in Lean, and they had to modify the pretty-printer of Lean upstream¹².

11: Apart from expressions in Peano arithmetic, for which we have ad hoc support.

12: Section 4.1 of [10].

Once one has support for custom notations displayed in an HTML page, it is tempting to also allow for arbitrary HTML/JS code, instead of just textual notations. This opens the space for very rich graphical and interactive representations of mathematical objects, which could greatly improve the accessibility of PAs, but also their expert usage by enabling domain-specific interfaces targetting non-standard methods of reasoning. A typical example is the *diagrammatic* reasoning pervasive in *category theory*, which is very hard and cumbersome to express as manipulation of logical statements. Actually a system very similar to `coq-actema` is currently being developed by Luc Chabassier [25], for the very purpose of integrating diagrammatic proofs in category theory to the traditional proof script workflow. One could imagine in the long-term embedding this system as a subsystem of `coq-actema`, through an advanced protocol for interactive notations.

In fact the ProofWidgets framework mentioned earlier has been designed with this usecase in mind from the outset. But they rely on a very different architecture compared to that of `coq-actema`, where the methods generating the HTML/JS code of pretty-printed terms are directly implemented in a DSL embedded in the meta-programming language of the PA. While this allows easy access to all meta-programming facilities for manipulating terms, this makes their framework only usable within Lean, while Actema could in principle be used with any PA that implements a corresponding plugin (for example with a `lean-actema` variant of our system).

Lemma search

We already described in Section ?? the *lemma search* feature of Actema. Currently it is implemented only in its standalone version. Adding support

for it in `coq-actema` would require additional efforts compared to other contextual actions like `Induction`. Indeed we do not only need access to the current goal, but also to the full global environment of `Coq` where lemmas are stored. While in the standalone version we had a toy lemma database with very few entries, the standard library of `Coq` contains thousands of lemmas. And to use our selection-based filtering algorithm implemented in `Actema`, we need to translate the entire library into statements understandable by `Actema`'s Backend, and then send it over HTTP. Thus it will be important to implement some cache mechanism to remember which lemmas have already been exported to `Actema`'s own database, to avoid recomputing the translation each time.

Proof evolution

An important question when designing a proving environment is how users will be able to manipulate an *existing* (partial) proof, either one they have built in the past, one that was built by other people, or a mix of both in a collaborative context. This is a complex problem spanning various activities that are involved in the lifecycle of a proof: modifying it while it is being constructed; reading it for the first time, or many months/years after it was written; updating it after slight changes to the statement of its theorem; etc^{13,14}.

In the literature and community of people designing proof assistants, these various problematics are generally regrouped under the term of *proof evolution*. A fundamental remark about the Proof-by-Action paradigm, and thus about the `coq-actema` system, is that it has not been designed with proof evolution in mind from the outset. Indeed, a proof built with the `actema` tactic will provide the least possible amount of information in the proof script, since we can just witness the call to that tactic. And currently there are no facilities to visualize the associated sequence of actions stored in the Database of graphical proofs.

The first question that should be answered is: how do we represent statically a sequence of graphical actions, let alone a single action? For a machine representation, we can just dump the data of the action invocation, and this is indeed what we do with the Database. But finding a human-readable representation that an average user can quickly manipulate and reason about is a lot more delicate. The most direct way may be to abandon text altogether, and just replay the action on the interface through a graphical animation. This is an intrinsically temporal and dynamic representation, akin to a mathematician unfolding her demonstration on the blackboard. One could then imagine an interface dedicated to the richly-structured navigation inside this sequence of animations, in the style of an improved video player.

A more conservative solution would be to find a systematic way to translate a sequence of actions into a proof text. The question of generating declarative proof texts from imperative proof scripts has already been explored by some authors, especially in the case of proofs expressed in natural language¹⁵. Our hope is that the structure of proofs in the Proof-by-Action paradigm might be well-suited to the generation of readable and concise proof texts, thanks notably to the subformula linking semantics of DnD actions that exhibit clearly the flow of argumentation.

13: Not very surprisingly, those activities are commonly found in the context of *programming* environments. Thus one might get insight by cross-pollinating ideas from both domains, in the spirit of the Curry-Howard correspondence (which also underlies the design of `Coq`).

14: One might even argue that thinking about the best way to *represent* a proof leads to more fundamental questions, that have been much debated both in proof theory and the history and philosophy of mathematics: what is the essence of a proof, seen as a meta-mathematical object [177]? What are the roles played by informal and formal proofs, both in the teaching of mathematics, and the social and scientific practice of mathematicians [11]?

15: See for example section 3.6 of E. Ayers' thesis [9]. We can also mention ongoing work of Patrick Massot in the Lean proof assistant [123].

An even more pragmatic solution, that should be straightforward to implement in the short-term, consists in inserting tactic invocations in the proof script that are in one-to-one correspondence with graphical actions. Since we actually compile actions into tactics, this is in principle easy to implement. However, there are currently two drawbacks to this approach:

- ▶ Since most tactics are deep inference-based, they take as arguments the paths to manipulated subterms, in the form of lists of integers. Those are hard to read by humans, and very sensible to small changes in the shape of the goal. This is even worse for the backward and forward tactics, because they also take as argument the subformula linking trace, which is a very complex data structure expressed in our deep embedding of first-order logic, and hence should not leak into the user interface. Hopefully, relying on Coq's unification instead of Actema's should mitigate the complexity of the trace, by removing the need to incorporate full substitutions. There is also the possibility of replacing integer-based paths by *patterns* in the SSREFLECT language, which are known to be a more robust way to designate subterms. But this would require the design of some clever algorithm, able to generate patterns that correctly generalize the User's intent from the sole data of selected paths.
- ▶ The interaction protocol described in Section ?? does not provide any way to send requests to the IDE, which would be necessary to actually insert the tactic invocation at the right location in the proof script, and this as soon as the action is performed by the User. A “brutal” solution would be to reimplement coq-actema as an extension of a specific IDE, typically VsCoq which is also based on web technologies [42]. But this would require some big implementation efforts, in addition to locking the User into this specific IDE. A better option might be to directly interact with a *language server* implementing the Language Server Protocol (LSP) [36]. The coq-lsp project aims to provide such a server for Coq, but at the time of writing of this thesis does not implement yet all methods of the LSP standard. The one that interests us in particular is the `textDocument/codeAction` method, for which support is currently planned [61]. Then coq-actema would stay compatible with all IDEs that run coq-lsp.

ICONIC MANIPULATIONS

Asymmetric Bubble Calculus

6

We introduce a new kind of nested sequent proof system dubbed *bubble calculus*. Inspired by the *membrane* mechanism of the chemical abstract machine (CHAM hereafter) [12], so-called *bubbles* internalize the notion of *subgoal* inside sequents, rather than through the tree structure induced by inference rules. This allows for a more hierarchical representation of the proof state, where contexts can be shared between different subgoals. In addition to the usual textual syntax, the bubble calculus can be expressed in a graphical syntax, where logical meaning is captured by *physical* constraints on diagrammatic manipulations, instead of *virtual* restrictions on available inference rules.

This chapter and the next are organized mostly chronologically, following the evolution of our idea of a bubble calculus through the addition of new features.

We start in Section ?? with the genesis of the idea of bubble calculus, coming from the observation that our Proof-by-Action paradigm (Chapter ??) lends itself quite naturally to a metaphorical interpretation, where actions are seen as *chemical* reactions. In Section ?? we introduce the concept of *bubble* as a way to control the scope of hypotheses inside nested sequents that we call *solutions*. In Section ?? we describe our proof system for intuitionistic logic dubbed *asymmetric bubble calculus*, based on multiset rewriting rules on solutions comprising at most one conclusion. Finally in Section ??, we import ideas from this bubble calculus back to the realm of GUIs for interactive proof building, analysing their possible impact for UX improvements.

Put this sentence in the introduction.

6.1 The chemical metaphor

The Proof-by-Action paradigm introduced in Chapter ?? offers multiple ways to the user to attack the proof of a theorem: DnD actions for subformula linking and equality rewriting are the main mechanism, but they only work in a goal comprising multiple items. Since it is customary in proof assistants to specify the goal to be proved as a single logical formula, one needs a way to decompose it into many items for further processing through DnD. This is precisely what the introduction rules for logical connectives in sequent calculus do, and following the Proof-by-Pointing paradigm [13] we map them to click actions (see Section ??).

So visually, a proof in Actema consists in breaking logical items into subitems positioned freely in space, and then bringing those subitems together to make them interact and produce a new item. This is quite evocative of a *chemical reaction* controlled by the user, where logical formulas are akin to molecules made of propositional atoms linked together by logical connectives¹. Click actions are then a mean to “heat” molecules to the point of breaking these chemical bonds. The most canonical examples are the right-introduction rule for implication \supset and the

1: This precise metaphor about the molecular structure of propositions can already be found in Russell’s introduction to Wittgenstein’s *Tractatus Logico-Philosophicus*, which was the main inspiration to his philosophy of *logical atomism* [193, p. 11][108]. Even earlier in the history of logic, C. S. Peirce took inspiration from chemical diagrams to devise his *existential graphs* — see [161, pp. 17-18], or our own presentation in Section ?? for more details.

left-introduction rule for conjunction \wedge , which break respectively a conclusion/red item/positive ion into a hypothesis/blue item/negative ion and a new conclusion, and a hypothesis into two hypotheses. In fact, it is strongly conjectured that these are the only click actions needed to obtain a complete deductive system for propositional logic: breaking red implications allows for backward DnDs, and blue conjunctions for forward DnDs².

Rather than completeness, the issue here is *consistency* of the user interface: if the user is allowed to decompose red \supset and blue \wedge , she will assume naturally that she can also decompose blue \supset and red \wedge , as well as \vee of any color. While red \vee can be handled by pointing directly at the disjunct to be proved, other configurations correspond to rules of sequent calculus with multiple premisses. In Actema, this corresponds to creating a new subgoal for each premise, where subgoals are displayed one at a time in different *tabs*: this new interface mechanism breaks the chemical metaphor. The root cause lies in the way sequent calculus implements *context-scoping*: each subgoal will share the same initial context of hypotheses, but future hypotheses “buried” in the conclusions must be available only in their respective subgoals. The tabs mechanism implements this by forcing the user to focus on exactly one tab/subgoal, thus making it impossible to display items from different subgoals on the same screen, which renders interaction between them physically impossible.

2: In predicate logic, one would also need the right (resp. left) introduction rule for \forall (resp. \exists). It might also be the case that backward DnDs alone are sufficient for completeness, since a linkage of the form $A \otimes \boxed{B} \supset C$ will involve a forward phase. In this case only the right introduction rules for \supset and \forall would be required.

6.2 Bubbles and solutions

In order to accomodate context-scoping within the chemical metaphor, we were led to explore a notion of *bubble* inspired by the *membranes* of the CHAM [12]. The latter are used to delineate zones of *local* interaction, which are still porous to external data. This is precisely what we want to do here: let us consider that the user tries to prove the sequent $\Gamma \Rightarrow A \wedge B$. By clicking on the red item $A \wedge B$, she will break it into two bubbles ($\vdash \Rightarrow A$) and ($\vdash \Rightarrow B$). Then she might decompose A and B further into sequents $\sigma_A = \Gamma_A \Rightarrow C_A$ and $\sigma_B = \Gamma_B \Rightarrow C_B$, and use hypotheses from Γ by dragging them inside either ($\vdash \sigma_A$) or ($\vdash \sigma_B$). However, hypotheses from Γ_A and Γ_B cannot be dragged out from their respective bubble, since then they could be used in the other bubble and violate context-scoping.

This situation is illustrated in Figure ??, where bubbles are represented by gray circles, and possible drag moves of formulas by arrows. More specifically, green and orange arrows symbolize respectively valid and invalid moves. Notice how this graphical depiction of bubbles exhibits their *topological* behavior: while objects can enter inside bubbles from the outside, they get blocked by the membrane in the opposite direction. Indeed the only relevant feature of the circle representation is that it divides the space into an *interior* and an *exterior*. Then the *nesting* of circles and the *positions* of formulas relative to them encode respectively the *tree* structure of the proof, and the scope of hypotheses in it.

Bubbles can also be seen as a way to internalize in the syntax of sequents the notion of *subgoal*, which requires in turn to allow nesting of sequents inside each other. The proof state is not a set of subgoals anymore, but a single nested sequent of this sort, that we call a *solution*³. In textual

3: The term “solution” refers here to the metaphor of a *chemical solution* made up of an unordered collection of molecules. Which is quite ironic, since we use it to denote goals waiting to be proved, that is problems lacking a solution...

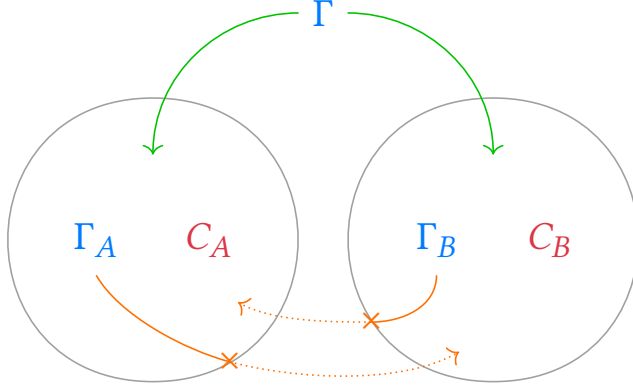


Figure 6.1: Context-scoping in bubbles as topological constraints

syntax, solutions S are generated by the following grammar:

$$S, T, U ::= \Gamma \langle S_1; \dots; S_n \rangle \Delta \quad \Gamma, \Delta ::= A_1, \dots, A_n$$

where the A_i are usual formulas of FOL. Thus solutions are just like sequents, except that we add a collection of nested solutions S_i that will represent subgoals, or premisses of usual inference rules. To be more precise, the collections of formulas A_i and solutions S_i are *multisets*, which gives the following mutually recursive definitions:

Definition 6.2.1 (Ion) *An ion is a formula charged either negatively (hypothesis) or positively (conclusion).*

Definition 6.2.2 (Bubble) *A bubble is a solution enclosed in a membrane.*

Definition 6.2.3 (Solution) *A solution S is a multiset of ions and bubbles. It is single-conclusion if it contains at most one positive ion. We will use letters $\mathcal{S}, \mathcal{T}, \mathcal{U}$ to denote multisets of solutions.*

Note that in the above definitions, bubbles play a purely metaphorical role and could be dispensed with. But it will be useful later on to distinguish them conceptually from solutions.

6.3 Asymmetric calculus

Interpreting solutions

A natural way to give logical meaning to a solution is to translate it into a formula. In the following we provide one such translation, which will play a determining role in the design of inference rules for manipulating solutions. We qualify it of *asymmetric* because it only works for single-conclusion solutions, in the same way that LJ only works for single-conclusion sequents.

Remark 6.3.1 In this section we only deal with single-conclusion solutions, but the more general case will be studied starting from Section ??.

Just like a sequent, a solution is semantically equivalent to an implication, except that we add the *conjunction* of all subgoals to the consequent:

Definition 6.3.1 (Asymmetric interpretation) *The asymmetric interpretation of a solution is defined recursively by:*

$$\llbracket \Gamma \langle S_1; \dots; S_n \rangle \Delta \rrbracket = \bigwedge \Gamma \supset \bigwedge \Delta \wedge \bigwedge_i \llbracket S_i \rrbracket$$

Note that we join formulas in Δ conjunctively: since we do not consider solutions with more than one conclusion, this is just to handle the case where $\Delta = \emptyset$, and thus $\bigwedge \Delta = \top$. This subtle detail is in fact essential to the way we encode the tree structure of proofs inside solutions:

- ▶ a solution with one conclusion corresponds to a *leaf* of the proof tree, i.e. a subgoal;
- ▶ a solution with no conclusion corresponds to a *node* of the proof tree, i.e. a branching point where we created multiple subgoals.

This will soon become clearer with examples of derivations in our calculus. In Section ??, we will consider a different interpretation of solutions that entails a different encoding of the proof structure in them.

Sequent-style rules

Our initial idea for a proof system based on solutions was quite simple: we take the inference rules of LJ, and turn them all into unary rules by encoding premisses as bubbles. This gives the basis for the set of rules presented in Figure ??, that defines our asymmetric bubble calculus for intuitionistic logic dubbed BJ. It is divided in five groups:

- ▶ The **IDENTITY**, **RESOURCE** and **HEATING** groups correspond respectively to the identity, structural and logical rules of sequent calculus, following the terminology of [68]. More precisely, rules $i\downarrow$ and $i\uparrow$ correspond to the axiom and cut rules; rules w and c to the weakening and contraction rules; and every rule of the form $\circ-$ (resp.) that is, the axiom and cut rules, the contraction and weakening rules, and introduction rules for logical connectives.
- ▶ The **FLOW** and **MEMBRANE** groups are new, and define the behavior of bubbles. More specifically, F-rules characterize how information flows in solutions by specifying what kinds of objects can traverse bubbles, and in which direction. They play the same role as *switch* rules in formalisms based on CoS [84], which includes our own subformula linking rules (Figure ??). In the asymmetric bubble calculus there is only one F-rule $f-$ allowing hypotheses to flow inside bubbles.

[68]: Girard (2011), *The blind spot*

As their name suggests, M-rules handle the behavior of the *membrane* of bubbles, but independently from other items as opposed to F-rules. In the asymmetric bubble calculus there is only one M-rule p allowing to *pop* any empty bubble, which can be interpreted as the action of dismissing a solved subgoal. In CoS it would correspond to congruence rules handling the truth unit \top , and in subformula linking to the unit rules (Figure ??).

IDENTITY		RESOURCE	
$\frac{\Gamma \langle \mathcal{S} \rangle}{\Gamma, A \langle \mathcal{S} \rangle A} \text{ i}\downarrow$	$\frac{\Gamma \langle \mathcal{S}; \langle \rangle A; A \langle \rangle \Delta \rangle}{\Gamma \langle \mathcal{S} \rangle \Delta} \text{ i}\uparrow$	$\frac{\Gamma \langle \mathcal{S} \rangle \Delta}{\Gamma, A \langle \mathcal{S} \rangle \Delta} \text{ w}$	$\frac{\Gamma, A, A \langle \mathcal{S} \rangle \Delta}{\Gamma, A \langle \mathcal{S} \rangle \Delta} \text{ c}$
FLOW		MEMBRANE	
$\frac{\Gamma \langle \mathcal{S}; \Gamma', A \langle \mathcal{S}' \rangle \Delta' \rangle \Delta}{\Gamma, A \langle \mathcal{S}; \Gamma' \langle \mathcal{S}' \rangle \Delta' \rangle \Delta} \text{ f-}$		$\frac{\Gamma \langle \mathcal{S} \rangle \Delta}{\Gamma \langle \mathcal{S}; \langle \rangle \rangle \Delta} \text{ p}$	
HEATING			
$\frac{\Gamma \langle \mathcal{S} \rangle \Delta}{\Gamma, \top \langle \mathcal{S} \rangle \Delta} \text{ T-}$	$\frac{\Gamma \langle \mathcal{S} \rangle}{\Gamma \langle \mathcal{S} \rangle \top} \text{ T+}$		
$\frac{\Gamma \langle \mathcal{S} \rangle}{\Gamma, \perp \langle \mathcal{S} \rangle \Delta} \text{ \perp-}$			
$\frac{\Gamma, A, B \langle \mathcal{S} \rangle \Delta}{\Gamma, A \wedge B \langle \mathcal{S} \rangle \Delta} \text{ \wedge-}$	$\frac{\Gamma \langle \mathcal{S}; \langle \rangle A; \langle \rangle B \rangle}{\Gamma \langle \mathcal{S} \rangle A \wedge B} \text{ \wedge+}$		
$\frac{\Gamma \langle \mathcal{S}; A \langle \rangle \Delta; B \langle \rangle \Delta \rangle}{\Gamma, A \vee B \langle \mathcal{S} \rangle \Delta} \text{ \vee-}$	$\frac{\Gamma \langle \mathcal{S} \rangle A}{\Gamma \langle \mathcal{S} \rangle A \vee B} \text{ \vee+}_1$		
	$\frac{\Gamma \langle \mathcal{S} \rangle B}{\Gamma \langle \mathcal{S} \rangle A \vee B} \text{ \vee+}_2$		
$\frac{\Gamma \langle \mathcal{S}; \langle \rangle A; B \langle \rangle \Delta \rangle}{\Gamma, A \supset B \langle \mathcal{S} \rangle \Delta} \text{ \supset-}$	$\frac{\Gamma, A \langle \mathcal{S} \rangle B}{\Gamma \langle \mathcal{S} \rangle A \supset B} \text{ \supset+}$		
$\frac{\Gamma, A \{t/x\} \langle \mathcal{S} \rangle \Delta}{\Gamma, \forall x. A \langle \mathcal{S} \rangle \Delta} \text{ \forall-}$	$\frac{\Gamma \langle \mathcal{S} \rangle A}{\Gamma \langle \mathcal{S} \rangle \forall x. A} \text{ \forall+}$		
$\frac{\Gamma, A \langle \mathcal{S} \rangle \Delta}{\Gamma, \exists x. A \langle \mathcal{S} \rangle \Delta} \text{ \exists-}$	$\frac{\Gamma \langle \mathcal{S} \rangle A \{t/x\}}{\Gamma \langle \mathcal{S} \rangle \exists x. A} \text{ \exists+}$		
In the $\forall+$ and $\exists-$ rules, x is not free in Γ, Δ and \mathcal{S} .			

Figure 6.2: Sequent-style presentation of the asymmetric bubble calculus BJ

Now that we have rules for manipulating solutions, and since solutions can be nested through bubbles, we need a notion of *context* for applying rules on subsolutions of arbitrary depth:

Definition 6.3.2 (Solution context) A solution context $S\Box$ is a solution which contains exactly one occurrence of the special solution \Box called the hole. Given another solution T , we write $S\Box T$ to denote the solution equal to $S\Box$ where \Box has been replaced by T .

Then every rule of Figure ?? is applicable in any context $U\Box$. That is:

$$\frac{S}{T} \text{ should be read as } \frac{U\Box S}{U\Box T} \text{ for all } U\Box$$

Definition 6.3.3 (BJ-step) We write $S \rightarrow T$ to denote the existence of a BJ-rule instance $r : S \rightarrow T$ in the empty context, i.e. S and T are respectively the conclusion and premiss of the rule r in Figure ??, modulo instantiation of meta-variables⁴. Then \rightarrow can be seen as a binary relation on solutions, whose contextual closure described above is the step relation $\rightarrow : S \rightarrow T$ if and only if there exist $U\Box$, S_0 and T_0 such that $S = U\Box S_0$, $T = U\Box T_0$ and $S_0 \rightarrow T_0$.

Definition 6.3.4 (BJ-derivation) A derivation $\mathcal{D} : S \rightarrow^* T$ in BJ is a list \mathcal{D} of BJ-steps with premiss T and conclusion S .

Definition 6.3.5 (BJ-proof) A proof of a solution S in BJ is a derivation $\mathcal{D} : S \rightarrow^* \langle \rangle$ that reduces S to the empty solution, which denotes the proof state where there are no subgoals left.

Proof-as-trace

An example of proof in BJ is shown in Figure ??, where the focused subsolution is squared for each inference. Notice that many rules could have been applied in a different order: for instance all applications of the p rule could have been postponed to the top/end of the derivation. This is generally true of all formalisms based on CoS, which is known in the deep inference literature for its “bureaucracy”. In BJ, H-rules aggravate the matter by adding all inessential rule permutations from sequent calculus to those of CoS. As our wording suggests, this is usually perceived negatively in deep inference proof theory, where a central question is that of finding *canonical* representations of proof objects [177].

However in our interactive proof-building setting, it should rather be seen as a *desirable* property of the system. Indeed, one consequence is that the user has more freedom to organize her reasoning in whichever order she wants, in an incremental and guided way. One should remember that in the Proof-by-Action paradigm, the focus is not the proof object, which is implicit and hidden to the user, but the *process* of building it. Then a BJ-derivation is better understood as the *trace* of this building process, rather than the constructed proof⁵. And the fact that this trace

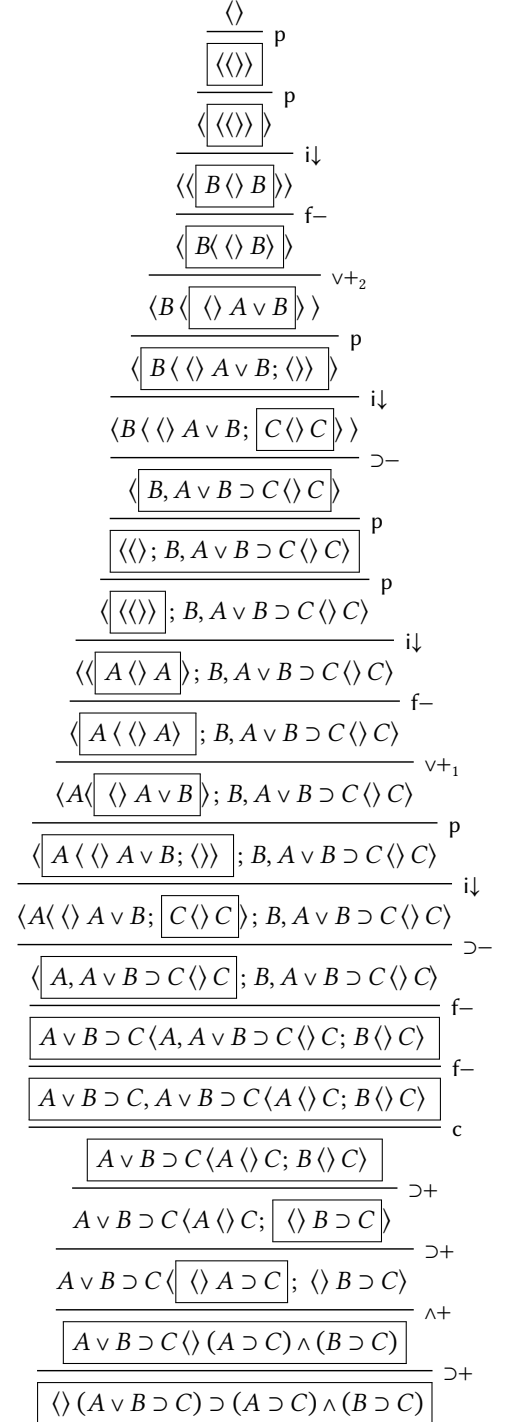


Figure 6.3: Example of sequent-style proof in BJ

[177]: Straßburger (2019), ‘The problem of proof identity, and why computer scientists should care about Hilbert’s 24th problem’

corresponds, or can be reduced to a more canonical representation is of no concern to the user. What matters for a good proof-building interface is to be as flexible as possible, in order to match the user's own mental process of argumentation.

Of course flexibility comes at a price, and the rules of BJ are probably too numerous and low-level to be mapped directly into individual proof actions in a user interface. Some of these concerns will be tackled in Chapter ??, but we think a better answer might have been found with the proof system introduced in Chapter ??, and its associated prototype of GUI presented in Chapter ??.

Graphical rules

While the sequent-style presentation of BJ clearly shows its filiation with sequent calculus, its syntax is quite heavy, and obscures an important property of the rules: they almost always preserve the contexts Γ, Δ of formulas and \mathcal{S} of bubbles. That is, the rules of BJ are *local*. This enables a more economical and graphical presentation of the rules in Figure ??, where BJ is seen as a multiset rewriting system just like the CHAM thanks to Definition ??. Instead of relying on a notion of solution context, we define formally what it means to be a subsolution:

Definition 6.3.6 (Subsolution) *S is a subsolution of T , written $S < T$, if either $S \subseteq T$ or $S < T_0$ for some $T_0 \in T$, where \subseteq denotes multiset inclusion.*

Then a multiset rewriting rule $S \rightarrow_r T$ can be applied in a solution U whenever $S < U$, by replacing one occurrence of S by T inside U . The notions of derivation (Definition ??) and proof (Definition ??) stay unchanged, by observing that the rewriting rule $S \rightarrow_r T$ from S to T and the inference rule $r : S \rightarrow T$ with premiss T and conclusion S denote the same rule r .

Figure ?? shows the graphical presentation of the same BJ-proof as in Figure ??. Whereas in Figure ?? we squared the whole subsolutions corresponding to the conclusions of inference rules, here we squared on each line the redex modified by the associated rewriting rule. This example highlights the greater locality of the rewriting approach, by indicating more precisely which parts of the proof state are changed by the rules. But it still over-approximates the modifications that really need to be performed to carry the transformations. Indeed, by only exposing the data of a redex S and a reddendum T , a rewriting rule $S \rightarrow_r T$ can only be interpreted as the deletion of S followed by the insertion T . Taking for instance the \supset -rule in Figure ??, one can describe its graphical behavior more finely as resulting from the following sequence of *edits*:

1. Erase the \supset connective;
2. Change the polarity of A from hypothesis to conclusion;
3. Insert a new empty bubble;
4. Move A in this bubble;
5. Insert a new empty bubble;
6. Move B in this bubble;
7. If Δ is not empty, also move Δ in this bubble.

5: The idea of *proof-as-trace* is relatively common in logic programming [128], but not so much in deep inference proof theory. It is Jean-Baptiste Joinet who shared with us his idea of applying it in this setting, based on his own work interpreting CoS for MLL as a system for building *multiplicative proof nets* [102].

This section might be getting too long with too many subsections; will probably need to move philosophical reflections like this somewhere else. Maybe a conclusion to this chapter? But the ideas seem to apply to all systems in this thesis, and thus may deserve a more general rewording in Chapter ??.

Add definition of multiset inclusion somewhere?

Maybe split both Figure ?? and Figure ?? in two figures, one for the beginning of the proof upto \vdash -, and a generic one for the two subproofs starting with \supset -.

6: As will become apparent in Section ??, BJ itself provides a finer-grained simulation of the rules of sequent calculus, which in turn is known to be a more detailed variant of *natural deduction*. Interestingly through the Curry-Howard isomorphism, this would correspond to a *chain of compilation*, starting from the higher-level λ -calculus (natural deduction), going into abstract machines (sequent calculus) [50], down to something akin to *assembly language* with jump instructions (Section 6.3.1 of [82]).

It would be interesting to consider the question of finding a minimal set of edit operations like these, that can simulate all the rules of BJ⁶. Note however that most of the above edits are *unsound* as reasoning steps. If not for logical insight, such an edit calculus could still be relevant *computationally*, typically by enabling efficient implementations of the rules with a small memory footprint.

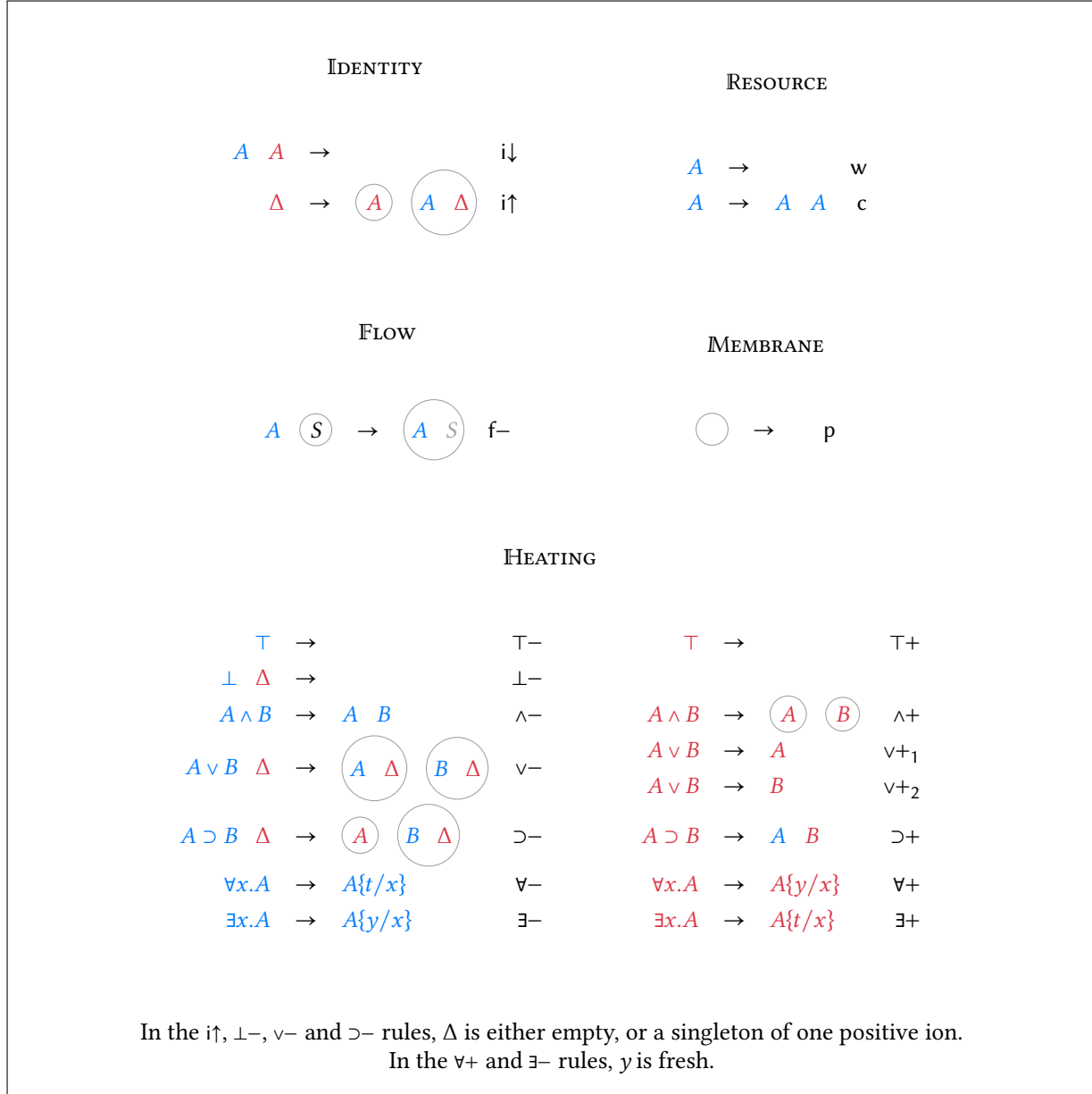


Figure 6.4: Graphical presentation of the asymmetric bubble calculus BJ

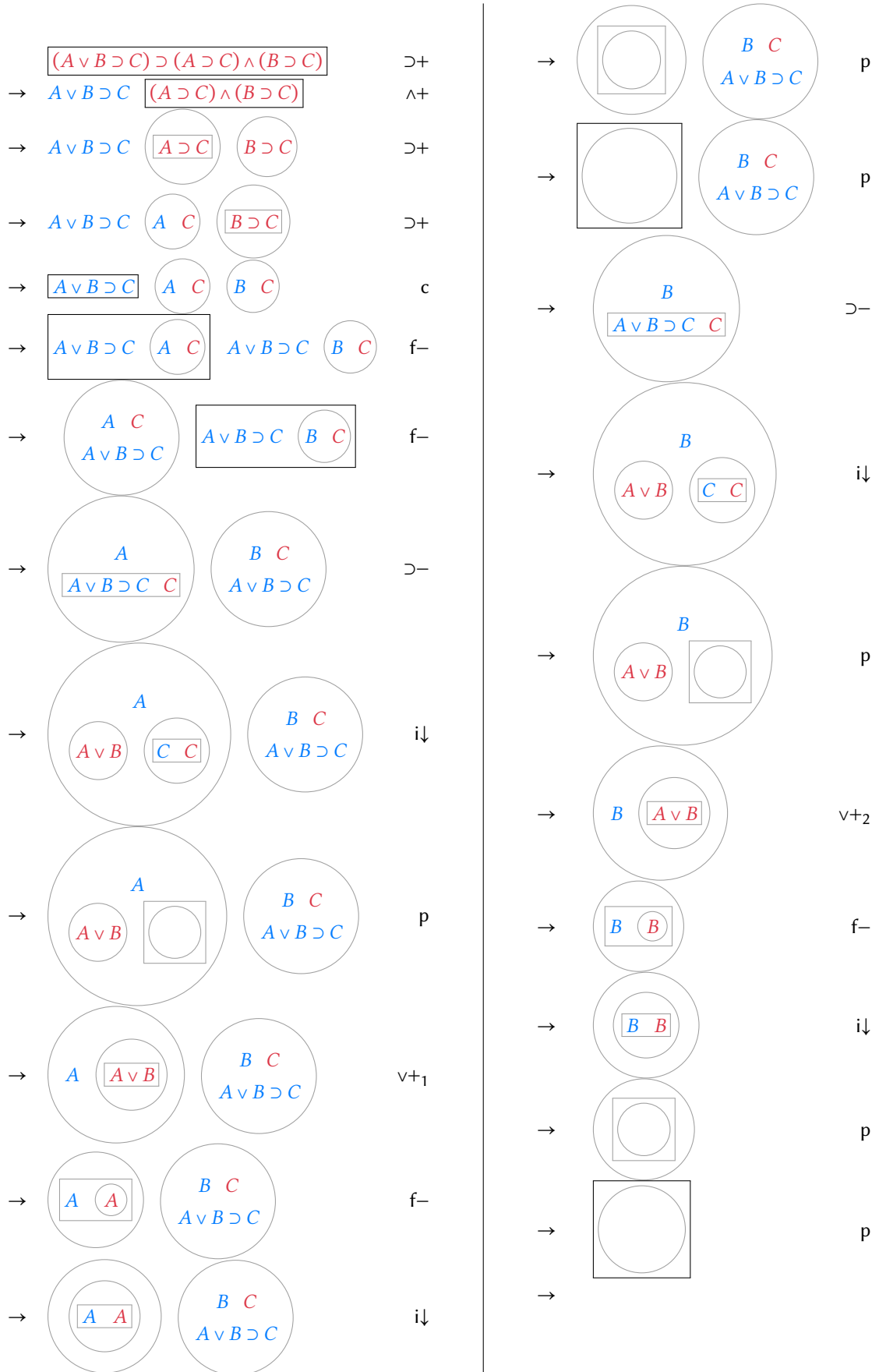


Figure 6.5: Example of graphical proof in BJ

6.4 Back to Proof-by-Action

When looking at the BJ-proof of Figure ??, the astute reader might have been reminded of the Proof-by-Action paradigm as introduced in Chapter ??, by seeing redexes as the items involved in a graphical action — there are always at most two. More precisely, H-rules correspond to *click* actions on blue ($\circ-$ rules) or red items ($\circ+$ rules), and the $i\downarrow$ rule corresponds to the most basic DnD action between dual occurrences of a formula.

As mentioned earlier when comparing BJ to LJ, the novelty here lies with H-rules, F-rules and M-rules that deal with *bubbles*. Remember that the goal behind the idea of bubble calculus was precisely to provide a new way to manipulate subgoals through bubbles instead of tabs, which are more in line with the chemical metaphor. It is quite easy to imagine a GUI presenting the proof state as a solution, in a graphical layout close to that of Figure ??⁷. Like formulas in blue and red items, whole subgoals could now be shown on the same screen in their respective bubbles, and be freely moved around with a pointing device. Following are some ideas for mapping the remaining rules of BJ in such a GUI:

FLOW The $f-$ rule plays a special role, in that it would not be mapped to any particular action. Indeed it captures the way information flows in solutions, and we already described in Section ?? how this is reflected in the topological behavior of bubbles. Thus it could be implemented in the graphical interface as a kind of *physics engine*: when dragging an item around the proof canvas, it would get stuck on the membrane of bubbles, except if it is blue and the drag movement goes inward. This of course would provide a level of interactivity unseen before in a proving interface, making it very discoverable and playful. It also combines nicely with DnD actions in general: for instance a sequence of applications of $f-$ followed by $i\downarrow$ could be performed as a single DnD action, where the dragged hypothesis crosses successively the various bubbles in its way.

MEMBRANE The p rule can be mapped very straightforwardly to the action of clicking on the area of an empty bubble, in order to pop it. It could also be entirely automated, by letting the proof engine eagerly pop empty bubbles as soon as they appear in a solution. Note that in this graphical setting, the p rule can be understood as resulting from a process of *contraction*⁸ of the membrane into a single point: if the bubble contains some items Δ , then this process fails because the membrane gets stuck on the boundaries of Δ . This is a topological way to check the emptiness of a bubble, which has the benefit of being completely *local*, on top of being very clear visually.

RESOURCE The contraction rule c could be mapped to a specific triggering input when starting to drag a blue item A (e.g. a shortcut if a keyboard is available, or a long press on the item on a touchscreen), which has the effect of keeping a copy of A at its original location in addition to moving the item⁹. As for the weakening rule w , it could be available as a contextual action when selecting blue items.

7: Although there might be some challenges in implementing an efficient layouting algorithm for bubbles, typically to make solutions fit into the screen.

$$\begin{array}{l} A \ B \rightarrow A \otimes B \ \otimes \\ A \ B \rightarrow A \oplus B \ \oplus \end{array}$$

Figure 6.6: Linkage creation rules in BJ

8: Not to be confused with the contraction rules c and w .

9: This mechanism is quite standard in GUIs that manipulate duplicable resources like file managers, where one maintains the CTRL key to enable copy mode. It was also chosen by K. Chaudhuri to implement contraction in his ProfInt prototype for subformula linking in intuitionistic logic [29].

IDENTITY Although the \downarrow rule only corresponds to the base case of DnD actions, it would be easy to integrate their full SFL semantics directly in BJ. Indeed our SFL rules (Figure ??) are already expressed as rewriting rules, just like the graphical rules of BJ (Figure ??). Thus it is just a matter of adding linkage creation rules like those of Section ??, but between adjacent formulas in a solution (see Figure ??).

The cut rule was handled in Actema with a separate +hyp button, which adds the cut formula A (input by the user in a dialog box) as a new hypothesis in the current goal, and as the conclusion in a new subgoal (see Section ??). Since subgoals are now reified as bubbles, the \uparrow rule could be mapped instead to a contextual action available on any red item Δ , which would have the effect of spawning a bubble around it with a blue item A , and another bubble nearby it with a red item A .

HEATING For H-rules that spawn bubbles like $\wedge+$, it is important that bubbles stay close to the item being clicked, in order to make the transformation clear visually. One could even imagine a small animation that smoothly turns the main connective into bubbles, to convey more effectively the intuition that heating rules break logical connectives seen as chemical bonds.

Beyond the recovered uniformity of the user interface in terms of the chemical metaphor, BJ exhibits some features that are interesting both at the proof-theoretical and user-experience levels:

Factorization It implements a form of *context-sharing* between subgoals: that is, one can perform transformations on shared hypotheses (forward reasoning) without going back to a proof state anterior to the splitting of said subgoals. This should simplify the navigation in the proof as it is being constructed, by avoiding the need to locate these splitting points. In fact often beginners (but also occasionally seasoned users) do not have the reflex to do this, precisely because the interface makes it difficult. This results in proofs with a lot of duplicated arguments, since splitting goals systematically duplicates the context of hypotheses. Thus bubbles can be seen as a mechanism that favors by default a style of proof with better factorization of subproofs.

Navigation The tree structure of subgoals is immediately apparent in the proof state through the nesting of bubbles. Thus part of the information on the proof construction process, which was made implicit and temporal in the proof state history, is now made explicit and spatial in the proof state itself¹⁰.

There are multiple ways to visualize trees on a planar surface, but if we are to maintain the bubble metaphor, *zoomable user interfaces* seem to be a right fit: they allow for efficient space management and navigation, and zooming in intuitively conveys the idea of focusing on a specific subgoal. One could also zoom out to have an overview of the different subgoals and their shared context, something which is hard to do in current proof assistants.

10: This concern of finding an explicit graphical representation of the “motions of reasoning *in actu*”, and not only the states of mind, can be found already in the works of Peirce on his existential graphs (pp. 112-113 in [Roberts1973-*inactu*]). We will come back to this in Chapter ??.

When zoomed in on a subgoal, the shared contexts around it will not be visible anymore. While this is useful to focus attention and avoid being distracted by other subgoals, it can quickly become cumbersome for the user to always have to zoom out in order to retrieve hypotheses from these shared contexts. One solution would be to rebrand the context zone of Actema as a *global* context zone, where all the shared contexts available in the subgoal under focus are merged in a single list, and immediately accessible for manipulation. Of course actions performed in the context zone would be reflected in the proof canvas, and vice versa.

Goal diffing From a user perspective, the locality of rules means that applying some action to one or two items will not involve other items¹¹. Non-local rules are less natural for a beginner because they modify a global state (here other items and subgoals) which is not clearly correlated to the transformed data, often because it is not immediately visible.

11: The only exceptions are clicks on blue \perp , \vee and \supset , but the only extra item they involve is the conclusion.

For instance in Actema, many users have reported difficulties in understanding the effect of click actions that create new subgoals. A first reason that can easily be remedied, is that there was not enough visual feedback to indicate the newly created tabs. But a deeper limitation is that the user needs to explicitly focus on these subgoals to show their content, which they might not do immediately. And then it gets difficult to keep track of the origin of said subgoals without a way to visualize the tree structure of the proof.

All these concerns can be addressed within the bubble metaphor: since bubbles are items freely positioned on the canvas, all the new items produced by an action can stay near the location where the action was initiated (i.e. the click or drop location); and since all transformations are local, all items not involved in the action can have their locations preserved. In other words, bubbles make it easier to understand the *difference* between a goal and subgoals generated by a proof action, which is crucial when learning the semantics of actions through practice.

In this chapter, we explore to what extent the bubble calculus of Chapter ?? can be made more *symmetric*, by relaxing the restriction that solutions must contain at most one conclusion. At a surface level, our approach is similar to that of Gentzen, who went from his single-conclusion sequent calculus LJ to the multi-conclusion calculus LK. Like him, we will uncover beautiful dualities that were hidden by the asymmetry of the initial calculus. But by sticking unwaveringly to intuitionism, we will be led to the exotic territory of *bi-intuitionistic* logic, an intermediate logic that conservatively extends intuitionistic logic, but does not prove the law of excluded middle. An underlying thread of our investigation will be the quest for a *fully iconic* proof system, where all logical connectives can be replaced by appropriate (new) kinds of bubbles. This will lead us to rediscover many principles already studied in the deep inference literature, with topological intuitions of the bubble metaphor shedding a new light on them. We will end up with two symmetric bubble calculi, each with their own tradeoffs on the properties satisfied by inference rules. In particular, their ability to *factorize* both forward and backward proof steps might prove useful to build concise proofs, all through direct manipulation.

The chapter is organized as follows: in Section ?? we motivate our quest for a system where all introduction rules for logical connectives are *invertible*, to reduce non-determinism in proof search and enable a fully *iconic* approach to proof building. To that effect, we relax in Section ?? the restriction to single-conclusion solutions, which requires a new distinction between *closed* and *open* solutions. This gives rise in Section ?? to an extension of the syntax of solutions, where bubbles can themselves be *polarized*. In Section ?? we identify key properties that will guide the design of inference rules, some of which were already aimed for implicitly through the evolution of our concept of bubble. In Section ?? we introduce a core *symmetric bubble calculus* for classical logic called “system B”, in reference to the symmetric system L of Herbelin [91]. Then in Section ?? we prove the soundness of system B, and show that by removing selectively among inference rules that define the *porosity* of polarized bubbles, one gets intuitionistic, dual-intuitionistic and bi-intuitionistic logic as fragments. In Section ?? we support this claim by showing that the bi-intuitionistic fragment is not only sound, but also *cut-free complete* with respect to the cut-free nested sequent calculus DBInt of Postniece [154]. Finally in Section ??, we introduce a fully invertible variant of system B that we conjecture to be complete, and present a canonical way to search for proofs in this system. Unfortunately, invertibility does not entail the full iconicity of the system, and we reflect on the fundamental reasons that might prevent any variant of system B from being fully iconic.

Remark 7.0.1 Although we include rules for quantifiers, in this thesis we only treat the soundness and completeness of bubble calculi for

propositional logic. Indeed quantifiers would make the algebraic semantics more involved when proving soundness, and during our literature review we found very few proof systems for bi-intuitionistic logic supporting them, at least none suitable for our syntactic completeness proof. More generally, bi-intuitionistic logic has received less attention in the first-order setting, probably because it is *not* a conservative extension of intuitionistic predicate logic, but only of *constant-domain* predicate logic (see [37] and [8]).

7.1 Non-determinism and iconicity

In all known sequent calculus formulations of intuitionistic logic, there are at least two rules which are invariably *non-invertible*:

1. a left introduction rule for \supset (there might be many ones, as in the calculus LJ_T of [52]);
2. the right introduction for either:
 - ▶ \vee when sequents have at most or exactly one conclusion;
 - ▶ \supset when sequents have multiple conclusions, e.g. in the multi-succedant variant of LJ_T in [52].

[52]: Dyckhoff (1992), ‘Contraction-Free Sequent Calculi for Intuitionistic Logic’

In BJ, this means that click actions on blue \supset and red \vee need to be performed in a specific order to be able to complete proofs.

In his thesis [82], Guenot introduced a specific kind of nested sequent system, where like in BJ inference rules can be expressed as rewriting rules. An interesting feature of these systems is that they satisfy a *decomposability* property: all introduction rules for connectives are *invertible*, and formulas can be completely decomposed with them until atoms are reached, before applying other rules. Thus introduction rules are *admissible* in these systems, because every formula can be translated into an equivalent pure nested sequent with the same number of atoms¹. Non-determinism then arises in the choice of atoms that are to be connected in axioms, as well as the choice of sub-sequents to be duplicated for reuse.

1: As far as we know, the admissibility of introduction rules is not proved, let alone mentioned in [82]. This is our own observation which lacks a proper formal proof, and is thus subject to caution.

In our graphical setting, this would translate to an interface where all click actions are redundant. Although we already considered this possibility in Section ??, here it goes further by making even *logical connectives* superfluous, since all other rules work purely on the structure of sequents. This means that all logical connectives could be replaced by metaphorical constructs like bubbles, which suggest *physically* the possible transformations on the proof state. We call this property of a proof system *iconicity*, following a terminology introduced by C. S. Peirce in his *semiotics* [138], which he also applied to his diagrammatic proof system of *existential graphs* [166]. Unfortunately, the systems in [82] only handle classical logic, and the implicative fragment of intuitionistic logic. Thus began our quest for a bubble calculus in the style of Guenot capturing full intuitionistic logic².

[138]: Nöth (1999), ‘Peircean Semiotics in the Study of Iconicity in Language’

[166]: Shin (2002), *The Iconic Logic of Peirce’s Graphs*

2: Other nested sequent systems for full intuitionistic logic exist ([154], [57]), but they are based on tree-shaped proofs, and thus ignore the whole *raison d’être* of our concept of bubble.

7.2 Conclusions and branching

The first direction we followed was to relax the constraint that solutions must be single-conclusion. Indeed as already noted in Section ??, a notable

property of sequent calculi with multiple conclusions is that their right introduction rule for \vee is invertible.

The main difficulty lies in the way one should interpret a multi-conclusion solution S as a formula $\llbracket S \rrbracket$. If we just take the asymmetric interpretation (Definition ??) and group conclusions disjunctively instead of conjunctively, we get

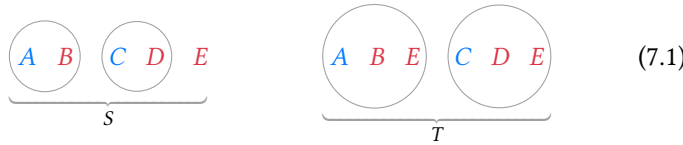
$$\llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket = \bigwedge \Gamma \supset \bigvee \Delta \wedge \bigwedge_{S \in \mathcal{S}} \llbracket S \rrbracket$$

But this interpretation breaks on the 0-ary case when Δ is empty: instead of seeing $\Gamma \langle \mathcal{S} \rangle$ as a node of the proof tree with hypotheses Γ and subgoals \mathcal{S} , it trivializes it to $\llbracket \Gamma \langle \mathcal{S} \rangle \rrbracket = \bigwedge \Gamma \supset \perp$, i.e. a goal where one has to find a contradiction in Γ ; which is obviously not what we have in mind.

A key observation was that in the rules of multi-conclusion sequent calculi, one usually distributes the context Δ of conclusions in all premisses: this restores a perfect symmetry with respect to the context of hypotheses Γ , as illustrated by the $\wedge R^*$ rule (Figure ??). Then our idea was that instead of implementing distribution/sharing of conclusions inside inference rules, we could do it implicitly in the interpretation of solutions. This is already what happens in the asymmetric interpretation for hypotheses (Definition ??); indeed the context Γ is shared among subgoals, because:

1. it appears on the left of an implication \supset
2. bubbles are joined conjunctively, and
3. implication distributes over conjunction thanks to the equivalence $A \supset B \wedge C \simeq (A \supset B) \wedge (A \supset C)$.

But what does it mean precisely to share conclusions among subgoals? If we consider the two following solutions:



we would like to have $\llbracket S \rrbracket \simeq \llbracket T \rrbracket \simeq (A \supset B \vee E) \wedge (C \supset D \vee E)$. Since disjunction distributes over conjunction, a first naive try would give the following interpretation, where we just replaced \wedge by \vee compared to the previous attempt:

$$\llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket = \bigwedge \Gamma \supset \bigwedge_{S \in \mathcal{S}} \llbracket S \rrbracket \vee \bigvee \Delta$$

But this immediately fails whenever $\mathcal{S} = \emptyset$, because it trivializes to $\bigwedge \Gamma \supset \top \vee \bigvee \Delta \simeq \top$ instead of $\bigwedge \Gamma \supset \bigvee \Delta$. The only way we found around this defect was to internalize *syntactically* a distinction between two kinds of solutions, by assigning them one of two *statuses*³:

- *closed* solutions $\Gamma \langle \mathcal{S} \rangle \Delta$ correspond to branching nodes in the proof tree, or to closed leaves when $\mathcal{S} = \emptyset$ (i.e. solved subgoals). Thus it becomes sensical to have $\llbracket \Gamma \langle \rangle \Delta \rrbracket = \top$. In the asymmetric interpretation, closed solutions were encoded by solutions with no conclusions;
- *open* solutions $\Gamma \Rightarrow \Delta$ correspond to open leaves in the proof tree (i.e. unsolved subgoals). In the asymmetric interpretation, they were encoded by solutions with one conclusion.

$$\frac{\Gamma \Rightarrow A, \Delta \quad \Gamma \Rightarrow B, \Delta}{\Gamma \Rightarrow A \wedge B, \Delta} \wedge R^*$$

Figure 7.1: Multi-conclusion right introduction rule for conjunction



3: In the terminology of Martin-Löf, we could say that we now have two distinct forms of *judgment*.

Then we keep the last proposed interpretation for closed solutions, and interpret open solutions like usual sequents:

$$\llbracket \Gamma \Rightarrow \Delta \rrbracket = \bigwedge \Gamma \supset \bigvee \Delta$$

To be able to abstract from the particular kind of solution at hand, we reframe the syntax of solutions with so-called *branching* operators \triangleright :

$$\begin{aligned} S, T, U &::= \Gamma \triangleright \Delta \\ \triangleright, \blacktriangleright &::= \Rightarrow \mid \langle \mathcal{S} \rangle \end{aligned}$$

Graphically, closed solutions with no bubbles can be distinguished from open solutions by painting their *background* on the proof canvas in green, the intent being to suggest that they have already been solved. A pathological example is the distinction between the closed empty bubble  and the open empty bubble , who are interpreted respectively by $\llbracket \langle \rangle \rrbracket = \top$ and $\llbracket \langle \Rightarrow \rangle \rrbracket = \perp$.

Now coming back to our target example, the interpretation still fails, because we associate two non-equivalent formulas to S and T . To show this, let us try to derive the equivalence through some algebraic developments:

$$\begin{aligned} \llbracket S \rrbracket &= \top \supset ((A \supset B) \wedge (C \supset D)) \vee E \\ &\simeq ((A \supset B) \wedge (C \supset D)) \vee E \\ &\simeq ((A \supset B) \vee E) \wedge ((C \supset D) \vee E) \\ &\simeq (A \supset B \vee E) \wedge (C \supset D \vee E) \\ &\simeq ((A \supset B) \wedge (C \supset D)) \vee E \\ \llbracket T \rrbracket &= \top \supset ((A \supset B \vee E) \wedge (C \supset D \vee E)) \vee \perp \end{aligned} \tag{7.2}$$

Wait, we did manage to prove it! The trick resides in Equation ??, which uses twice the equivalence $(A \supset B) \vee C \simeq A \supset (B \vee C)$. It turns out that this equivalence is true in classical logic, but *not* in intuitionistic logic. More precisely, it is the implication $G \triangleq (A \supset (B \vee C)) \supset ((A \supset B) \vee C)$ which is not provable intuitionistically, since it can easily be shown equivalent to the law of excluded middle⁴. Thus according to this interpretation, S entails T but T does not entail S , which means that it is not able to account for the *factorization* of common conclusions in distinct subgoals.

To remedy this situation, we opted for a different strategy: instead of finding a logical formula capturing the distributive semantics of conclusions over subgoals, we hardcode the latter by defining the interpretation function on closed solutions through *non-structural* recursion. This gives the following final definitions:

Definition 7.2.1 (Mix operator) *The commutative mix operator \uplus on solutions is defined by:*

$$\begin{aligned} (\Gamma \triangleright \Delta) \uplus (\Gamma' \Rightarrow \Delta') &= \Gamma, \Gamma' \triangleright \Delta, \Delta' \\ (\Gamma \langle \mathcal{S} \rangle \Delta) \uplus (\Gamma' \langle \mathcal{S}' \rangle \Delta') &= \Gamma, \Gamma' \langle \mathcal{S}; \mathcal{S}' \rangle \Delta, \Delta' \end{aligned}$$

4: This was already noticed in [35], with the linear version $(A \multimap (B \wp C)) \multimap ((A \multimap B) \wp C)$ of G called Grishin (a) and its converse Grishin (b). More precisely, it is affirmed that while Grishin (b) is valid in FILL, the restriction of the classical multiplicative linear logic MLL to single-conclusion sequents, adding Grishin (a) makes FILL collapse to MLL.

Definition 7.2.2 (Symmetric interpretation) *The symmetric interpretation of a solution is defined recursively by:*

$$\begin{aligned} \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket \\ \llbracket \Gamma \Rightarrow \Delta \rrbracket &= \bigwedge \Gamma \supset \bigvee \Delta \end{aligned}$$

This is the right approach for interpreting solutions with multiple conclusions, as will be demonstrated formally in Section ??.

7.3 Coloring bubbles

Red bubbles

With our new symmetric interpretation, we can start generalizing the rules of BJ to multiple conclusions. While for most rules one just has to replace single-conclusion (resp. no-conclusion) solutions with open (resp. closed) ones (more details will be given in the next section), the $\supset+$ rule stands out as particularly problematic. Indeed if we content ourselves with the natural generalization $\supset+c$ of Figure ??, then we can easily build a proof of the excluded middle like in Figure ??, and thus collapse to classical logic. This fact is well-known in the literature on multi-conclusion intuitionistic sequent calculi, and the solution is usually to discard the context of conclusions Δ , as in the $\supset R * i$ rule of Figure ?. But this would make our rule both non-local and non-invertible.

A better solution comes from the nested sequent systems of Fitting [57] and Clouston et al. [35], where sequents can appear as *conclusions* of other sequents. In our chemical metaphor, this corresponds to having *red bubbles*. Then the key idea is to allow hypotheses to flow into sequents that appear as conclusions⁵, but *not other conclusions*. Graphically, this means that blue items can enter red bubbles (rule $f\multimap$ of Figure ??), but red items cannot: this is reminiscent of the electromagnetic phenomenon of *repulsion* between objects charged with the same polarity.

To illustrate why this works, let us consider how one can manipulate with red bubbles the classical equivalence $(A \supset B) \vee C \approx A \supset (B \vee C)$, that we already stumbled upon in the previous section. The beginnings of the proofs for both directions of the equivalence are depicted parallelly in Figure ?. Indeed both proofs have a very similar structure:

1. the first step is to decompose the conclusion with the new version of the rules $\vee+$ and $\supset+$. While the former simply splits disjunctions in two, the latter encapsulates the antecedent and consequent of implications in a red bubble: the goal is to forbid the use of the antecedent to prove conclusions other than the consequent, as will become apparent later;
2. then in both cases we want to apply the hypothesis A in a forward step, either with $A \supset B$ or $A \supset (B \vee C)$. To do so, we need to bring the two hypotheses together in the same solution. And since items are trapped within bubbles, the only way to go is to move the blue A inside the red bubble with the $f\multimap$ rule;

$$\frac{\Gamma, A \supset B, \Delta}{\Gamma \supset A \supset B, \Delta} \supset+c$$

Figure 7.2: Classical multi-conclusion version of $\supset+$

$$A \quad (S) \rightarrow (A \quad S) \quad f\multimap\downarrow$$

Figure 7.3: F-rule for red bubbles

[57]: Fitting (2014), ‘Nested Sequents for Intuitionistic Logics’

[35]: Clouston et al. (2013), ‘Annotation-Free Sequent Calculi for Full Intuitionistic Linear Logic’

5: This corresponds to the *Lift* rule of [57] and pl_1 rule of [35].

3. this time we decompose the hypothesis with the new version of the rules $\vee-$ and $\supset-$. They are basically a local variant of those of BJ: we encapsulate both subformulas in separate bubbles, but without touching to the conclusions of the ambient solution;
4. now that all formulas have been decomposed, it only remains to bring together dual atoms for annihilation, and pop all empty bubbles. In Grishin (b) this is easy, because all necessary movements (indicated by green arrows) are valid: they only cross gray bubbles inward. In Grishin (a) this works for A and B , but not for C (orange dotted arrow): it would cross the red bubble, which is expressly forbidden.

Thus in order to prove Grishin (a) and recover classical logic, it suffices either to add the $f++$ rule allowing red items to enter red bubbles (Figure ??), or to use the $\supset+c$ rule which avoids red bubbles altogether. In the following we will settle for the first option: we find it more elegant, because it explains the distinction between intuitionistic and classical logic as a kind of *physical law* independent of logical connectives.

Blue bubbles

Now it is only natural to wonder: since bubbles can be colored in red, or charged positively, would it also make sense to have *blue* bubbles charged *negatively*? The answer is *yes*, but we need to broaden our logical view and consider more exotic beasts: the adequately named *dual-intuitionistic* logic, and *bi-intuitionistic* logic.

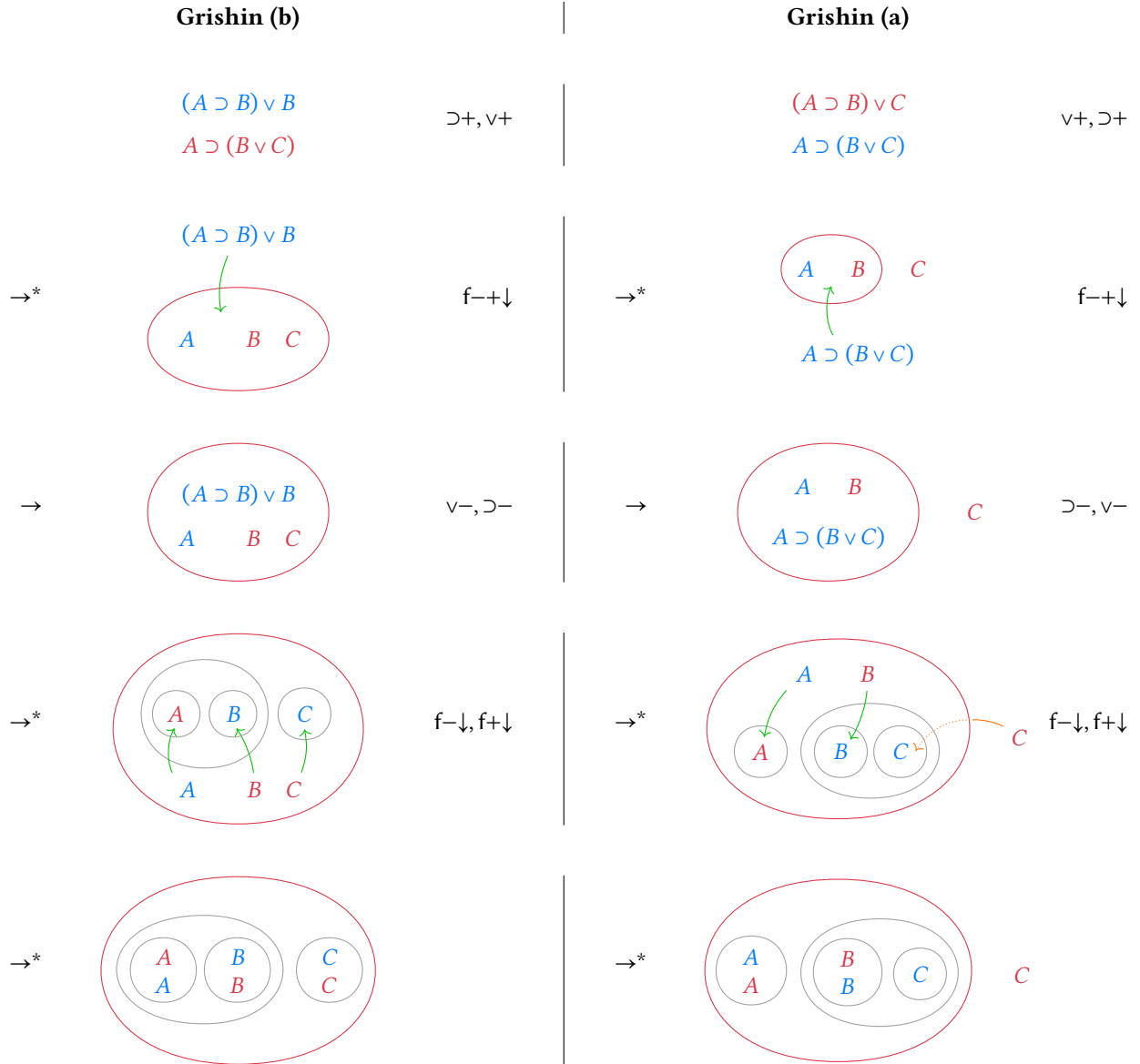


Figure 7.4: Proof attempts for Grishin (a) and Grishin (b)

But for now let us stay at a purely syntactic level. The idea is very simple, and can be summarized in two words: *color swap*. Thus the law that “blue items can enter red bubbles, but red items cannot” becomes a new law that “red items can enter blue bubbles, but blue items cannot”, which is enforced by allowing only the use of the $f+-$ rule in Figure ?? . Well this is neat, but will not be of much use if there is no way to spawn blue bubbles. Be it as it may: we can just craft a new logical connective! Since red bubbles are produced by the implication connective $A \supset B$, we define a dual *exclusion* connective $A \subset B$ (read “A excludes B”⁶), whose heating rules are those of \supset with swapped colors (Figure ??).

Not very surprisingly, the exclusion connective has already been studied in the literature on intuitionistic logic, starting with the seminal paper of Rauszer on *Heyting-Brouwer logic*, i.e. intuitionistic logic to which we add exclusion [158]. In this paper, exclusion was called *pseudo-difference*, to evoke its close connection with set-theoretical difference. Indeed given two sets A and B , one can define the set $A \setminus B$ by comprehension as $\{x \mid x \in A \wedge x \notin B\}$, which is the set A from which all elements of B have been *excluded*. With an interpretation in boolean algebras, this corresponds to the classical connective defined by the truth table of $A \wedge \neg B$, which is dual to the truth table of $\neg A \vee B$ defining material implication.

While the first paper of Rauszer [158] belongs to the Polish tradition of algebraic logic, she also explored in later works the proof-theoretic [157] and model-theoretic [159] sides of the question. Many authors have then deepened the proof theory of exclusion, whether in isolation from implication in *dual-intuitionistic* logic [188][76], or with both connectives in *bi-intuitionistic* logic as in Rauszer’s original work⁷ [155][153]. In particular, we are going to rely in Section ?? on the deep inference calculus developed by Postniece to get completeness and cut admissibility of our symmetric bubble calculus introduced in the next section.

Polarized interpretation

Let us now extend the formal definition of bubbles so that they can be colored:

Definition 7.3.1 (Bubble) *A bubble is a solution enclosed in a membrane, which can be either unpolarized (neutral), charged positively, or charged negatively.*

Neutral bubbles are the usual ones depicted in gray, while positive and negative bubbles correspond respectively to red and blue bubbles. We also update the definition of solutions, which can now be open or closed:

Definition 7.3.2 (Solution) *A solution is a multiset of ions and bubbles. Its status is either closed or open, and open solutions cannot contain neutral bubbles. Solutions S can be represented textually with the following syntax:*

$$\begin{aligned} S, T, U &::= \Gamma \triangleright \Delta & \mathcal{S} &::= S_1 ; \dots ; S_n \\ I, J, K &::= A \mid S & \Gamma, \Delta &::= I_1, \dots, I_n \\ \triangleright, \blacktriangleright &::= \Rightarrow \mid \langle \mathcal{S} \rangle \end{aligned}$$

$$A \text{ (red) } \circlearrowleft S \rightarrow \text{ (blue) } \circlearrowleft A \text{ (red) } S \quad f+-\downarrow$$

Figure 7.5: F-rule for blue bubbles

6: We ask for the reader’s leniency regarding our choice of symbol and terminology: in set theory this would be total nonsense, since $A \subset B$ would read “A is included in B”. Even worse, in the boolean algebra induced by set operations, $A \subset B$ is interpreted as A *implies* B ... But all the arrow symbols were already taken, and we want to emphasize the duality between exclusion and implication by mirroring the symbol, as it is traditionally done with conjunction \wedge and disjunction \vee .

$$\begin{aligned} A \subset B &\rightarrow \text{ (blue) } \circlearrowleft A \text{ (red) } B \quad C- \\ A \subset B &\rightarrow \text{ (red) } \circlearrowleft A \text{ (red) } \text{ (blue) } B \quad C+ \end{aligned}$$

Figure 7.6: H-rules for exclusion \subset

[158]: Rauszer (1974), ‘Semi-Boolean Algebras and Their Applications to Intuitionistic Logic with Dual Operations’

[157]: Rauszer (1974), ‘A Formalization of the Propositional Calculus of H-B Logic’

[159]: Rauszer (1977), ‘Applications of Kripke Models to Heyting-Brouwer Logic’

[188]: Urbas (1996), ‘Dual-Intuitionistic Logic’

[76]: Goré (2000), ‘Dual Intuitionistic Logic Revisited’

7: Crolard [37] and Aschieri [8] have also explored the computational counterpart of exclusion through the Curry-Howard correspondence, which is claimed by the first author to be a typing operator for *first-class coroutines*.

[155]: Postniece (2010), ‘Proof theory and proof search of bi-intuitionistic and tense logic’

[153]: Pinto et al. (2011), ‘Relating Sequent Calculi for Bi-intuitionistic Propositional Logic’

Note that in the textual syntax, bubbles are identified with *subsolutions* (Definition ??), and their polarity is determined by their position relative to branching operators; that is, for any solutions S, T, U such that $T < U$, S is either:

- ▶ *neutral* if $T = \Gamma \langle \mathcal{S} \rangle \Delta$ and $S \in \mathcal{S}$;
- ▶ *positive* if $T = \Gamma \triangleright \Delta$ and $S \in \Delta$;
- ▶ *negative* if $T = \Gamma \triangleright \Delta$ and $S \in \Gamma$.

Then we need to split our symmetric interpretation accordingly, so that positive bubbles are mapped to implications, and negative bubbles to exclusions⁸:

Definition 7.3.3 (Polarized symmetric interpretation) *The positive and negative symmetric interpretations of solutions $\llbracket - \rrbracket^+$ and $\llbracket - \rrbracket^-$ are defined by mutual recursion as follows:*

$$\begin{aligned}
 \llbracket A \rrbracket^+ &= A & \llbracket A \rrbracket^- &= A \\
 \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus \Gamma \Rightarrow \Delta \rrbracket^+ & \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^- &= \bigvee_{S \in \mathcal{S}} \llbracket S \uplus \Gamma \Rightarrow \Delta \rrbracket^- \\
 \llbracket \Gamma \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ & \llbracket \Gamma \Rightarrow \Delta \rrbracket^- &= \llbracket \Gamma \rrbracket^- \subset \llbracket \Delta \rrbracket^+ \\
 \llbracket \Gamma \rrbracket^+ &= \bigvee_{I \in \Gamma} \llbracket I \rrbracket^+ & \llbracket \Gamma \rrbracket^- &= \bigwedge_{I \in \Gamma} \llbracket I \rrbracket^-
 \end{aligned}$$

One can easily check that the interpretation of a solution that has no negative (resp. positive) subsolution will not contain any occurrence of the exclusion (resp. implication) connective. This will be crucial later to represent proofs of both intuitionistic, dual-intuitionistic and bi-intuitionistic logic in the same system.

7.4 Designing for properties

With our new syntax and interpretation of solutions at hand, we can design a new proof calculus including the rules previously discussed for manipulating polarized bubbles. The rich structure of solutions offers many possibilities in the precise formulation of rules, depending on the properties we expect from the calculus. We identified *six* of these properties, whose consequences range from aesthetic and theoretical considerations on paper, to concrete usability matters in a graphical proof-building interface. Let us summarize them in order of prioritization relatively to the latter:

Invertibility A rule is invertible when it could in principle be applied in the converse direction, while staying logically sound⁹. In other words, it corresponds to a logical *equivalence*: when all rules in a (bubble) calculus are invertible, we get that $S \rightarrow T$ implies $\llbracket S \rrbracket \simeq \llbracket T \rrbracket$. This entails in particular that a user can apply the rule without fear of turning a provable goal into an unprovable one¹⁰, eliminating an important source of non-determinism in proof search: the need for *backtracking*¹¹.

8: Here we took inspiration from the work of Clouston et al. on nested sequents for FILL [35].

9: The “in principle” part is important: more often than not, adding the converse of a rule only brings unnecessary complexity in proof search, especially in a user interface that aims for simplicity.

10: Assuming that the calculus is *complete* (Section ??).

11: See also Section ?? for a discussion on this matter.

Decomposability We already mentioned this property in Section ?? as one of the main motivations for this chapter: the ability to decompose all logical connectives “for free”, and thus reason solely on solutions that comprise only bubbles and atomic formulas. As far as we know, it has never been identified explicitly in the literature before, although it can loosely be seen as an extension of the decomposition procedures of existing deep inference systems¹². One reason is that logical connectives are widely considered as *primitive* in the tradition of mathematical logic: they *are* the objects of the reasoning activity, rather than a tool for representing and structuring arguments. Thus the idea of an alternative does not even occur. But even if it does, it is not clear that it would bring any interesting viewpoint on the problems usually studied in proof theory. In our case, it was brought by a very concrete application: making formal proofs accessible to a broader audience, by replacing symbolic and linguistic means of representation by iconic and directly manipulable ones.

Factorizability We say that a proof calculus is *factorizable* when it makes it easier to avoid duplicating arguments in subproofs. In Section ??, we already remarked that the ability to share hypotheses between subgoals in BJ enables the factorization of *forward* reasoning steps at any stage of the proof construction. With our new symmetric interpretation of multi-conclusion solutions, we will now be able to factorize *backward* reasoning steps as well, which was in fact the main motivation behind Example ?? in Section ??.

Locality There does not seem to be a general consensus on what it means precisely for an inference rule to be *local*. This terminology has been employed by various authors in proof theory, in ways that are often hard to compare. For instance in [134], sequent rules are said to be local because the contexts of hypotheses involved in a rule are located in the sequents of that rule, by opposition to natural deduction rules in their labelled presentation where hypotheses are located in arbitrary distant leaves of the derivation. In the setting of deep inference, local rules are those that can be applied without “inspection of expressions of arbitrary size”¹³. Finally in his Transcendental Syntax, Girard evokes a related but more elusive notion, concerned with the *genericity* of logical objects involved in a rule¹⁴.

Our conception of locality is related to all the previous ones, although it is guided by the idea of direct manipulation of logical entities by humans, rather than purely proof-theoretical considerations. For instance, BJ has some locality in the deep inference sense because all rules are applicable in arbitrary contexts; but we relax the *atomicity* constraint that reduces I-rules and R-rules to their atomic version, because it would be unnecessarily restrictive for the purpose of building proofs manually. Still, we want to avoid as much as possible referring to generic objects that are not directly related to the manipulated data, in the spirit of Girard’s locality. A typical example is the elimination rule for disjunction in natural deduction, corresponding to the $\vee-$ rule of BJ that involves an arbitrary conclusion Δ . The benefits of locality from a UX point of view have already been discussed at the end of Section ??.

12: One could argue that more “semantic” approaches in proof theory have achieved connective-free explanations of proofs, like strategies in game semantics or the combinatorial proofs of D. Hughes [90]. But this is more of a side effect than a goal of these approaches, which intentionally abstract from the syntactic process of building proofs. A notable exception is the Girardian line of works starting from Ludics [67] and culminating in Transcendental Syntax [55], where both frameworks are founded upon the syntactic mechanisms of proof search (focusing in sequent calculus, and unification in the resolution algorithm of Robinson, respectively). Here the aim to rid proofs of connectives is greatly emphasized by Girard, but the focus is again on *proofs* and not *proof states*. Also Girard embraces the full space of incomplete but also *incorrect* proofs, while we still want a framework where proofs are correct by construction.

[134]: Negri et al. (2001), *Structural Proof Theory*

13: Definition 2.1.1 in [185]. The same definition is used in [184].

14: See the section *Globality and locality in logical systems* in Chapter 6 of Boris Eng’s thesis [55].

Linearity We consider an inference rule to be *linear* when it preserves the number of atomic formulas in solutions. This is a strong requirement, which for instance excludes the identity rules of BJ since they can insert or remove (even numbers of) atoms. Thus we cannot achieve full linearity in that sense, but it is still interesting to maximize it. The first reason is *methodological*: by the words of its creator A. Guglielmi, “[...] *deep inference is obtained by applying some of the main concepts behind linear logic to the formalisms, i.e., to the rules by which proof systems are designed.*” [85]. The second reason is *computational*: it can enable a measure on solutions that is strictly decreasing with the application of rules, avoiding infinite loops during proof search as in the calculus LJ_T of R. Dyckhoff [52]. The third reason is *ergonomical*: as already remarked by the authors of the Proof-by-Pointing paradigm¹⁵, rules that systematically duplicate formulas can quickly overload the goal with useless copies, making it harder to read and navigate.

[85]: Guglielmi (2015), *All about Proofs, Proofs for All*

15: Section 4.1 of [13].

Symmetry In classical logic, both sequent calculi like LK and deep inference systems like CoS are known for their very rich *symmetries*. In fact, one of our ambitions with bubbles was to bring back the symmetry of classical logic in a constructive setting, without resorting to linear logic. This chapter stems in great part from our lack of satisfaction with the asymmetry at work in the BJ calculus, which looked quite unnatural. Of course we will not be able to completely eliminate it, but it will be distilled into the flow rules governing the *porosity* of bubbles that were hinted at in Section ??, rather than through the arbitrary restriction of sequents to one conclusion¹⁶. Our treatment of dual and bi-intuitionistic logic through blue bubbles is also motivated by this quest for symmetry. It should be noted that although we use naming conventions for rules that resemble those of CoS (e.g. with the identity rules), we do not aim for a perfect symmetry where one can get a complete calculus by simply taking the dual of each rule. Thus we will content ourselves with the hypothesis/conclusion symmetry coming from sequent calculus. Interestingly, the calculus lSgq of Tiu for intuitionistic predicate logic does the opposite, by having a perfect dual system clSgq but no symmetries among its switch rules (the equivalent of our flow rules) [184].

16: Whether it is enforced in the syntax of sequents themselves, or through restriction on rules that manipulate conclusions like contraction or the introduction rule for \supset .

In the next section we present a core calculus called “system B” that maximizes *symmetry*, *linearity* and *locality*. In our opinion this makes for a good proof-theoretical foundation, around which variant calculi with different tradeoffs can be designed.

7.5 Symmetric calculus

As for the asymmetric bubble calculus BJ, the rules of our full symmetric bubble calculus system B enjoy both a sequent-style and a graphical presentation, given respectively in Figure ?? and Figure ??. The presence of closed and open solutions complicates quite a bit the graphical representation of rules, thus some explanations are in order:

<p style="text-align: center; margin: 0;">IDENTITY</p> $\frac{\Gamma \langle \rangle \Delta}{\Gamma, A \Rightarrow A, \Delta} \text{ i}\downarrow \quad \frac{\Gamma \langle \Rightarrow A; A \Rightarrow \rangle \Delta}{\Gamma \Rightarrow \Delta} \text{ i}\uparrow$	<p style="text-align: center; margin: 0;">RESOURCE</p> $\frac{\Gamma \triangleright \Delta}{\Gamma, I \triangleright \Delta} \text{ w-} \quad \frac{\Gamma \triangleright \Delta}{\Gamma \triangleright I, \Delta} \text{ w+}$ $\frac{\Gamma, I, I \triangleright \Delta}{\Gamma, I \triangleright \Delta} \text{ c-} \quad \frac{\Gamma \triangleright I, I, \Delta}{\Gamma \triangleright I, \Delta} \text{ c+}$
<p style="text-align: center; margin: 0;">FLOW</p> $\frac{\Gamma \langle \mathcal{S}; \Gamma' \langle \mathcal{S}' \rangle \Delta'; S \rangle \Delta}{\Gamma \langle \mathcal{S}; \Gamma' \langle \mathcal{S}' \rangle S \rangle \Delta'} \text{ f}\uparrow$ $\frac{\Gamma \langle \Gamma', I \triangleright \Delta'; \mathcal{S} \rangle \Delta}{\Gamma, I \langle \Gamma' \triangleright \Delta'; \mathcal{S} \rangle \Delta} \text{ f-}\downarrow \quad \frac{\Gamma \langle \mathcal{S}; \Gamma' \triangleright I, \Delta' \rangle \Delta}{\Gamma \langle \mathcal{S}; \Gamma' \triangleright \Delta' \rangle I, \Delta} \text{ f+}\downarrow$ $\frac{\Gamma \triangleright (\Gamma', I \triangleright \Delta'), \Delta}{\Gamma, I \triangleright (\Gamma' \triangleright \Delta'), \Delta} \text{ f-+}\downarrow \quad \frac{\Gamma, (\Gamma' \triangleright I, \Delta') \triangleright \Delta}{\Gamma, (\Gamma' \triangleright \Delta') \triangleright I, \Delta} \text{ f+-}\downarrow$ $\frac{\Gamma, I, (\Gamma' \triangleright \Delta') \triangleright \Delta}{\Gamma, (\Gamma' \triangleright \Delta') \triangleright \Delta} \text{ f--}\uparrow \quad \frac{\Gamma \triangleright (\Gamma' \triangleright \Delta'), I, \Delta}{\Gamma \triangleright (\Gamma' \triangleright I, \Delta'), \Delta} \text{ f++}\uparrow$ $\frac{\Gamma, I \triangleright (\Gamma' \triangleright \Delta'), \Delta}{\Gamma \triangleright (\Gamma', I \triangleright \Delta'), \Delta} \text{ f-+}\uparrow \quad \frac{\Gamma, (\Gamma' \triangleright \Delta') \triangleright I, \Delta}{\Gamma, (\Gamma' \triangleright I, \Delta') \triangleright \Delta} \text{ f+-}\uparrow$ $\frac{\Gamma, (\Gamma', I \triangleright \Delta') \triangleright \Delta}{\Gamma, I, (\Gamma' \triangleright \Delta') \triangleright \Delta} \text{ f--}\downarrow \quad \frac{\Gamma \triangleright (\Gamma' \triangleright I, \Delta'), \Delta}{\Gamma \triangleright (\Gamma' \triangleright \Delta'), I, \Delta} \text{ f++}\downarrow$	<p style="text-align: center; margin: 0;">MEMBRANE</p> $\frac{\Gamma \langle \mathcal{S} \rangle \Delta}{\Gamma \langle \mathcal{S}; \langle \rangle \rangle \Delta} \text{ p}$ $\frac{\Gamma \langle \rangle \Delta}{\Gamma, \langle \rangle \Rightarrow \Delta} \text{ p-} \quad \frac{\Gamma \langle \rangle \Delta}{\Gamma \Rightarrow \langle \rangle, \Delta} \text{ p+}$ $\frac{\Gamma \langle S \rangle \Delta}{\Gamma \langle \langle S \rangle \rangle \Delta} \text{ a}$ $\frac{\Gamma, S \triangleright \Delta}{\Gamma, \langle \langle S \rangle \rangle \triangleright \Delta} \text{ a-} \quad \frac{\Gamma \triangleright S, \Delta}{\Gamma \triangleright \langle \langle S \rangle \rangle, \Delta} \text{ a+}$
<p>HEATING</p>	
$\frac{\Gamma \triangleright \Delta}{\Gamma, \top \triangleright \Delta} \top- \quad \frac{\Gamma \langle \rangle \Delta}{\Gamma \Rightarrow \top, \Delta} \top+$ $\frac{\Gamma \langle \rangle \Delta}{\Gamma, \perp \Rightarrow \Delta} \perp- \quad \frac{\Gamma \triangleright \Delta}{\Gamma \triangleright \perp, \Delta} \perp+$ $\frac{\Gamma, A, B \triangleright \Delta}{\Gamma, A \wedge B \triangleright \Delta} \wedge- \quad \frac{\Gamma \langle \Rightarrow A; \Rightarrow B \rangle \Delta}{\Gamma \Rightarrow A \wedge B, \Delta} \wedge+$ $\frac{\Gamma \langle A \Rightarrow; B \Rightarrow \rangle \Delta}{\Gamma, A \vee B \Rightarrow \Delta} \vee- \quad \frac{\Gamma \triangleright A, B, \Delta}{\Gamma \triangleright A \vee B, \Delta} \vee+$ $\frac{\Gamma \langle \Rightarrow A; B \Rightarrow \rangle \Delta}{\Gamma, A \supset B \Rightarrow \Delta} \supset- \quad \frac{\Gamma \triangleright (A \Rightarrow B), \Delta}{\Gamma \triangleright A \supset B, \Delta} \supset+$ $\frac{\Gamma, (A \Rightarrow B) \triangleright \Delta}{\Gamma, A \subset B \triangleright \Delta} \subset- \quad \frac{\Gamma \langle \Rightarrow A; B \Rightarrow \rangle \Delta}{\Gamma \Rightarrow A \subset B, \Delta} \subset+$ $\frac{\Gamma, A\{t/x\} \triangleright \Delta}{\Gamma, \forall x. A \triangleright \Delta} \forall- \quad \frac{\Gamma \triangleright A, \Delta}{\Gamma \triangleright \forall x. A, \Delta} \forall+$ $\frac{\Gamma, A \triangleright \Delta}{\Gamma, \exists x. A \triangleright \Delta} \exists- \quad \frac{\Gamma \triangleright A\{t/x\}, \Delta}{\Gamma \triangleright \exists x. A, \Delta} \exists+$	
<p>In the $\forall+$ and $\exists-$ rules, x is not free in Γ, Δ and \triangleright.</p>	

Figure 7.7: Sequent-style presentation of system B

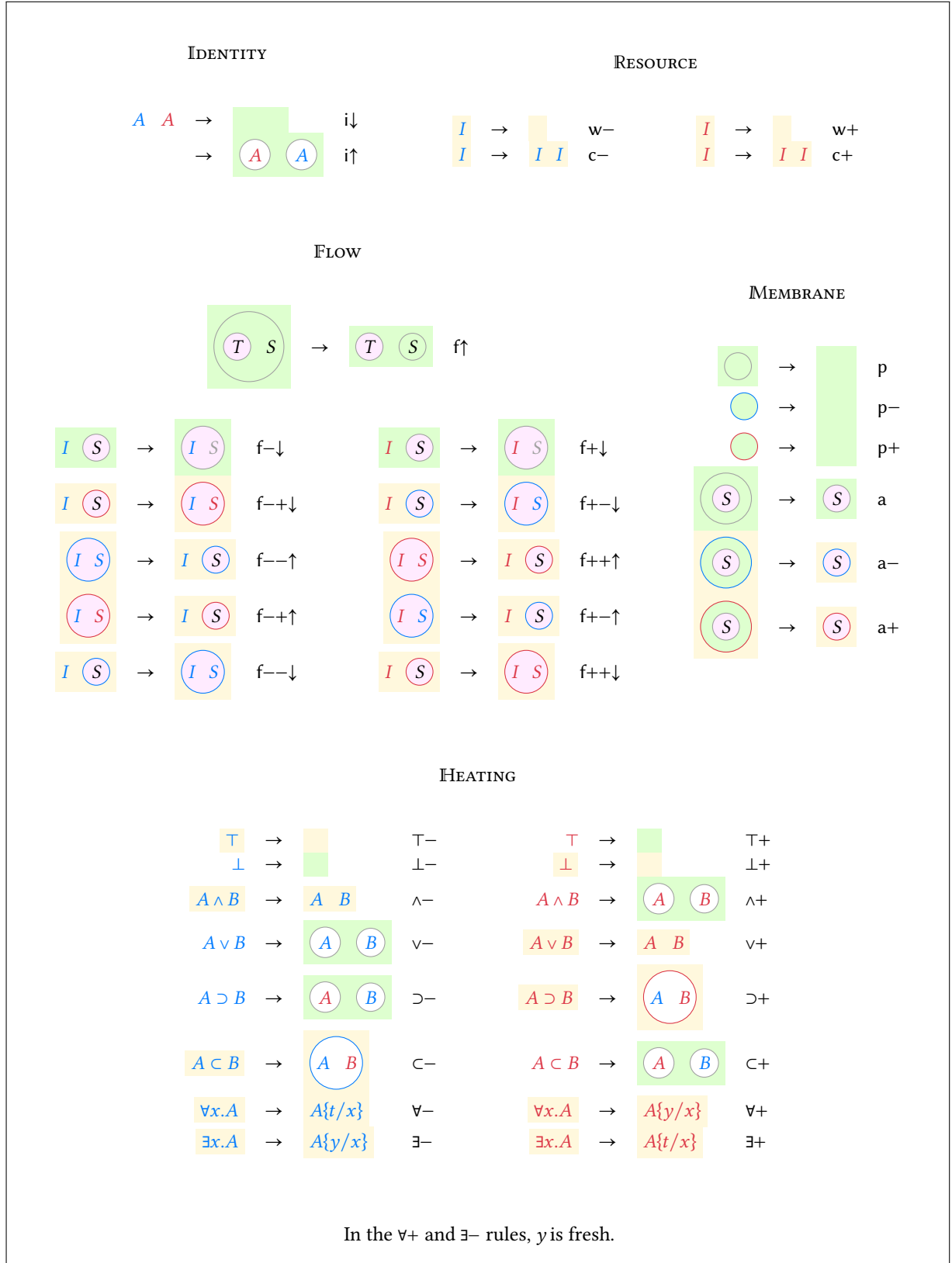


Figure 7.8: Graphical presentation of system B

Closed solutions In Section ??, we mentioned that closed solutions with no neutral bubbles can be distinguished visually from open solutions by painting their background in a different color; we chose a light green, to suggest that they denote *solved* subgoals. In Figure ??, we emphasize systematically the distinction by extending this convention to all closed solutions.

Generic statuses As can be seen in Figure ??, many rules of system B are *generic* over branching operators $\triangleright, \blacktriangleright$, which determine whether a solution is closed or open, i.e. its *status*. The challenge is thus to find an iconic counterpart to the symbols $\triangleright, \blacktriangleright$, that fulfills the same function of *meta-variable* ranging over solution statuses. Since we already use the background color to represent the status of concrete solutions, we chose to do the same with abstract ones: each new color other than green will stand for the status of the solution associated to the given location of the canvas. For instance in the $f \rightarrow \downarrow$ rule, the status of the ambient solution where the rule is applied is denoted by a light yellow background, while the status of the solution S enclosed in a red bubble is denoted by the light pink background.

Status changes Last but not least, many rules like $i \downarrow$ change the status of the ambient solution from open to closed: graphically, this means that the background must become green *everywhere*, not only in the portion of the canvas depicted by the rule. At first it might appear as breaking locality, but it should rather be understood as the result of a perfectly local and continuous process: one can imagine a literal *drop* of green paint that soaks a growing portion of the canvas, until it reaches an enclosing bubble — for the sake of metaphor, let us say a cut in the papersheet — that stops its progression¹⁷.

We will now analyze the various groups of rules of system B, by comparing them to those of the BJ calculus:

IDENTITY A first difference, that we will find in most rules of system B, is that we rely on the distributive interpretation of conclusions in solutions. For instance in the $i \uparrow$ rule, Δ is available potentially in both subgoals, and we do not need to move it manually: this will be the role of the flow rules for red items.

A second difference is that the rules are not applicable in arbitrary subsolutions, but only *open* ones. This will also be the case of some membrane and heating rules. In the case of the $i \downarrow$ rule, it guarantees its *locality*: if the conclusion was $\Gamma, A \langle \mathcal{S} \rangle A, \Delta$, then the distributive semantics would entail that all subgoals in \mathcal{S} must be solved at once, despite the fact that they are not directly related to A ¹⁸. As for the $i \uparrow$ rule, restricting to open solutions makes the rule *invertible*, without sacrificing locality. This will in fact be the case of all rules that create multiple subgoals.

RESOURCE Here we still have weakening and contraction for negative items (hypotheses), and we also allow them for positive items (conclusions). Note that contrary to the I-rules which apply only to a formula A , R-rules apply to an arbitrary item I , which can either be a formula or a solution. Combined to the fact that the ambient

17: We will come back to this *cuts in a sheet* metaphor, first introduced by C. S. Peirce, in Chapter ??. When closing the top-level solution — Peirce called it the *sheet of assertions*, the drop expansion process becomes *infinite*. I find it to be a beautiful allegory of the *unreachability* of global, unconditional truth: it is only by being confined to a finite, well-delimited space, that we can affirm unequivocally our certainty. As Wittgenstein famously said at the end of the *Tractatus*: “Whereof one cannot speak, thereof one must be silent”.

18: If we were to give up on locality, we could opt for this variant, which gives better *factorizability*. In fact we will precisely do that in Section ??.

solution can be either open or closed, this gives the most general and expressive formulation of the rules. We believe that like in CoS, the atomic version where I is restricted to an atomic formula might be sufficient for completeness.

Flow Compared to BJ where we only had neutral bubbles, the presence of polarized bubbles in system B creates a mini-combinatorial explosion in the number of possible F-rules. Indeed, the general scheme is to consider what types of items are allowed to flow through bubbles, either inwards or outwards. With i item types and b bubble types, this makes for a total of $i \times b \times 2$ possible rules. In BJ items consisted only of polarized formulas and neutral bubbles ($i = 3$ and $b = 1$), thus we had a total of 6 possible F-rules. It turns out that only the $f\text{--}\downarrow$ rule was necessary, and it is also present in system B. Now with positive and negative bubbles added to the mix ($b = 3$), we get up to a total of 18 possible F-rules in system B. Out of these, 11 were identified as being sound logically, and thus we decided to include all of them in system B.

Some of them we have already encountered in Section ??: first the $f\text{+}\downarrow$ rule for distributing conclusions in subgoals, which would not have made sense with the asymmetric interpretation of solutions (Definition ??); but also the $f\text{--}\text{+}\downarrow$ and $f\text{+}\text{--}\downarrow$ rules, which allow a polarized item to flow *into* a bubble of *opposite* polarity. However to get *cut-free* completeness, we will also need a sort of dual of these rules, $f\text{+}\text{+}\uparrow$ and $f\text{--}\text{--}\uparrow$, which allow a polarized item to flow *out* of a bubble with the *same* polarity. Thus in addition to the duality that *swaps* polarities ($f\text{--}\text{+}\downarrow$ versus $f\text{+}\text{--}\downarrow$), we have this new duality which *reverses* at the same time the *direction* of the flow, and the *relationship* between polarities ($f\text{--}\text{+}\downarrow$ versus $f\text{+}\text{+}\uparrow$).

Taken together, these 6 rules capture provability in *bi-intuitionistic* logic, as will be demonstrated by the soundness and completeness theorems for system B. By adding any one of the converses to the 4 rules that define the porosity of polarized bubbles ($f\text{--}\text{+}\uparrow$, $f\text{+}\text{--}\uparrow$, $f\text{--}\text{--}\downarrow$, $f\text{+}\text{+}\downarrow$), the system collapses to *classical* logic. This situation is summarized in Figure ??: as in Figure ??, green and orange arrows represent respectively valid and invalid moves, but in bi-intuitionistic rather than intuitionistic logic. To recover the latter, one can just ignore all arrows that cross the blue bubble, which are only useful in dual-intuitionistic logic. Then the purple arrows represent moves that are valid only in classical logic. The reader can easily check that there is a total of 18 arrows, and map the green and purple arrows back to the corresponding F-rules of Figure ??.

Remark 7.5.1 Since all items can freely go in and out of polarized bubbles in classical logic, the latter are useless. In fact, one could restrict the syntax of solutions to neutral bubbles and only one polarity of formulas, say conclusions. This corresponds to the possibility of having one-sided formulations of sequent calculi for classical logic, by restricting negation to atomic formulas and extending it to arbitrary formulas through De Morgan dualities¹⁹

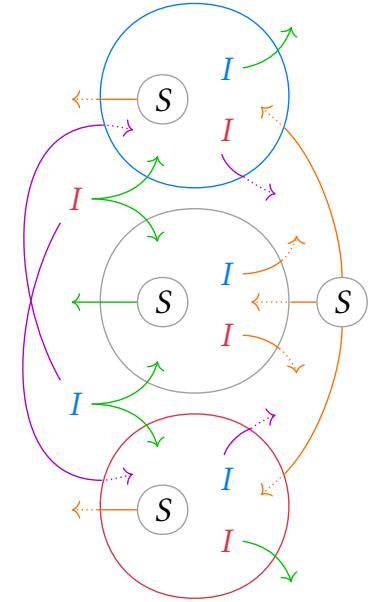


Figure 7.9: Porosity of bubbles in system B

In their graphical representation, the bi-intuitionistic F-rules of

system B are equivalent to the three following *topological laws*, that we call the *F-laws*²⁰:

Fact 7.5.1 (\mathbb{F} -laws)

1. Polarized bubbles trap (resp. repel) items with a different (resp. identical) polarity.
2. Neutral bubbles trap (resp. repel) polarized (resp. neutral) items.
3. Polarized bubbles both trap and repel neutral bubbles.

In Figure ??, the ability of bubbles to trap (resp. repel) items corresponds to outward (resp. inward) orange arrows. F-laws are thus the “negative” counterpart — in the grammatical sense — of F-rules, represented by green arrows. The fact that purple arrows are demoted to orange arrows in bi-intuitionistic logic, can be interpreted as resulting from their violation of the first F-law. The second and third F-laws characterize the behavior of neutral bubbles, and are respected by all rules of system B.

In particular, they suggest the addition of a new F-rule \uparrow , which allows to move neutral bubbles out of other neutral bubbles. When looking at it as a graphical rewrite rule in Figure ??, it can be seen as the act of *abstracting* the subgoal T from its parent subgoal S , since the hypotheses and conclusions of S cannot be brought to interact with those of T anymore. More generally in bi-intuitionistic logic, all flow rules can be understood as *abstraction* moves, that strengthen the goal by moving irreversibly an item I out of its subgoal S . In the case of outward rules (whose name ends with \uparrow), I is brought closer to the *root* of the proof tree; and in the case of inward rules (whose name ends with \downarrow), I is brought closer to the *leaves* of the proof tree.

It would be interesting to try to formalize F-laws, and more generally the graphical presentation of system B, with the rigorous tools of mathematical topology. This has been done for instance in [16] for the existential graphs of C. S. Peirce (see Chapter ??).

MEMBRANE We still have the popping rule p of BJ, which is now restricted to closed empty bubbles. We add two popping rules $p-$ and $p+$ for popping respectively negative and positive closed empty bubbles. Like the $i\downarrow$ rule, these have the effect of closing the ambient solutions, and for the same reasons we thus restrict them to open ambient solutions.

The novelty compared to BJ is that we also add so-called *absorption rules* $\{a, a-, a+\}$ for membranes. These rules state that when a bubble contains only a single neutral bubble, the membrane of the latter can be absorbed into the membrane of the former. This is mainly useful when one wants to apply an outward F-rule to an item that has the same polarity as the outer bubble, as witnessed by the use of the $a+$ rule in the proof of Uustalu’s formula in Figure ?? . This formula was first introduced in [152] as a counter-example to the cut-elimination theorem of Rauszer’s sequent calculus for bi-intuitionistic logic [157], and our initial motivation for introducing

20: Hopefully, those are not *flaws* of our *flow* rules, but rather the opposite...

$$\begin{array}{c}
\frac{\langle \rangle}{\langle \rangle} \text{p} \\
\frac{\langle \rangle}{\langle \rangle; \langle \rangle} \text{p} \\
\frac{\langle \rangle; \langle \rangle}{\langle \rangle; q \Rightarrow q} \text{i}\downarrow \\
\frac{\langle \rangle; q \Rightarrow q}{\langle p \Rightarrow p; q \Rightarrow q \rangle} \text{i}\downarrow \\
\frac{\langle p \Rightarrow p; q \Rightarrow q \rangle}{\langle p \Rightarrow p; q \Rightarrow q \rangle} \text{f}+ \\
\frac{\langle p \Rightarrow p; q \Rightarrow q \rangle}{p \langle \Rightarrow p; q \Rightarrow q \rangle} \text{f}- \\
\frac{p \langle \Rightarrow p; q \Rightarrow q \rangle}{p \Rightarrow q, p \subset q} \text{c}+ \\
\frac{p \Rightarrow q, p \subset q}{p \Rightarrow q, p \subset q, (\Rightarrow)} \text{w}+ \\
\frac{p \Rightarrow q, p \subset q, (\Rightarrow)}{p \Rightarrow q, (\Rightarrow p \subset q)} \text{f}++ \\
\frac{p \Rightarrow q, (\Rightarrow p \subset q)}{p \Rightarrow q, (\langle \Rightarrow p \subset q \rangle)} \text{a}+ \\
\frac{p \Rightarrow q, (\langle \Rightarrow p \subset q \rangle)}{p \Rightarrow q, (\langle \Rightarrow p \subset q; \langle \rangle \rangle)} \text{p} \\
\frac{p \Rightarrow q, (\langle \Rightarrow p \subset q; \langle \rangle \rangle)}{p \Rightarrow q, (\langle \Rightarrow p \subset q; r \Rightarrow r \rangle)} \text{i}\downarrow \\
\frac{p \Rightarrow q, (\langle \Rightarrow p \subset q; r \Rightarrow r \rangle)}{p \Rightarrow q, (r \langle \Rightarrow p \subset q; \Rightarrow r \rangle)} \text{f}-\downarrow \\
\frac{p \Rightarrow q, (r \langle \Rightarrow p \subset q; \Rightarrow r \rangle)}{p \Rightarrow q, (r \Rightarrow ((p \subset q) \wedge r))} \wedge+ \\
\frac{p \Rightarrow q, (r \Rightarrow ((p \subset q) \wedge r))}{p \Rightarrow q, r \supset ((p \subset q) \wedge r)} \supset+
\end{array}$$

Figure 7.10: A proof of Uustalu’s formula in system B

[152]: Pinto et al. (2009), ‘Proof Search and Counter-Model Construction for Bi-intuitionistic Propositional Logic with Labelled Sequents’

[157]: Rauszer (1974), 'A Formalization of the Propositional Calculus of H-B Logic'

absorption rules was precisely to provide a cut-free proof of this formula in system B.

Later, we realized that there is an interesting *symmetry* at play between popping rules and absorption rules. As mentioned in Section ??, popping rules can be understood as resulting from a process of *contraction* of membranes into a single point. Dually, absorption rules can be seen as the result of a process of *expansion* of the inner bubble towards the outer bubble. While contraction gets stuck on polarized items because they cannot cross neutral membranes outwards, expansion gets stuck on neutral items because they cannot cross neutral membranes inwards. Thus there is a very natural interplay between M-rules, and the F-laws induced by F-rules.

HEATING Like the \uparrow rule, the $\perp-$, $\vee-$ and $\supset-$ rules become truly local in system B by letting F-rules handle the distribution of conclusions in subgoals. Together with their dual rules $\top+$, $\wedge+$ and $\supset+$, they constitute the *closing* H-rules of system B. All other H-rules work in arbitrary solutions just as in BJ. But thanks to the ability to have multiple conclusions (Section ??) and positive bubbles (Section ??), both the $\vee+$ and $\supset+$ rules are now *invertible*: this was the initial motivation for designing the symmetric bubble calculus.

7.6 Soundness

Heyting and Brouwer algebras

We are now going to prove the soundness of system B with respect to various classes of *algebras*. While the full system is classical and thus sound only in *Boolean* algebras, most rules are sound in larger classes of algebras, namely: *Heyting* algebras for intuitionistic logic, *Brouwer* algebras for dual-intuitionistic logic, and *Heyting-Brouwer* algebras for bi-intuitionistic logic. These 4 classes are all instances of *bounded lattices*, and their relationship is summarized in the Venn diagram of Figure ??.

First we recall the definitions of the various algebras:

Definition 7.6.1 (Bounded lattice) *A bounded lattice is a structure $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee)$ such that:*

- ▶ (\mathcal{A}, \leq) is a partial order, i.e. for every $a, b, c \in \mathcal{A}$ we have:
 - $a \leq a$;
 - if $a \leq b$ and $b \leq a$ then $a = b$;
 - if $a \leq b$ and $b \leq c$ then $a \leq c$.
- ▶ \perp and \top are respectively the smallest and greatest elements of (\mathcal{A}, \leq) , i.e. for every $a \in \mathcal{A}$ we have $\perp \leq a$ and $a \leq \top$;
- ▶ For every pair of elements $a, b \in \mathcal{A}$, $a \vee b$ is their join (least upper bound) and $a \wedge b$ their meet (greatest lower bound), that is:
 - $a \leq a \vee b$, $b \leq a \vee b$ and $a \vee b \leq c$ for all $c \in \mathcal{A}$ s.t. $a \leq c$ and $b \leq c$;

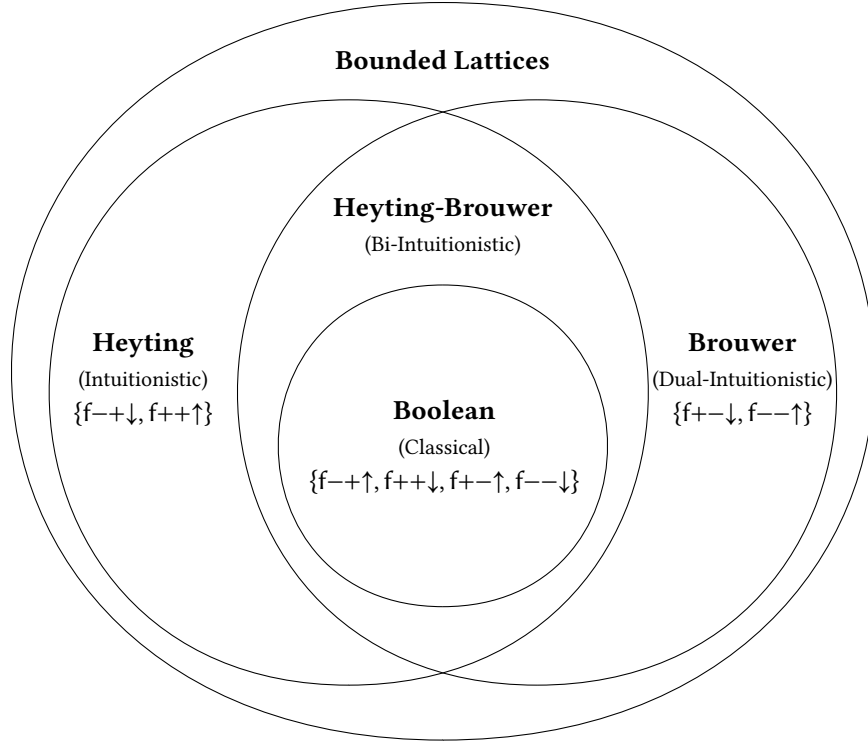


Figure 7.11: Relationship between the various algebras interpreting system B

- $a \wedge b \leq a, a \wedge b \leq b$ and $c \leq a \wedge b$ for all $c \in \mathcal{A}$ s.t. $c \leq a$ and $c \leq b$.

Remark 7.6.1 As mentioned in the introduction, we only conjecture the soundness of rules for quantifiers: this would require considering *complete* lattices, i.e. with meets and joins for arbitrary sets rather than just pairs²¹.

As the notation strongly suggests, the greatest and smallest elements \top and \perp will model respectively truth and falsehood, while the meet \wedge and join \vee will model conjunction and disjunction. In fact the conditions of Definition ?? are very close to the rules of natural deduction for these connectives, by replacing the sequent operator \Rightarrow with the partial order relation \leq . The same idea can be applied to the implication connective, and adding a corresponding *exponential* operation \supset indeed gives the definition of a Heyting algebra:

Definition 7.6.2 (Heyting algebra) A Heyting algebra is a structure $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee, \supset)$ such that $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee)$ is a bounded lattice and for every pair $a, b \in \mathcal{A}$, the exponential $a \supset b$ is the greatest element of the set $\{c \in \mathcal{A} \mid c \wedge a \leq b\}$. That is, $(a \supset b) \wedge a \leq b$ and $c \leq a \supset b$ for all $c \in \mathcal{A}$ s.t. $c \wedge a \leq b$.

By dualizing this definition, we get a *co-exponential* operation \subset that models the exclusion connective, and thus dual-intuitionistic logic in so-called Brouwer algebras:

21: see for instance section 2.1 of [1] for a concise treatment of the completeness of intuitionistic natural deduction for Heyting algebras with respect to algebraic semantics.

Definition 7.6.3 (Brouwer algebra) *A Brouwer algebra is a structure $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee, \multimap)$ such that $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee)$ is a bounded lattice and for every pair $a, b \in \mathcal{A}$, the co-exponential $a \multimap b$ is the smallest element of the set $\{c \in \mathcal{A} \mid b \leq a \vee c\}$. That is, $b \leq a \vee (b \multimap a)$ and $b \multimap a \leq c$ for all $c \in \mathcal{A}$ s.t. $b \leq a \vee c$.*

Then we can model bi-intuitionistic logic, which comprises both implication and exclusion, by just taking pairs of a Heyting and a Brouwer algebra on the same bounded lattice:

Definition 7.6.4 (Heyting-Brouwer algebra) *A Heyting-Brouwer algebra is a structure $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee, \multimap, \multimap)$ such that $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee, \multimap)$ is a Heyting algebra and $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee, \multimap)$ is a Brouwer algebra.*

Finally, we recover classical logic by collapsing exponentials and co-exponentials to their classical definitions, giving a characterization of Boolean algebras:

Definition 7.6.5 *A Boolean algebra is a Heyting-Brouwer algebra $(\mathcal{A}, \leq, \top, \perp, \wedge, \vee, \multimap, \multimap)$ such that for every $a, b \in \mathcal{A}$, $a \multimap b = (\top \multimap a) \vee b$ and $a \multimap b = a \wedge (b \multimap \perp)$.*

Remark 7.6.2 Definition ?? can be shown equivalent to more usual definitions of Boolean algebras, that are based only on lattice operations and a primitive complement operation modelling negation; but including the proof here would lead us out of the scope of this chapter.

In the rest of this chapter, we will freely assimilate formulas and their interpretation in the various algebras. Indeed, since we only consider the abstract classes of all algebras and never deal with a particular instance, they will stand in perfect bijection.

Definition 7.6.6 (Semantic entailment) *We will write $A \leq_{\mathcal{X}} B$ (resp. $A \simeq_{\mathcal{X}} B$) to express that $A \leq B$ (resp. $A \leq_{\mathcal{X}} B$ and $B \leq_{\mathcal{X}} A$) in every algebra of the class \mathcal{X} . More precisely, \mathcal{X} can be one of $\mathcal{L}, \mathcal{H}, \mathcal{B}, \mathcal{HB}$ or \mathcal{C} , which stand respectively for bounded lattices, Heyting, Brouwer, Heyting-Brouwer and Boolean algebras. We will write $A \leq B$ (resp. $A \simeq B$) as a shorthand for $A \leq_{\mathcal{H}} B$ (resp. $A \simeq_{\mathcal{H}} B$).*

Duality

We now prove a number of lemmas that characterize *duality* both semantically, typically between Heyting and Brouwer algebras, and syntactically in the rules of system B. This will be useful later on to shorten some proofs.

Definition 7.6.7 (Dual formula) *The dual formula \bar{A} of a formula A is*

defined recursively as follows:

$$\begin{array}{ll}
 \bar{a} = a & \bar{\perp} = \top \\
 \bar{\top} = \perp & \bar{\top} = \top \\
 \overline{A \wedge B} = \bar{A} \vee \bar{B} & \overline{A \vee B} = \bar{A} \wedge \bar{B} \\
 \overline{A \supset B} = \bar{B} \subset \bar{A} & \overline{A \subset B} = \bar{B} \supset \bar{A}
 \end{array}$$

Fact 7.6.1 (Duality)

- ▶ $A \leq_{\mathcal{H}} B$ if and only if $\bar{B} \leq_{\mathcal{B}} \bar{A}$
- ▶ $A \leq_{\mathcal{B}} B$ if and only if $\bar{B} \leq_{\mathcal{H}} \bar{A}$
- ▶ $A \leq_{\mathcal{X}} B$ if and only if $\bar{B} \leq_{\mathcal{X}} \bar{A}$ when $\mathcal{X} \in \{\mathcal{HB}, \mathcal{C}\}$.

We omit the proof of Fact ??, but this can easily be obtained from the soundness and completeness of a symmetric sequent calculus for bi-intuitionistic logic, see for instance Lemma 2 of [160].

[160]: Restall (1997), *Extending Intuitionistic Logic with Subtraction*

Definition 7.6.8 (Dual solution) *The dual solution \bar{S} of a solution S is defined mutually recursively as follows:*

$$\begin{array}{ll}
 \overline{\Gamma \triangleright \Delta} = \bar{\Delta} \triangleright \bar{\Gamma} & \overline{S_1; \dots; S_n} = \bar{S}_1; \dots; \bar{S}_n \\
 \bar{A} = \bar{A} & \overline{I_1, \dots, I_n} = \bar{I}_1, \dots, \bar{I}_n \\
 \overline{\Rightarrow} = \Rightarrow & \overline{\langle \mathcal{S} \rangle} = \langle \bar{\mathcal{S}} \rangle
 \end{array}$$

For solution contexts, the hole is self-dual: $\bar{\square} = \square$. This entails in particular that $\bar{S[\bar{T}]} = S[\bar{T}]$.

Graphically, the dual of a solution S is S where the colors of items have been swapped — i.e. blue items become red and red items become blue — and formulas have been dualized (Definition ??).

Definition 7.6.9 *The depth $|I|$ of an item I is defined recursively as follows:*

$$\begin{array}{l}
 |A| = 0 \\
 |\Gamma \Rightarrow \Delta| = 1 + \max_{J \in \Gamma \cup \Delta} |J| \\
 |\Gamma \langle \mathcal{S} \rangle \Delta| = 1 + \max_{J \in \Gamma \cup \mathcal{S} \cup \Delta} |J|
 \end{array}$$

Lemma 7.6.1 (Involutivity) $\bar{\bar{I}} = I$.

Proof. By recurrence on $|I|$.

Formula Suppose $I = A$. Then we conclude by a straightforward induction on A .

Open solution Suppose $I = \Gamma \Rightarrow \Delta$. Then by definition we have $\overline{\overline{\Gamma \Rightarrow \Delta}} = \overline{\bar{\Delta} \Rightarrow \bar{\Gamma}} = \bar{\bar{\Delta}} \Rightarrow \bar{\bar{\Gamma}} = \bar{\bar{\Gamma}} \Rightarrow \bar{\bar{\Delta}}$, and we conclude by IH.

Closed solution Suppose $I = \Gamma \langle \mathcal{S} \rangle \Delta$. Then by definition we have $\overline{\overline{\Gamma \langle \mathcal{S} \rangle \Delta}} = \overline{\overline{\Gamma}} \langle \overline{\overline{\mathcal{S}}} \rangle \overline{\overline{\Delta}} = \overline{\overline{\Gamma}} \langle \overline{\overline{\mathcal{S}}} \rangle \overline{\overline{\Delta}}$, and we conclude by IH.

□

Lemma 7.6.2 (Local rule duality) *If $S \rightarrow T$ then $\bar{S} \rightarrow \bar{T}$.*

Proof. There is a bijection among the rules of system B, that matches each rule $r : S \rightarrow T$ to its dual $\bar{r} : \bar{S} \rightarrow \bar{T}$. By involutivity (Lemma ??), this bijection is self-inverse: $\bar{\bar{r}} = r$. It is most easily observed in the graphical presentation of the rules (Figure ??), where looking for the dual rule boils down to swapping red and blue (and mirroring logical connectives). The mapping goes as follows:

$$\begin{array}{ll}
 i\downarrow \leftrightarrow i\downarrow & w- \leftrightarrow w+ \\
 i\uparrow \leftrightarrow i\uparrow & c- \leftrightarrow c+ \\
 \\
 f- \leftrightarrow f+ & p \leftrightarrow p \\
 f-+\downarrow \leftrightarrow f+-\downarrow & p- \leftrightarrow p+ \\
 f--\uparrow \leftrightarrow f++\uparrow & a \leftrightarrow a \\
 f-+\uparrow \leftrightarrow f+-\uparrow & a- \leftrightarrow a+ \\
 f--\downarrow \leftrightarrow f++\downarrow & \\
 \\
 \top- \leftrightarrow \perp+ & \\
 \perp- \leftrightarrow \top+ & \\
 \wedge- \leftrightarrow \vee+ & \\
 \vee- \leftrightarrow \wedge+ & \\
 \supset- \leftrightarrow \subset+ & \\
 \subset- \leftrightarrow \supset+ & \\
 \forall- \leftrightarrow \exists+ & \\
 \exists- \leftrightarrow \forall+ &
 \end{array}$$

Notice that some rules are self-dual, namely the identity rules $i\downarrow$ and $i\uparrow$, and the membrane rules p and a .

□

Lemma 7.6.3 (Rule duality) *If $S \rightarrow T$ then $\bar{S} \rightarrow \bar{T}$.*

Proof. Let $U\Box$, S_0 and T_0 such that $S = U\Box S_0$, $T = U\Box T_0$ and $S_0 \rightarrow T_0$. By Lemma ?? we have $\bar{S}_0 \rightarrow \bar{T}_0$, and thus $\bar{U}\Box \bar{S}_0 \rightarrow \bar{U}\Box \bar{T}_0$, or equivalently $\overline{U\Box S_0} \rightarrow \overline{U\Box T_0}$.

□

Lemma 7.6.4 (Interpretation duality) $\overline{[\![I]\!]}^+ = [\![\bar{I}]\!]^-$ and $\overline{[\![I]\!]}^- = [\![\bar{I}]\!]^+$.

Proof. By a straightforward recurrence on $|I|$.

□

Lemma 7.6.5 $\llbracket \bar{S} \rrbracket^+ \leq_{\mathcal{X}} \llbracket \bar{T} \rrbracket^+$ if and only if $\llbracket T \rrbracket^- \leq_{\mathcal{X}} \llbracket S \rrbracket^-$ when $\mathcal{X} \in \{\mathcal{HB}, \mathcal{C}\}$.

Proof. By duality (Fact ??) we have $\overline{\llbracket \bar{T} \rrbracket^+} \leq_{\mathcal{X}} \overline{\llbracket \bar{S} \rrbracket^+}$, and then by Lemma ?? $\llbracket \bar{T} \rrbracket^- \leq_{\mathcal{X}} \llbracket \bar{S} \rrbracket^-$. We conclude by involutivity (Lemma ??). \square

Local soundness

In the following we give a number of (in)equalities that hold in the various classes of algebras. They can easily be checked by building derivations in an adequate sequent calculus.

Fact 7.6.2 (Commutativity) $A \vee B \simeq_{\mathcal{L}} B \vee A$ and $A \wedge B \simeq_{\mathcal{L}} B \wedge A$.

Fact 7.6.3 (Idempotency) $A \vee A \simeq_{\mathcal{L}} A$ and $A \wedge A \simeq_{\mathcal{L}} A$.

Fact 7.6.4 (Currying)

$$\begin{aligned} A \supset (B \supset C) &\simeq (A \wedge B) \supset C \\ (A \subset B) \subset C &\simeq_{\mathcal{B}} A \subset (B \vee C) \end{aligned}$$

Fact 7.6.5 (Distributivity)

$$\begin{aligned} A \wedge (B \vee C) &\simeq_{\mathcal{L}} (A \wedge B) \vee (A \wedge C) \\ A \vee (B \wedge C) &\simeq_{\mathcal{L}} (A \vee B) \wedge (A \vee C) \\ A \supset B \wedge C &\simeq (A \supset B) \wedge (A \supset C) \\ A \vee B \supset C &\simeq (A \supset B) \wedge (A \supset C) \\ A \vee B \subset C &\simeq_{\mathcal{B}} (A \subset B) \vee (A \subset C) \\ A \subset B \wedge C &\simeq_{\mathcal{B}} (A \subset B) \vee (A \subset C) \end{aligned}$$

Fact 7.6.6 (Weak distributivity)

$$\begin{aligned} (A \supset B) \vee C &\leq A \supset (B \vee C) \\ A \supset (B \vee C) &\leq_{\mathcal{C}} (A \supset B) \vee C \\ (A \wedge B) \subset C &\leq_{\mathcal{B}} A \wedge (B \subset C) \\ A \wedge (B \subset C) &\leq_{\mathcal{C}} (A \wedge B) \subset C \end{aligned}$$

Fact 7.6.7

$$\begin{aligned} (A \vee B) \wedge (C \supset D) &\leq (A \supset C) \supset (B \vee D) \\ (A \vee B) \wedge (C \supset D) &\leq_{\mathcal{HB}} (A \subset C) \vee (B \vee D) \\ (A \vee B) \wedge (A \supset B) &\simeq B \end{aligned}$$

Fact 7.6.8 $(A \subset B) \supset C \leq_{\mathcal{HB}} A \supset B \vee C$.

The following definition will be used pervasively to reason by induction on the tree structure induced by branching operators:

Definition 7.6.10 The depth $|\triangleright|$ of a branching operator \triangleright is defined recursively as follows:

$$\begin{aligned} |\Rightarrow| &= 0 \\ |\langle \mathcal{S} \rangle| &= 1 + \max_{S \in \mathcal{S}} |S| \end{aligned}$$

Now we can give a few lemmas that generalize some semantic (in)equalities to the interpretation of solutions with arbitrary branching operators. All detailed proofs are available in appendix (Section ??).

Lemma 7.6.6 (Generalized weakening) $\llbracket S \rrbracket^+ \leq \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+$.

Proof. By recurrence on $|\triangleright|$, with $S = \Gamma' \triangleright \Delta'$. □

Lemma 7.6.7 (Generalized contraction) $\llbracket S \uplus (\Rightarrow I, I) \rrbracket^+ \simeq \llbracket S \uplus (\Rightarrow I) \rrbracket^+$ and $\llbracket S \uplus (I, I \Rightarrow) \rrbracket^+ \simeq \llbracket S \uplus (I \Rightarrow) \rrbracket^+$.

Proof. By recurrence on $|\triangleright|$, with $S = \Gamma \triangleright \Delta$. □

Lemma 7.6.8 (Generalized weak distributivity)

$$\llbracket \Gamma \triangleright \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ \leq \llbracket \Gamma \triangleright I, \Delta \rrbracket^+ \quad (7.3)$$

$$\llbracket \Gamma \triangleright I, \Delta \rrbracket^+ \leq_C \llbracket \Gamma \triangleright \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ \quad (7.4)$$

$$\llbracket \Gamma, I \triangleright \Delta \rrbracket^- \leq_B \llbracket I \rrbracket^- \wedge \llbracket \Gamma \triangleright \Delta \rrbracket^- \quad (7.5)$$

$$\llbracket I \rrbracket^- \wedge \llbracket \Gamma \triangleright \Delta \rrbracket^- \leq_C \llbracket \Gamma, I \triangleright \Delta \rrbracket^- \quad (7.6)$$

Proof. (??) holds by recurrence on $|\triangleright|$, using the corresponding inequality from Lemma ?? . The proof of (??) is the same, except that we use the converse inequality of Fact ?? that holds in Boolean algebras. (??) and (??) hold by duality from (??) and (??). □

Lemma 7.6.9 (Generalized currying)

$$\llbracket \Gamma, I \triangleright \Delta \rrbracket^+ \simeq \llbracket I \rrbracket^- \supset \llbracket \Gamma \triangleright \Delta \rrbracket^+ \quad (7.7)$$

$$\llbracket \Gamma \triangleright I, \Delta \rrbracket^- \simeq_B \llbracket \Gamma \triangleright \Delta \rrbracket^- \subset \llbracket I \rrbracket^+ \quad (7.8)$$

Proof. (??) holds by recurrence on $|\triangleright|$, and (??) by duality. □

Lastly, we mention a technical property of rules that will be necessary for the final proof of soundness to go through:

Fact 7.6.9 (Top-level genericity) If $S \rightarrow T$, then $S \cup (\Gamma \Rightarrow \Delta) \rightarrow T \cup (\Gamma \Rightarrow \Delta)$.

All the previous facts and lemmas can now be used to prove *local soundness*, i.e. that the interpretation of each rule of system B maps to an (in)equality in some class of algebras:

Lemma 7.6.10 (Local soundness) If $S \rightarrow T$ then $\llbracket T \cup (\Gamma \Rightarrow \Delta) \rrbracket^+ \leq_{\mathcal{C}} \llbracket S \cup (\Gamma \Rightarrow \Delta) \rrbracket^+$.

Proof. $S \rightarrow T$ implies $\llbracket T \rrbracket^+ \leq_{\mathcal{C}} \llbracket S \rrbracket^+$, which is shown by inspection of each rule of system B (see Section ??). That we can mix an arbitrary top-level context $\Gamma \Rightarrow \Delta$ into S and T follows from Fact ??. \square

Since some rules only hold classically, the statement for the full system is relative to Boolean algebras. But from the detailed proof in Section ??, we can identify two fragments $B_{\mathcal{H}}$ and $B_{\mathcal{HB}}$ of system B that are sound with respect to Heyting and Heyting-Brouwer algebras:

Corollary 7.6.11 Let

$$\begin{aligned} B_{\mathcal{HB}} &\triangleq B \setminus \{f \multimap \uparrow, f \multimap \downarrow, f \multimap \uparrow, f \multimap \downarrow\} \\ B_{\mathcal{H}} &\triangleq B_{\mathcal{HB}} \setminus \{f \multimap \downarrow, f \multimap \uparrow, \multimap, \multimap\} \end{aligned}$$

Then we have:

- $S \rightarrow_{B_{\mathcal{H}}} T$ implies $\llbracket T \rrbracket^+ \leq \llbracket S \rrbracket^+$
- $S \rightarrow_{B_{\mathcal{HB}}} T$ implies $\llbracket T \rrbracket^+ \leq_{\mathcal{HB}} \llbracket S \rrbracket^+$

In order to get the last missing fragment $B_{\mathcal{B}}$ sound with respect to Brouwer algebras, we need dual lemmas that are relative to the negative interpretation $\llbracket \cdot \rrbracket^-$ instead of the positive interpretation $\llbracket \cdot \rrbracket^+$, since implication is replaced by exclusion. To avoid verbosity, we only formulate the main lemma, and assume that its proof will go through mechanically:

Lemma 7.6.12 (Local co-soundness) If $S \rightarrow T$ then $\llbracket S \cup (\Gamma \Rightarrow \Delta) \rrbracket^- \leq_{\mathcal{C}} \llbracket T \cup (\Gamma \Rightarrow \Delta) \rrbracket^-$.

Then from the (assumed) proof of Lemma ?? we get:

Corollary 7.6.13 Let $B_{\mathcal{B}} \triangleq B_{\mathcal{HB}} \setminus \{f \multimap \downarrow, f \multimap \uparrow, \multimap, \multimap\}$. Then $S \rightarrow_{B_{\mathcal{B}}} T$ implies $\llbracket S \rrbracket^- \leq_{\mathcal{B}} \llbracket T \rrbracket^-$.

The full situation is summarized in Figure ??.

Contextual soundness

Lemma 7.6.14 (Functoriality) Let $\mathcal{X} \in \{\mathcal{H}, \mathcal{HB}, \mathcal{C}\}$.

- $\llbracket I \rrbracket^+ \leq_{\mathcal{X}} \llbracket J \rrbracket^+$ implies $\llbracket (\Rightarrow I) \cup S \rrbracket^+ \leq_{\mathcal{X}} \llbracket (\Rightarrow J) \cup S \rrbracket^+$

► $\llbracket J \rrbracket^- \leq_{\mathcal{X}} \llbracket I \rrbracket^-$ implies $\llbracket (I \Rightarrow) \cup S \rrbracket^+ \leq_{\mathcal{X}} \llbracket (J \Rightarrow) \cup S \rrbracket^+$

Proof. Let $S = \Gamma \triangleright \Delta$. We proceed by recurrence on $|\triangleright|$.

Base case Suppose $|\triangleright| = 0$. Then $\triangleright = \Rightarrow$, and we have

$$\begin{aligned} \llbracket (\Rightarrow I) \cup S \rrbracket^+ &= \llbracket \Gamma \Rightarrow I, \Delta \rrbracket^+ \\ &= \llbracket \Gamma \rrbracket^- \supset \llbracket I \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \\ &\leq_{\mathcal{X}} \llbracket \Gamma \rrbracket^- \supset \llbracket J \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \quad (\text{Hypothesis}) \\ &= \llbracket \Gamma \Rightarrow J, \Delta \rrbracket^+ \\ &= \llbracket (\Rightarrow J) \cup S \rrbracket^+ \end{aligned}$$

$$\begin{aligned} \llbracket (I \Rightarrow) \cup S \rrbracket^+ &= \llbracket \Gamma, I \Rightarrow \Delta \rrbracket^+ \\ &= \llbracket \Gamma \rrbracket^- \wedge \llbracket I \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\ &\leq_{\mathcal{X}} \llbracket \Gamma \rrbracket^- \wedge \llbracket J \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \quad (\text{Hypothesis}) \\ &= \llbracket \Gamma, J \Rightarrow \Delta \rrbracket^+ \\ &= \llbracket (J \Rightarrow) \cup S \rrbracket^+ \end{aligned}$$

Recursive case Suppose $|\triangleright| > 0$. Then $\triangleright = \langle \mathcal{S} \rangle$, and for all $S_0 = \Gamma_0 \blacktriangleright \Delta_0 \in \mathcal{S}$ we have that $|\blacktriangleright| < |\triangleright|$. Thus we have

$$\begin{aligned} \llbracket (\Rightarrow I) \cup S \rrbracket^+ &= \llbracket \Gamma \langle \mathcal{S} \rangle I, \Delta \rrbracket^+ \\ &= \bigwedge_{S_0 \in \mathcal{S}} \llbracket (\Gamma \Rightarrow I, \Delta) \cup S_0 \rrbracket^+ \\ &= \bigwedge_{S_0 \in \mathcal{S}} \llbracket (\Rightarrow I) \cup ((\Gamma \Rightarrow \Delta) \cup S_0) \rrbracket^+ \\ &\leq_{\mathcal{X}} \bigwedge_{S_0 \in \mathcal{S}} \llbracket (\Rightarrow J) \cup ((\Gamma \Rightarrow \Delta) \cup S_0) \rrbracket^+ \quad (\text{IH}) \\ &= \bigwedge_{S_0 \in \mathcal{S}} \llbracket (\Gamma \Rightarrow J, \Delta) \cup S_0 \rrbracket^+ \\ &= \llbracket \Gamma \langle \mathcal{S} \rangle J, \Delta \rrbracket^+ \\ &= \llbracket (\Rightarrow J) \cup S \rrbracket^+ \end{aligned}$$

$$\begin{aligned} \llbracket (I \Rightarrow) \cup S \rrbracket^+ &= \llbracket \Gamma, I \langle \mathcal{S} \rangle \Delta \rrbracket^+ \\ &= \bigwedge_{S_0 \in \mathcal{S}} \llbracket (\Gamma, I \Rightarrow \Delta) \cup S_0 \rrbracket^+ \\ &= \bigwedge_{S_0 \in \mathcal{S}} \llbracket (I \Rightarrow) \cup ((\Gamma \Rightarrow \Delta) \cup S_0) \rrbracket^+ \\ &\leq_{\mathcal{X}} \bigwedge_{S_0 \in \mathcal{S}} \llbracket (J \Rightarrow) \cup ((\Gamma \Rightarrow \Delta) \cup S_0) \rrbracket^+ \quad (\text{IH}) \\ &= \bigwedge_{S_0 \in \mathcal{S}} \llbracket (\Gamma, J \Rightarrow \Delta) \cup S_0 \rrbracket^+ \\ &= \llbracket \Gamma, J \langle \mathcal{S} \rangle \Delta \rrbracket^+ \\ &= \llbracket (J \Rightarrow) \cup S \rrbracket^+ \end{aligned}$$

□

In order to ease reasoning by induction on solution contexts, we give a formulation equivalent to Definition ?? as a context-free grammar:

Fact 7.6.10 Solution contexts $S\Box$ are generated by the following grammar:

$$S\Box ::= \Box \mid \Gamma \triangleright S\Box, \Delta \mid \Gamma, S\Box \triangleright \Delta \mid \Gamma \langle \mathcal{S}; S\Box \rangle \Delta$$

Definition 7.6.11 The depth $|S\Box|$ of a solution context $S\Box$ is defined recursively as follows:

$$|\Box| = 0$$

$$|\Gamma \triangleright S\Box, \Delta| = |\Gamma, S\Box \triangleright \Delta| = |\Gamma \langle \mathcal{S}; S\Box \rangle \Delta| = 1 + |S\Box|$$

Lemma 7.6.15 (Contextual soundness) *If $S \rightarrow T$ then $\llbracket U\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \leq_C \llbracket U\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+$.*

Proof. By recurrence on $|U\Box|$.

Base case Suppose $|U\Box| = 0$. Then $U\Box = \Box$, and we conclude by local soundness (Lemma ??).

Positive case Suppose $|U\Box| > 0$ and $U\Box = \Gamma' \triangleright U_0\Box, \Delta'$. Then by IH we have $\llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \leq_C \llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+$, and thus

$$\begin{aligned} \llbracket (\Gamma' \triangleright U_0\Box, \Delta') \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ &= \llbracket (\Rightarrow U_0\Box) \triangleright (\Gamma, \Gamma' \triangleright \Delta', \Delta) \rrbracket^+ \\ &\leq_C \llbracket (\Rightarrow U_0\Box) \triangleright (\Gamma, \Gamma' \triangleright \Delta', \Delta) \rrbracket^+ \quad (\text{Lemma ??}) \\ &= \llbracket (\Gamma' \triangleright U_0\Box, \Delta') \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \end{aligned}$$

Negative case Suppose $|U\Box| > 0$ and $U\Box = \Gamma', U_0\Box \triangleright \Delta'$. Then by Lemma ?? we have $\bar{S} \rightarrow \bar{T}$, and thus by IH $\llbracket \bar{U}_0\bar{\Box} \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \leq_C \llbracket \bar{U}_0\bar{\Box} \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+$,

or equivalently $\llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \leq_C \llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+$. Then by Lemma ?? we get $\llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^- \leq_C \llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^-$, and thus

$$\begin{aligned} \llbracket (\Gamma', U_0\Box \triangleright \Delta') \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ &= \llbracket (U_0\Box \Rightarrow) \triangleright (\Gamma, \Gamma' \triangleright \Delta', \Delta) \rrbracket^+ \\ &\leq_C \llbracket (U_0\Box \Rightarrow) \triangleright (\Gamma, \Gamma' \triangleright \Delta', \Delta) \rrbracket^+ \quad (\text{Lemma ??}) \\ &= \llbracket (\Gamma', U_0\Box \triangleright \Delta') \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \end{aligned}$$

Neutral case Suppose $|U\Box| > 0$ and $U\Box = \Gamma \langle \mathcal{S}; U_0\Box \rangle \Delta$. Then by IH we have $\llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \leq_C \llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+$, and thus

$$\begin{aligned} \llbracket \Gamma \langle \mathcal{S}; U_0\Box \rangle \Delta \rrbracket^+ &= \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^+ \wedge \llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \\ &\leq_C \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^+ \wedge \llbracket U_0\Box \triangleright (\Gamma \Rightarrow \Delta) \rrbracket^+ \\ &= \llbracket \Gamma \langle \mathcal{S}; U_0\Box \rangle \Delta \rrbracket^+ \end{aligned}$$

□

Theorem 7.6.16 (Soundness) *If $S \rightarrow T$ then $\llbracket T \rrbracket^+ \leq_C \llbracket S \rrbracket^+$.*

Proof. By definition of \rightarrow , and then applying Lemma ?? with $\Gamma = \Delta = \emptyset$. □

We also get for free soundness with respect to the negative interpretation, which we call *co-soundness*:

Theorem 7.6.17 (Co-soundness) *If $S \rightarrow T$ then $\llbracket S \rrbracket^- \leq_{\mathcal{C}} \llbracket T \rrbracket^-$.*

Proof. By Lemma ?? we have $\bar{S} \rightarrow \bar{T}$, and thus by soundness $\llbracket \bar{T} \rrbracket^+ \leq_{\mathcal{C}} \llbracket \bar{S} \rrbracket^+$. Then we can conclude by Lemma ??.

As for local soundness (Corollaries ?? and ??), we can easily generalize the proof of Lemma ?? to Heyting and Heyting-Brouwer algebras, and thus extend our soundness result to intuitionistic and bi-intuitionistic logic:

Corollary 7.6.18

- ▶ $S \rightarrow_{\mathcal{B}_{\mathcal{H}}} T$ implies $\llbracket T \rrbracket^+ \leq \llbracket S \rrbracket^+$
- ▶ $S \rightarrow_{\mathcal{B}_{\mathcal{HB}}} T$ implies $\llbracket T \rrbracket^+ \leq_{\mathcal{HB}} \llbracket S \rrbracket^+$

Proof. Lemma ?? is the only lemma used in Lemma ?? that relies on Boolean algebras. Thus we can easily replace it by Corollary ?? to get soundness in Heyting-Brouwer algebras.

For soundness in Heyting algebras, we know that the negative case will never happen because formulas cannot contain exclusions. The other cases only depend on Lemma ??, thus we can again replace it by Corollary ??.

Once again in order to extend contextual soundness to dual-intuitionistic logic, we need to dualize lemmas to the negative interpretation:

Lemma 7.6.19 (Co-functoriality) *Let $\mathcal{X} \in \{\mathcal{B}, \mathcal{HB}, \mathcal{C}\}$.*

- ▶ $\llbracket I \rrbracket^- \leq_{\mathcal{X}} \llbracket J \rrbracket^-$ implies $\llbracket (I \Rightarrow J) \cup S \rrbracket^- \leq_{\mathcal{X}} \llbracket (I \Rightarrow J) \cup S \rrbracket^-$
- ▶ $\llbracket J \rrbracket^+ \leq_{\mathcal{X}} \llbracket I \rrbracket^+$ implies $\llbracket (I \Rightarrow J) \cup S \rrbracket^- \leq_{\mathcal{X}} \llbracket (I \Rightarrow J) \cup S \rrbracket^-$

Lemma 7.6.20 (Contextual co-soundness) *If $S \rightarrow T$ then $\llbracket U[S] \cup (\Gamma \Rightarrow \Delta) \rrbracket^- \leq_{\mathcal{C}} \llbracket U[T] \cup (\Gamma \Rightarrow \Delta) \rrbracket^-$.*

From the assumed proof of Lemma ??, we finally get:

Corollary 7.6.21 $S \rightarrow_{\mathcal{B}_{\mathcal{B}}} T$ implies $\llbracket S \rrbracket^- \leq_{\mathcal{B}} \llbracket T \rrbracket^-$.

Combined with the completeness proof of Section ??, this will give us our main result that $\mathcal{B}_{\mathcal{H}}$, $\mathcal{B}_{\mathcal{B}}$, $\mathcal{B}_{\mathcal{HB}}$ and \mathcal{B} capture exactly provability in intuitionistic, dual-intuitionistic, bi-intuitionistic and classical logic.

7.7 Completeness

We are now going to prove the *completeness* of the bi-intuitionistic (and propositional) fragment $B_{\mathcal{H}\mathcal{B}}$ of system B, by simulating the nested sequent system DBilnt of Postniece. In [154] she shows that this calculus is sound and complete with respect to another calculus LBilnt, and in Chapter 4 of her thesis [155] she proves that LBilnt is sound and complete with respect to the Kripke semantics of bi-intuitionistic logic. Importantly, the cut rule is shown to be *admissible* in both systems, through a syntactic process of cut-elimination in LBilnt. We will rely on this result to obtain admissibility of the cut rule $i\uparrow$ in $B_{\mathcal{H}\mathcal{B}}$, and by extension in B, $B_{\mathcal{H}}$ and $B_{\mathcal{B}}$. It might be interesting to have our own internal cut-elimination procedure for system B, notably to unveil its computational content in the spirit of the Curry-Howard correspondence. But this would lead us astray from the purpose of this thesis, and thus we leave this task for future work.

[154]: Postniece (2009), ‘Deep Inference in Bi-intuitionistic Logic’

[155]: Postniece (2010), ‘Proof theory and proof search of bi-intuitionistic and tense logic’

Definition 7.7.1 (Structure) *The structures of DBilnt are generated by the following grammar:*

$$X, Y ::= \emptyset \mid A \mid (X, Y) \mid X \Vdash Y$$

The structural connective “,” (comma) is associative and commutative and \emptyset is its unit. We always consider structures modulo these equivalences.

Definition 7.7.2 (Structure translation) *The translation X^\bullet of a structure X as a multiset of items Γ is defined recursively as follows:*

$$\begin{aligned} \emptyset^\bullet &= \emptyset & (X, Y)^\bullet &= X^\bullet, Y^\bullet \\ A^\bullet &= A & (X \Vdash Y)^\bullet &= X^\bullet \Rightarrow Y^\bullet \end{aligned}$$

Note that the translation $(-)^{\bullet}$ is clearly *injective*: in fact structures are isomorphic to multisets of items that contain only *open* subsolutions. Thus from now on, we will always apply the translation implicitly, and rely on meta-variables X, Y to distinguish structures from arbitrary solutions when necessary.

The rules of DBilnt are given in Figure ???. Note that like bubble calculi, DBilnt is truly a *deep inference* system, in the sense that rules can be applied on sequents nested arbitrarily deep inside structures²². The main difference lies in the fact that proofs in DBilnt are *trees* built up by composing traditional inference rules with multiple premisses, while we use closed solutions (neutral bubbles) to internalize the tree structure of proofs inside solutions. This gives a lot of expressive power since closed solutions can themselves be nested in open solutions and thus *polarized*, a phenomenon which cannot be simulated in DBilnt. This is why we did not prove soundness in Section ?? by simulating directly system B in DBilnt, and conversely this will explain the ease with which DBilnt can be simulated inside system B.

22: Our presentation of rules is slightly different from [154]: the contexts in which rules apply are left implicit, and thus we do not rely on their polarity. The counterpart is that rules always apply on sequents and never on formulas, which makes them more verbose. Also we do not rely on the notion of “top-level formulas” of a structure, making the propagation rules yet more verbose.

Definition 7.7.3 (Syntactic entailment) *We say that Γ entails Δ in a fragment F of rules of system B, written $\Gamma \vdash_F \Delta$, if and only if $\Gamma \Rightarrow \Delta \rightarrow_F^* \langle \rangle$. Similarly, we say that X entails Y in a fragment F of rules of DBilnt, written*

IDENTITY		PROPAGATION	
$\frac{}{X, A \Rightarrow A, Y} \text{ id}$		$\frac{X, A, (X', A \Rightarrow Y') \Rightarrow Y}{X, (X', A \Rightarrow Y') \Rightarrow Y} \Rightarrow_{L1}$	$\frac{X \Rightarrow (X' \Rightarrow A, Y'), A, Y}{X \Rightarrow (X' \Rightarrow A, Y'), Y} \Rightarrow_{R1}$
		$\frac{X, A \Rightarrow (X', A \Rightarrow Y'), Y}{X, A \Rightarrow (X' \Rightarrow Y'), Y} \Rightarrow_{L2}$	$\frac{X, (X' \Rightarrow A, Y') \Rightarrow A, Y}{X, (X' \Rightarrow Y') \Rightarrow A, Y} \Rightarrow_{R2}$
LOGIC			
$\frac{}{X, \perp \Rightarrow Y} \perp_L$		$\frac{}{X \Rightarrow \top, Y} \top_R$	
$\frac{X, A \wedge B, A, B \Rightarrow Y}{X, A \wedge B \Rightarrow Y} \wedge_L$		$\frac{X \Rightarrow A, A \wedge B, Y \quad X \Rightarrow B, A \wedge B, Y}{X \Rightarrow A \wedge B, Y} \wedge_R$	
$\frac{X, A \vee B, A \Rightarrow Y \quad X, A \vee B, B \Rightarrow Y}{X, A \vee B \Rightarrow Y} \vee_L$		$\frac{X \Rightarrow A, B, A \vee B, Y}{X \Rightarrow A \vee B, Y} \vee_R$	
$\frac{X, A \supset B \Rightarrow A, Y \quad X, A \supset B, B \Rightarrow Y}{X, A \supset B \Rightarrow Y} \supset_L$		$\frac{X \Rightarrow (A \Rightarrow B), A \supset B, Y}{X \Rightarrow A \supset B, Y} \supset_R$	
$\frac{X, A \subset B, (A \Rightarrow B) \Rightarrow Y}{X, A \subset B \Rightarrow Y} \subset_L$		$\frac{X \Rightarrow A, A \subset B, Y \quad X, B \Rightarrow A \subset B, Y}{X \Rightarrow A \subset B, Y} \subset_R$	

Figure 7.12: Rules of the deep nested sequent system DBilnt

$X \mid_F Y$, if and only if $X \Rightarrow Y$ has a proof in DBilnt using only rules in F.

Lemma 7.7.1 (Simulation of DBilnt) *If $X \mid_{\text{DBilnt}} Y$ then $X \mid_{B_{\mathcal{HB}} \setminus \{\uparrow\}} Y$.*

Proof. By induction on the derivation of $X \mid_{\text{DBilnt}} Y$. The detailed proof is available in appendix (Section ??). \square

Assuming that the consequence relation of the Kripke semantics used by Postniece to prove the completeness of DBilnt coincides with the order relation of Heyting-Brouwer algebras, we get the following fact:

Fact 7.7.1 (Completeness of DBilnt) *If $A \leq_{\mathcal{HB}} B$ then $A \mid_{\text{DBilnt}} B$.*

Combined with the simulation of DBilnt from Lemma ??, this gives us the *cut-free* completeness of $B_{\mathcal{HB}}$:

Theorem 7.7.2 (Cut-free completeness) *If $A \leq_{\mathcal{HB}} B$ then $A \mid_{B_{\mathcal{HB}} \setminus \{\uparrow\}} B$.*

In fact there are other rules of $B_{\mathcal{HB}}$ that were not used in the simulation, namely the F-rule \uparrow , and all M-rules other than p. Combined with the

soundness of B_{HB} (Corollary ??), this gives us the following *admissibility* theorem:

Theorem 7.7.3 (Admissibility) *If $\frac{}{B_{HB}} A$ then $\frac{}{B_{HB} \setminus \{i\uparrow, f\uparrow, p-, p+, a-, a+\}} A$.*

Although these rules are admissible, they do not seem to be derivable from other rules. We believe that they might help in making proofs more *compact* by improving *factorizability*, just like the cut rule does.

As in sequent calculus, every rule of system B other than $i\uparrow$ satisfies the *subformula property*:

Fact 7.7.2 (Subformula property) *If $S \rightarrow_{B \setminus \{i\uparrow\}} T$ and $A < T$, then there is a formula B such that A is a subformula of B and $B < S$.*

Thanks to cut admissibility, we thus get that B_{HB} is *analytic*. This has many nice consequences, a well-known one being that when searching for a proof of a given solution S , one does not need to come up with or “invent” a formula that does not appear in S . This is crucial when designing *automated* decision procedures because it reduces drastically the search space, but is also desirable in the setting of *interactive* proof building. Indeed with our Proof-by-Action interpretation of bubble calculi (Section ??), this means that all logical reasoning can be performed by direct manipulation of *what is already there*. Then the cut rule is indispensable, but confined to a role of *theory building*: it allows the creation of *lemmas*, in order to make proofs shorter and more tractable by humans.

As noted in [154], one can simply ignore rules related to the exclusion connective \complement to get a sound and complete system for intuitionistic logic. In DBilnt, these rules are the introduction rules \complement_r and \complement_l , as well as the propagation rules \Rightarrow_{L1} and \Rightarrow_{R2} . Indeed the latter are only useful in combination with the former, since \complement_l is the only rule of DBilnt that can introduce nested sequents in negative contexts. The situation is similar in system B, and in fact the proof of Lemma ?? shows that the intuitionistic fragment B_H is sufficient to simulate DBilnt without the aforementioned rules. The dual argument can be made for dual-intuitionistic logic, and thus we obtain (cut-free) intuitionistic (resp. dual-intuitionistic) completeness of B_H (resp. B_B):

Corollary 7.7.4 (Intuitionistic completeness)

- If $A \leq_H B$ then $A \frac{}{B_H \setminus \{i\uparrow\}} B$.
- If $A \leq_B B$ then $A \frac{}{B_B \setminus \{i\uparrow\}} B$.

Figure ?? shows a proof of the double-negation elimination law $DNE \triangleq \neg\neg A \Rightarrow A$ in system B. Since B_H is intuitionistically complete, the well-known double-negation embedding of classical logic into intuitionistic logic tells us that $\neg\neg A$ is provable in B_H (and a fortiori in B) if A is a theorem of classical logic. Combining the two previous facts, we obtain the classical completeness of system B. In fact the proof of DNE only relies on the use of the $f++\downarrow$ rule, so we can make the following stronger statement:

$$\begin{array}{c}
 \frac{}{\langle \rangle} p \\
 \frac{}{\langle \langle \rangle \rangle} p \\
 \frac{}{\langle \Rightarrow (\langle \rangle) \rangle} p+ \\
 \frac{}{\langle \Rightarrow (A \Rightarrow A) \rangle} i\downarrow \\
 \frac{}{\langle \Rightarrow (A \Rightarrow), A \rangle} f++\downarrow \\
 \frac{}{\langle \Rightarrow (A \Rightarrow) \rangle A} f+\downarrow \\
 \frac{}{\langle \Rightarrow (A \Rightarrow); \langle \rangle \rangle A} p \\
 \frac{}{\langle \Rightarrow (A \Rightarrow); \perp \Rightarrow \rangle A} \perp- \\
 \frac{}{\langle \Rightarrow (A \Rightarrow \perp); \perp \Rightarrow \rangle A} \perp+ \\
 \frac{}{\langle \Rightarrow \neg A; \perp \Rightarrow \rangle A} \supset+ \\
 \frac{}{\neg\neg A \Rightarrow A} \supset-
 \end{array}$$

Figure 7.13: Proof of DNE in system B

Corollary 7.7.5 (Classical completeness) *If A is a theorem of classical logic, then $\frac{}{\text{B}_{\mathcal{H}} \cup \{f++\downarrow\}} A$.*

Proof. By the double-negation embedding, we have $\frac{}{\text{B}_{\mathcal{H}}} \neg\neg A$. Then we can build the following derivation:

$$\begin{array}{c}
 \frac{\langle \rangle}{\langle \rangle} \text{p} \\
 \frac{\langle \rangle}{\langle \rangle} \text{DNE} \\
 \frac{\langle \neg\neg A \Rightarrow A \rangle}{\langle \neg\neg A \Rightarrow \rangle A} f+\downarrow \\
 \frac{\langle \rangle; \neg\neg A \Rightarrow \rangle A}{\langle \Rightarrow \neg\neg A; \neg\neg A \Rightarrow \rangle A} \text{p} \\
 \frac{\dots \dots \dots}{\langle \Rightarrow \neg\neg A; \neg\neg A \Rightarrow \rangle A} \text{i}\uparrow \\
 \Rightarrow A
 \end{array}$$

□

Alas this argument makes use of the $\text{i}\uparrow$ rule. Note however that the reason we chose to prove completeness of $\text{B}_{\mathcal{HB}}$ by simulating a rather exotic system like DBilnt, was that standard sequent calculi for bi-intuitionistic logic like the one of Rauszer [157] are not *cut-free* complete; and in our literature review, DBilnt was the cut-free system closest in its syntax and rules to system B. But for classical logic we do not have this limitation, and thus it is straightforward to simulate directly a cut-free sequent calculus such as G3cp [134]:

[157]: Rauszer (1974), ‘A Formalization of the Propositional Calculus of H-B Logic’

[134]: Negri et al. (2001), *Structural Proof Theory*

Lemma 7.7.6 (Simulation of G3cp) *If $\Gamma \frac{}{\text{G3cp}} \Delta$, then $\Gamma \frac{}{\text{B}_{\mathcal{H}} \cup \{f++\downarrow\} \setminus \{\text{i}\uparrow\}} \Delta$.*

Proof. By induction on the G3cp derivation, see Section ?? for the detailed proof. □

Lastly, let us mention a recent result of Goré and Shillito [75], where they uncover a distinction between a *weak* and a *strong* consequence relation in the semantics of bi-intuitionistic logic. Although they define the same set of theorems, these two relations have different properties at the meta-level, and thus the authors argue that they define two distinct logics, called respectively wBIL and sBIL. At the end of the article, they conjecture that the various existing calculi in the literature are sound and complete for wBIL, including a calculus designed by Postniece. Since our completeness proof is by simulation of the system DBilnt by the same author, we follow this conjecture regarding the completeness of the bi-intuitionistic fragment $\text{B}_{\mathcal{HB}}$ of system B. For soundness, we would need to clarify the relationship between Heyting-Brouwer algebras and these consequence relations, which stem instead from an analysis of the Kripke semantics of bi-intuitionistic logic. Since system B offers a very expressive syntax, it would be interesting to investigate its ability to capture both wBIL and sBIL, maybe by using distinct sets of flow rules. Goré and Shillito suggest that a framework that captures both *provability* and *refutability* “in one shot” would be needed, and we believe system B

might just provide this: indeed a derivation $S \rightarrow^* \langle \rangle$ can be read both as a *proof* of $\llbracket S \rrbracket^+$, and a *refutation* of $\llbracket S \rrbracket^-$.

7.8 Invertible calculus

Modifying rules

An important thing to note, is that all the rules of DBilnt are *invertible*²³. Thus it follows immediately from Lemma ?? that one can just take the translation of the rules of DBilnt in system B, and get a complete, fully invertible calculus. But this would be a waste of the expressive power and nice properties of system B, like linearity and locality.

Instead, we will target precisely the non-invertible rules of system B, and modify only those. From the proof of Lemma ??, we can identify which rules of system B are invertible, and which are probably not. Indeed if the soundness of a rule only relies on a chain of equivalences, then it is necessarily invertible. On the contrary if it relies on an inequality, then it is probably not invertible²⁴.

Fact 7.8.1 (Invertibility of system B) All rules in the fragment $\mathbb{I} \cup \{c-, c+\} \cup \mathbb{M} \cup \mathbb{H} \setminus \{\supset-, \supset+\}$ of system B are invertible.

Thus the only remaining rules of system B that are (most probably) not invertible are the weakening rules $\{w-, w+\}$, all the F-rules, and the H-rules $\{\supset-, \supset+\}$ that *apply* an implication/exclusion²⁵. In Figure ?? we define the B_{inv} calculus, which results from the following modifications to the previous rules:

Weakening Here we follow a standard technique in sequent calculus, that merges the weakening rule in all *terminal* rules of the calculus (i.e. rules with no premisses). In bubble calculi, the notion of premiss is captured by neutral bubbles; thus we incorporate weakenings in all rules that solve subgoals by closing solutions with no neutral bubbles. Those are the rules $\{i\downarrow, p-, p+\}$, which for the occasion have also been generalized to arbitrary solutions. Indeed in system B we restricted them to open solutions to make them *local*, but here the weakenings break locality anyway, and the general version improves *factorizability* by solving instantly all subgoals inside \triangleright .

Flow As shown by the simulation of Lemma ??, the *propagation* rules of DBilnt combine an instance of *contraction* followed by the application of a flow rule on the duplicated formula. Thus we can make all F-rules of system B invertible by systematically duplicating the moved formula, although this breaks *linearity*.

A downside of propagation rules in the style of DBilnt, is that they create a lot of unnecessary copies of the moved formula A . Often, one will want to move A in a subgoal/supergoal at a distance n in the proof tree, with $n > 1$. Usually this would be performed by n applications of F-rules, which by linearity indeed just move the formula. But with propagation rules, n copies of A will be created, with one copy in each subgoal met on the path to the destination.

23: Lemma 5.2.4 in Postniece's thesis [155].

24: To ensure that it is not invertible, we would need additionally to find a counter-model that invalidates the converse inequality.

25: For quantifier rules, we conjecture that as in sequent calculus, the rules $\{\forall+, \exists-\}$ are invertible, while the rules $\{\forall-, \exists+\}$ are not. And as in sequent calculus, this can be remedied by systematically duplicating the instantiated formula.

IDENTITY		
$\frac{\langle \rangle}{\Gamma, A \triangleright A, \Delta} \text{ i}\downarrow$		
FLOW		
$\frac{\Gamma, I \langle \Gamma', I \blacktriangleright \Delta'; \mathcal{S} \rangle \Delta}{\Gamma, I \langle \Gamma' \blacktriangleright \Delta'; \mathcal{S} \rangle \Delta} \text{ f-}\downarrow$ $\frac{\Gamma, I \triangleright (\Gamma', I \blacktriangleright \Delta'), \Delta}{\Gamma, I \triangleright (\Gamma' \blacktriangleright \Delta'), \Delta} \text{ f-}\downarrow$ $\frac{\Gamma, I, (\Gamma', I \blacktriangleright \Delta') \triangleright \Delta}{\Gamma, (\Gamma', I \blacktriangleright \Delta') \triangleright \Delta} \text{ f-}\uparrow$ $\frac{\Gamma, I \triangleright (\Gamma', I \blacktriangleright \Delta'), \Delta}{\Gamma \triangleright (\Gamma', I \blacktriangleright \Delta'), \Delta} \text{ f-}\uparrow$ $\frac{\Gamma, I, (\Gamma', I \blacktriangleright \Delta') \triangleright \Delta}{\Gamma, I, (\Gamma' \blacktriangleright \Delta') \triangleright \Delta} \text{ f-}\downarrow$	$\frac{\Gamma \langle \mathcal{S}; \Gamma' \blacktriangleright I, \Delta' \rangle I, \Delta}{\Gamma \langle \mathcal{S}; \Gamma' \blacktriangleright \Delta' \rangle I, \Delta} \text{ f+}\downarrow$ $\frac{\Gamma, (\Gamma' \blacktriangleright I, \Delta') \triangleright I, \Delta}{\Gamma, (\Gamma' \blacktriangleright \Delta') \triangleright I, \Delta} \text{ f+}\downarrow$ $\frac{\Gamma \triangleright (\Gamma' \blacktriangleright I, \Delta'), I, \Delta}{\Gamma \triangleright (\Gamma' \blacktriangleright I, \Delta'), \Delta} \text{ f+}\uparrow$ $\frac{\Gamma, (\Gamma' \blacktriangleright I, \Delta') \triangleright I, \Delta}{\Gamma, (\Gamma' \blacktriangleright \Delta') \triangleright I, \Delta} \text{ f+}\uparrow$ $\frac{\Gamma \triangleright (\Gamma' \blacktriangleright I, \Delta'), I, \Delta}{\Gamma \triangleright (\Gamma' \blacktriangleright \Delta'), I, \Delta} \text{ f+}\downarrow$	MEMBRANE
$\frac{\Gamma \langle \mathcal{S} \rangle \Delta}{\Gamma \langle \mathcal{S}; \langle \rangle \rangle \Delta} \text{ p}$ $\frac{\langle \rangle}{\Gamma, (\langle \rangle) \triangleright \Delta} \text{ p-} \quad \frac{\langle \rangle}{\Gamma \triangleright (\langle \rangle), \Delta} \text{ p+}$ $\frac{\Gamma \langle S \rangle \Delta}{\Gamma \langle \langle S \rangle \rangle \Delta} \text{ a}$ $\frac{\Gamma, S \triangleright \Delta}{\Gamma, (\langle S \rangle) \triangleright \Delta} \text{ a-} \quad \frac{\Gamma \triangleright S, \Delta}{\Gamma \triangleright (\langle S \rangle), \Delta} \text{ a+}$		
HEATING		
$\frac{\Gamma \triangleright \Delta}{\Gamma, \top \triangleright \Delta} \top-$ $\frac{\Gamma, (\langle \rangle) \triangleright \Delta}{\Gamma, \perp \triangleright \Delta} \perp-$ $\frac{\Gamma, A, B \triangleright \Delta}{\Gamma, A \wedge B \triangleright \Delta} \wedge-$ $\frac{\Gamma \langle A \Rightarrow; B \Rightarrow \rangle \Delta}{\Gamma, A \vee B \Rightarrow \Delta} \vee-$ $\frac{\Gamma, A \supset B \langle \Rightarrow A; B \Rightarrow \rangle \Delta}{\Gamma, A \supset B \Rightarrow \Delta} \supset-$ $\frac{\Gamma, (A \Rightarrow B) \triangleright \Delta}{\Gamma, A \subset B \triangleright \Delta} \subset-$ $\frac{\Gamma, \forall x. A, A\{t/x\} \triangleright \Delta}{\Gamma, \forall x. A \triangleright \Delta} \forall-$ $\frac{\Gamma, A \triangleright \Delta}{\Gamma, \exists x. A \triangleright \Delta} \exists-$	$\frac{\Gamma \triangleright (\langle \rangle), \Delta}{\Gamma \triangleright \top, \Delta} \top+$ $\frac{\Gamma \triangleright \Delta}{\Gamma \triangleright \perp, \Delta} \perp+$ $\frac{\Gamma \langle \Rightarrow A; \Rightarrow B \rangle \Delta}{\Gamma \Rightarrow A \wedge B, \Delta} \wedge+$ $\frac{\Gamma \triangleright A, B, \Delta}{\Gamma \triangleright A \vee B, \Delta} \vee+$ $\frac{\Gamma \triangleright (A \Rightarrow B), \Delta}{\Gamma \triangleright A \supset B, \Delta} \supset+$ $\frac{\Gamma \langle \Rightarrow A; B \Rightarrow \rangle A \subset B, \Delta}{\Gamma \Rightarrow A \subset B, \Delta} \subset+$ $\frac{\Gamma \triangleright A, \Delta}{\Gamma \triangleright \forall x. A, \Delta} \forall+$ $\frac{\Gamma \triangleright A\{t/x\}, \exists x. A, \Delta}{\Gamma \triangleright \exists x. A, \Delta} \exists+$	
In the $\forall+$ and $\exists-$ rules, x is not free in Γ, Δ and \triangleright .		

Figure 7.14: Rules for the invertible bubble calculus B_{inv}

To prevent this, one would need a way to copy formulas at an arbitrary distance. This can be done with inference rules that are *doubly* deep, by encoding the path to the destination as a second solution context inside the context where the rule is applied²⁶. It turns out to be hard to express in bubbles, because this requires a syntactic way to describe contexts that correspond to valid flow paths of arbitrary length²⁷. But in principle it should be feasible, and would enable a more comfortable use in a Proof-by-Action setting.

Note also that we removed the $f\uparrow$ rule of Figure ?? . Indeed even after turning it into a propagation rule, the moved copy of the duplicated subgoal S cannot be weakened because it lives in a neutral bubble. Thus the rule stays non-invertible, and cannot be included in B_{inv} . Fortunately, we showed that it is admissible in Theorem ??, so this is not problematic.

Implication/Exclusion The last source of non-invertibility is the \mathbb{H} -rules $\supset-$ and $\subset+$, that respectively allow to use an implication hypothesis, and prove an exclusion conclusion. Here we can just duplicate the implication/exclusion formula, as in the introduction rules of $DBilnt$. Also like in $DBilnt$, we removed the contraction rules $c-$ and $c+$, which are now merged with these two rules as well as the F -rules. Although contraction rules are invertible, they induce a lot of complexity in proof search, because it is hard to predict the (occurrences of) formulas that need to be duplicated, and one can duplicate *ad infinitum*. Thus it is preferable to design a calculus where they are admissible. But unlike what is done in $DBilnt$, we did not incorporate contractions in other \mathbb{H} -rules. Thus we cannot simulate exactly all the introduction rules of $DBilnt$ in B_{inv} .

Remark 7.8.1 We also changed the $\perp-$ and $\top+$ rules, so that they create polarized, closed empty solutions. This makes them both local, and generic with respect to the status of the ambient solution. The previous version can then be simulated by combination with the popping rules $p-$ and $p+$.

These modifications only change superficially the proof of soundness, and thus we do not redo it. As for completeness, we would need to prove that the contraction rules are admissible, in order to solve the aforementioned problem of simulating $DBilnt$'s introduction rules:

Lemma 7.8.1 (Admissibility of contraction)

- If $\frac{}{B_{inv}} S \boxed{\Gamma, A, A \triangleright \Delta}$, then $\frac{}{B_{inv}} S \boxed{\Gamma, A \triangleright \Delta}$.
- If $\frac{}{B_{inv}} S \boxed{\Gamma \triangleright A, A, \Delta}$, then $\frac{}{B_{inv}} S \boxed{\Gamma \triangleright A, \Delta}$.

Note that it is sufficient to prove admissibility of contraction on formulas, rather than on arbitrary items. Indeed we only need it to simulate the introduction rules of $DBilnt$, which always duplicate formulas. For now we only conjecture completeness of B_{inv} , since it not clear what method should be used to prove Lemma ?? . In her thesis [155] (Lemma 5.2.3), Postniece does a proof by recurrence on the depth of the derivation,

26: Such rules are sometimes called *super-switch* rules in the deep inference literature, see for instance Chapter 8, Section 2.1 of [82].

27: This problem is solved trivially in the flower calculus (Chapter ??), by using so-called *pollination* rules.

relying on the fact that all introduction rules of DBilnt preserve the principal formula; but this is precisely what we are trying to avoid with our version of the rules. Of course, if we either give up on this constraint or include contraction rules in B_{inv} , then we immediately get our desired result: B_{inv} is a fully invertible calculus, where the same fragments as system B capture intuitionistic, dual-intuitionistic, bi-intuitionistic and classical logic.

Semi-automated proof search

In the intuitionistic (propositional) fragment of B_{inv} , a canonical way to search for a proof of a formula A consists in the following 5 *phases*, applied successively in a loop until the empty closed solution is reached:

Decomposition Decompose A by applying recursively H -rules, until either atoms, negative implications \supset , negative disjunctions \vee , or positive conjunctions \wedge are reached. Indeed since the \supset -rule duplicates the implication, it cannot be used to decompose it.

As for the \vee - and \wedge -rules, they can only be applied when the formula is in an *open* solution. A first option is to let the system automatically distribute them in all open subsolutions that are reachable, so that it can keep decomposing them. But this might create an explosion in the number of created subgoals. Another option is to let the user manually decompose them. We believe this second option is preferable, if one wants to keep control over the proof search process. Indeed, it is only natural that the user should be able to choose which *cases* to consider when building a proof.

Absorption Apply the absorption rules $\{a, a-, a+\}$ wherever possible. This will prevent atoms from being unnecessarily stuck on neutral membranes in the next phase. This phase can also be trivially automated.

Linking Try to bring together every pair of dual atoms, so that they annihilate each other in an instance of the $i\downarrow$ rule. This is reminiscent of our *drag-and-drop* actions of Chapter ???. In a touch-based GUI, rather than dragging a complex formula onto another complex formula, one could *pinch* together the two atoms: if there is no F -law sticking one of the atoms on some membrane (orange arrows in Figure ??), then the pinch succeeds, by closing the subsolution at the location where it ends with $i\downarrow$. Thus the user can choose the subgoal to solve by controlling the destination of the pinch, which can be seen as a more symmetric and powerful version of DnD actions. Generally though, one will want to apply the following *rule of thumb* (pun intended):

Fact 7.8.2 (Rule of thumb) When linking a pair of dual atoms, follow these steps:

1. put your *thumb* on the *outermost* atom, and your *index* on the *innermost* atom;
2. try to bring your index to your thumb;

3. if you get stuck on a membrane, try to bring your thumb to your index;
4. if you again get stuck, then give up on this pair.

The point of this heuristic, is that it should maximize the *factorization* of the proof: when it succeeds, it will solve the subgoal that is located closest to the root of the goal, maximizing the size of the pruned branch, and thus the number of subgoals solved in one go. It can also be used to completely automate this phase.

Popping Pop every closed empty bubble in the goal with the rules $\{p, p-, p+\}$. This phase can also be trivially automated, and corresponds to the unit elimination phase in subformula linking (Section ??).

Application When there are no more pairs of dual atoms, or all the remaining pairs have been given up (last step of the rule of thumb), let S be the current goal, and

$$\text{imp}(S) \triangleq \{(S_0\Box, A, B, \triangleright, \Delta) \mid S = S_0\Box \Gamma, A \supset B \triangleright \Delta \text{ for some } \Gamma\}$$

If $\text{imp}(S) = \emptyset$, then S should not be provable, and we can stop the proof search procedure. Otherwise for each $(S_0\Box, A, B, \triangleright, \Delta) \in \text{imp}(S)$, we might need to apply the $\supset-$ rule on $A \supset B$, either directly in $S_0\Box$ if $\triangleright = \Rightarrow$ and $\max_{I \in \Delta} |I| = 0$ (Definition ??), otherwise in some subgoal $T\Box \in \triangleright \cup \Delta$. This is where the proof needs *insight*, because it is not clear if the antecedent A will be provable with the context available in $S_0\Box$ or in one of the $T\Box$, or if the hypothesis B is even needed at all.

A first possibility is to let the user rely on her intuition, by choosing manually a specific subsolution in $\text{imp}(S)$ to apply the $\supset-$ rule upon. Additionally, she might need to determine a subgoal $T\Box$ in which A is provable, and first duplicate $A \supset B$ in $T\Box$ before applying $\supset-$. This will always be possible with the F-rules $f-\downarrow$ and $f-\uparrow$. Ideally, she would also pick the most general $T\Box$ to factorize the proof, by minimizing its depth $|T\Box|$ (Definition ??).

A second possibility is to duplicate eagerly every $A \supset B$ of $\text{imp}(S)$ in every open subsolutions of S where it can be so, and then apply $\supset-$ on all the newly created copies. To avoid an explosion of the size of S , the system should mark all the copies as *used*, so that during the next **Application** phases, all the already *used* copies are ignored, and only the original occurrence of $A \supset B$ is considered.

Then we can restart the procedure, by applying the **Decomposition** phase to every copy of A and B .

Remark 7.8.2 By adopting H-rules in the style of DBInt's introduction rules, we would make the **Decomposition** phase, and thus the whole procedure inoperable, since the **Linking** phase depends crucially on it. Allowing contraction rules would also jeopardize the potential completeness of the procedure, because contractions might be needed at unpredictable moments, and on unpredictable formulas.

A strength of our proof search procedure, compared to the state-of-the-art in other formalisms, is that most of its automation preserves the *size* (number of atoms) and the *structure* of the goal:

- ▶ In the **Decomposition** phase, if we opt out of the automatic distribution of negative \neg and positive \wedge , then the system will only apply H-rules that split logical connectives, and create a *partition* of the atoms of the goal by enclosing them in bubbles. Thus the size of the goal is kept intact, and the structure modified but in a controlled, local way.
- ▶ In the **Absorption** phase, we simply merge some membranes together, preserving both the size and the structure of the goal.
- ▶ In the **Linking** phase, the particular way in which we use F-rules ensures that we only decrease the number of atoms. Indeed, if we assume as discussed earlier that we have “super-flow” rules that copy at a distance, then either:
 1. the link is successful, and the two created copies of atoms are immediately destroyed by the $i\downarrow$ rule. Then the solved subsolution is entirely pruned out, decreasing the size of the goal; or
 2. the link fails, but then we can instantly “undo” it. Or rather, one should consider that rules are applied only when the link is successful.
- ▶ In the **Popping** phase, entire branches of the goal are pruned out, decreasing the size of the goal.

Then only the automation of the **Application** phase (and part of the **Decomposition** phase) is susceptible of both significantly increasing the size of the goal, and altering its global structure. But as is the case for every phase, the user can easily opt out of this automation, and do the reasoning manually when it is necessary to keep the goal understandable by humans. Typically in an educational setting, it should be quite instructive to have the ability to perform **Decomposition** and **Linking** by hand (literally).

Failure of full iconicity

Because of the implicit contraction in the rules $\supset-$ and $\subset+$, one cannot fully decompose a formula into an equivalent solution by deterministically applying a sequence of H-rules (and possibly F-rules, to distribute positive conjunctions and negative disjunctions). Thus B_{inv} fails to be *fully iconic*, because it relies on the *symbolic* connectives \supset and \subset to represent logical statements.

This can be understood as resulting from the inability of solutions to represent natively *negative implications* and *positive subtractions*, although they can represent natively all other polarizations of connectives. This is illustrated by the mapping of Figure ?? from polarized formulas to equivalent solutions, which is really just the H-rules of system B (Figure ??) where the right-hand solution is enclosed in a bubble of the corresponding polarity. The reader can easily check that if A is mapped to S , then $\llbracket A \rrbracket^+ \simeq \llbracket S \rrbracket^+$.

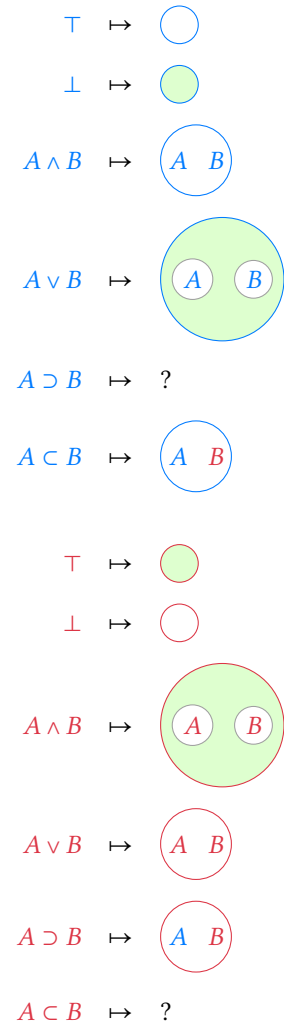


Figure 7.15: Mapping of formulas to equivalent solutions

$$\frac{\Gamma, (\Delta, A \Rightarrow B) \Rightarrow C}{\Gamma, (\Delta \Rightarrow A \supset B) \Rightarrow C} e$$

Figure 7.16: Left introduction rule for \supset in JN

This seems to be a fundamental limitation of system B, caused by its symmetric treatment of implication and subtraction. For instance in the nested sequent calculus JN of Guenot for implicative logic [82, Chapter 3], which is fully decomposable, nested sequents that appear in negative contexts are interpreted as implications, as illustrated by the left introduction rule e (Figure ??). But we cannot do this in system B, because this would conflict with the subtractive reading of negative solutions, i.e. $\llbracket A \Rightarrow B \rrbracket^- = \llbracket A \rrbracket^- \subset \llbracket B \rrbracket^-$. In Chapter ??, the problem will also be solved through an asymmetric treatment of nested sequents, capturing only intuitionistic logic instead of bi-intuitionistic logic. But this is a small price to pay, since bi-intuitionistic logic does not (currently) have any applications in the realm of interactive theorem proving.

The System of Existential Graphs which I have now sufficiently described — or, at any rate, have described as well as I know how, leaving the further perfection of it to others — greatly facilitates the solution of problems of Logic, as will be seen in the sequel, not by any mysterious properties, but simply by substituting for the symbols in which such problems present themselves, concrete visual figures concerning which we have merely to say whether or not they admit certain describable relations of their parts. Diagrammatic reasoning is the only really fertile reasoning. If logicians would only embrace this method, we should no longer see attempts to base their science on the fragile foundations of metaphysics or a psychology not based on logical theory; and there would soon be such an advance in logic that every science would feel the benefit of it.

Charles S. Peirce, *Prolegomena to an Apology for Pragmaticism*, 1906

C. S. Peirce is famous for his contributions to symbolic logic, including among others his eponymous law for classical logic, and his pioneering work on the algebra of relations and quantification [147]. But far less widespread are his achievements in the realm of graphical logic, or *iconic logic* as Shin calls it [166]. He dedicated a large chunk of his life investigating diagrammatic systems, starting in 1882 with the *entitative graphs* and culminating with the *existential graphs*, which he developed from 1896 until his death in 1914 [161]. Interestingly, Peirce perceived existential graphs (thereafter “EG”) as his “*chef d’oeuvre*”, and that they “*ought to be the logic of the future*”¹.

Recent works have started to realize this vision: for example Sowa based his conceptual graphs for computerized knowledge representation on EG [169], Brady, Trimble [16][17] and Haydon, Sobociński [88] proposed various reconstructions of EG through the lens of *topology* and *category theory*, and Melliès and Zeilberger [126] refined the interpretation of Brady and Trimble by making further connections with *linear logic* [66]. The full story has yet to be told, but we hope that our work will constitute one more step towards the vision Peirce had in mind.

In this chapter, we propose a self-contained exposition of EG, that tries at the same time to be faithful to the original presentation of the systems by Peirce, and more modern in some aspects of their formalization. The goal will be to familiarize the reader with the unique approach to proofs inherent to EG, which can be difficult to relate to more standard frameworks like Hilbert and Gentzen proof systems, and even deep inference proof systems like the calculus of structures. This shall prove useful to get a good understanding of the historical and technical foundations behind our *flower calculus*, to be introduced in Chapter ??.

The chapter is organized as follows: we start in Section ?? by presenting the diagrammatic syntax of the system Alpha of EG for classical propositional logic. In Section ??, we introduce the inference rules of Alpha for manipulating existential graphs, called *illative transformations* by Peirce. In Section ??, we give an equivalent formulation of the syntax and rules of

1: Both citations are from p. 11].

Alpha as a *multiset* rewriting system. In Section ??, we formalize a variant of the (de)iteration principle described by Peirce in [150] that eliminates the need for the double-cut principle, and discuss how it was motivated by Peirce’s quest for *illative atomicity*. In Section ??, we take advantage of our reformulation to give a simple proof of soundness for Alpha, based on a direct truth-evaluation of graphs. In Section ?? we give a novel syntactic proof of completeness for Alpha, by simulating the calculus of structures SKS of Brünnler and Tiu [21]. In this way, Alpha is shown to have subsystems that inherit the *locality* property of SKS, and where the deletion and insertion rules are respectively admissible for *provability* and *refutability*, making Alpha *analytic*. In Section ??, we illustrate the original mechanism of *lines of identity* used by Peirce to handle quantifiers and equality in his Beta system. We end in Section ?? by showing how to recast lines of identity in a more traditional binder-based syntax.

8.1 Alpha graphs

Existential Graphs Peirce designed in total three systems of EG, which he called respectively Alpha, Beta and Gamma. They were invented chronologically in that order, which also captures their relationship in terms of complexity: Alpha is the foundation on which the other systems are built, and can today be understood as a diagrammatic calculus for classical *propositional* logic. As we will see in Section ??, Beta corresponds to a variable-free representation of *predicate* logic without function symbols, and with primitive support for *equality*. The last system Gamma is more experimental, with various unfinished features that have been interpreted as attempts to capture *modal* [199] and *higher-order* logics².

Sheet of Assertions The most fundamental concept of Alpha is the *sheet of assertion*, denoted by SA thereafter. It is the space where statements are scribed by the reasoner, typically a sheet of paper or a blackboard. In a proof assistant, this would either be the buffer of a text editor holding the theory the user is developing, or the proof view displaying goals to be proved, depending on who the reasoner is (the user or the computer, respectively). This last analogy suggests an important property of SA: it must offer a *virtually infinite* amount of space, so that one can perform as much reasoning as needed. Just like a Turing machine has an infinite tape, so that one can perform as much computation as needed. In symbolic logic, this is captured by the fact that formulas, although usually finite, can have an unbounded size.

As its name indicates, scribing a statement on SA amounts to *asserting its truth*. Thus very naturally, the empty SA where nothing is scribed will denote vacuous truth, traditionally symbolized by the formula \top .

Juxtaposition As we know from natural deduction, asserting the truth of the conjunction $a \wedge b$ of two propositions a and b , amounts to asserting *both* the truth of a and the truth of b . In Alpha, there is no need to introduce the symbolic connective \wedge , since one can just write both a and b at distinct locations on SA:

$$a \quad b$$

[150]: Peirce (1906), ‘Prolegomena to an Apology for Pragmaticism’

[199]: Zeman (1964), ‘The Graphical Logic of C. S. Peirce’

2: A less known fact is that at the end of his life, Peirce pushed his experiments beyond the scope of *logic* in the contemporary sense of the word, with so-called *tinctured existential graphs* (Chapter 6 in [161]). Roughly, the idea was to represent a variety of *modes of expression* with different background shades on the canvas where sentences are scribed, not unlike our graphical depiction of the *status* of solutions in Figure ??. In addition to the usual act of asserting the truth of a proposition, one could for instance express a *subjective* or *objective* possibility, or signify an interrogative or imperative mood, all by using different colors. For print in publications, he would in fact use *heraldic tinctures* instead of colors, hence the “tinctured” qualificative. The precise meaning and purpose of tinctured EG remains elusive to this day, and might constitute the most esoteric part of his work.

More generally, one might consider any two portions G and H of SA, and interpret their *juxtaposition* GH as signifying that we assert the truth of their conjunction.

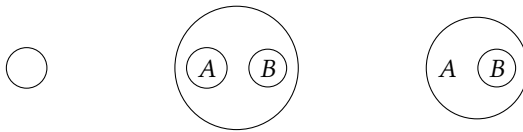
Cuts Asserting the truth of the negation $\neg a$ of a proposition a , amounts to *denying* the truth of a . Using the original notation of Peirce, this is done in Alpha by *enclosing* a in a closed curve like so:



Peirce called such curves *cuts*³, because they ought to be seen as literal cuts in the paper sheet that embodies SA. Note that they do not need to be circles: all that matters is that a is in a separate area from the rest of SA. This is precisely the content of the *Jordan curve theorem* in topology, and thus we can take cuts to be arbitrary Jordan curves. This entails in particular that cuts cannot intersect each other, but can be freely nested inside each other. Then as for juxtaposition, one can replace a by any graph G , i.e. any portion of SA, as long as the cut does not intersect other cuts in G .

Relationship with formulas With just these two *icons*, juxtaposition and cuts, one can therefore assert the truth of any proposition made up of conjunctions and negations, and built from atomic propositions. Importantly, the only symbols needed for doing so are letters $a, b, c \dots$ denoting atomic propositions, that is “pure” symbols that do not have any logical meaning associated to them.

Now, it is well-known that $\{\wedge, \neg\}$ is *functionally complete*, meaning that any boolean truth function can be expressed as the composition of boolean conjunctions and negations. In particular, the symbolic definitions of falsehood $\perp \triangleq \neg\top$, classical disjunction $A \vee B \triangleq \neg(\neg A \wedge \neg B)$ and classical implication $A \supset B \triangleq \neg(A \wedge \neg B)$ can be expressed by the following three graphs⁴:



Thus one can easily encode any propositional formula into a classically equivalent graph. Conversely, one can translate a graph into a classically equivalent formula, as has been shown for instance in [166]. In fact, there are usually many possible formula readings of a given graph: this is because juxtaposition of graphs is a *variadic* operation, as opposed to conjunction of formulas which is *binary*. Also, because of the topological nature of SA, juxtaposition is naturally *associative* and *commutative*: the locations of two juxtaposed graphs do not matter, as long as they live in the same area delimited by cuts. This property is called the *isotropy* of SA in [130]. Hence, graphs can be seen as an associative-commutative normal form for propositional formulas built from atoms with $\{\wedge, \neg\}$.

Remark 8.1.1 In a first version of EG called *entitative graphs*, Peirce used juxtaposition to denote *disjunction* instead of conjunction. Al-

3: Not to be confused with the name given to instances of the *cut rule* in sequent calculus. Although there is a connection, since in the one-sided version of LK, one occurrence of the cut formula in the premisses of the rule is negated.

4: Note the resemblance with the translation of formulas as solutions in Figure ??, in particular for negative disjunctions.

[166]: Shin (2002), *The Iconic Logic of Peirce's Graphs*

though $\{\vee, \neg\}$ is also functionally complete, Peirce quickly grew unsatisfied with these entitative graphs, stating that EG formed “a far preferable system on the whole” (Ms 280, pp. 21-22). I find it interesting that more contemporary works in logic have also made the choice to take conjunction and negation as their primitive operations, like the tensorial logic of Melliès [125], or the realizability constructions for linear logic in Girard’s transcendental syntax [56].

8.2 Illative transformations

Deep inference In order to have a proof system, one needs a collection of *inference rules* for deducing true statements from other true statements. In Alpha, inference rules are implemented by what Peirce called *illative transformations* on graphs. In modern terminology, they correspond to *rewriting* rules that can be applied to any subgraph/portion of SA. By measuring the depth of a subgraph as the number of cuts in which it is enclosed, we thus have that the rules of Alpha are applicable on subgraphs of arbitrary depth. This makes Alpha deserving of the title of *deep* inference system.

Polarity Before introducing the rules, let us make a small change in the way we depict the graphs. The idea is that we want to visualize more clearly the *polarity* of any subgraph G , understood as the *parity* of the number of cuts (negations) enclosing G . In one of his unpublished manuscripts (Ms 514), Peirce did this by *shading* negative areas — those enclosed in an odd number of cuts — in gray, as illustrated in Figure ?? [170]. Unconstrained by hand-drawing, one could adopt an even more iconic notation, where negative areas are *literally* drawn like a negative in photography, by inverting white and black. The example of Figure ?? would then be drawn as in Figure ??. However in this thesis, we will stick to Peirce’s notation, which is both less straining for the eyes by being less contrasted, and more economical in ink for print. A nice advantage of these notations is that they remove the need to count manually the number of cuts starting from the top-level of SA: the information is immediately apparent in the subgraph, and thus completely *local*⁵.

Remark 8.2.1 Whereas in bubble calculi the concept of polarity was understood as a property of *objects* — i.e. utterances of propositions — by assigning them opposite colors (blue and red), the previous notations for graphs suggest that it is instead a property of the *space* in which objects reside. This is more natural from the point of view of *game semantics*: for instance in a game of chess, the two players can easily exchange their roles by switching places or rotating the board by 180°, rather than by repainting laboriously each piece in the opposite color.

Inference rules Quite surprisingly, Peirce showed that one only needs five inference rules to get a *strongly complete* system, in the sense that if the truth of a graph G entails the truth of another graph H , then G can always be rewritten into H by applying exclusively instances of these five rules⁶. A nice way to understand the rules of Alpha is as *edition principles*,

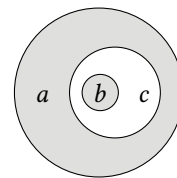


Figure 8.1: Peirce’s notation for emphasizing negative areas

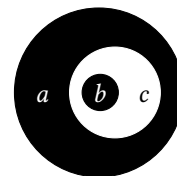


Figure 8.2: Drawing negative areas literally in negative

[170]: Sowa (2011), ‘Peirce’s Tutorial on Existential Graphs’

5: A similar device is used in the deep inference system ISp of Tiu [184], where the polarities of substructures are attached to them as explicit labels.

6: Of course Peirce did not show completeness formally in the sense of modern model theory, although Sowa argues in [170] (Section 4) that he had started to develop his own model theory equivalent to Tarski’s (but closer to the *game-theoretical semantics* of Hintikka [94]).

like the most basic actions one executes pervasively when editing text on a computer⁷. The first two rules are the most powerful and mysterious in all systems of EG, and can be applied in areas of any polarity:

Iteration (*Copy & Paste*) A graph G may be duplicated at any depth inside of a juxtaposed graph H . Using our notation for holed contexts from previous chapters, this can be represented schematically like so:

$$G \ H \square \rightarrow G \ H \boxed{G} \quad G \ H \square \rightarrow G \ H \boxed{G}$$

It can be seen as a deep generalization of the *identity* axiom of sequent calculus, where the top-level occurrence of G justifies the occurrence inside $H\square$ ⁸. Note that while in the identity axiom, the justifying (resp. justified) occurrence must be a negative hypothesis (resp. a positive conclusion), the Iteration rule also allows the opposite relationship of a conclusion justifying a hypothesis, thus also exhibiting one aspect of the *cut* rule of sequent calculus.

Deiteration (*Factorization*) Formally, this is the converse of Iteration:

$$G \ H \boxed{G} \rightarrow G \ H \square \quad G \ H \boxed{G} \rightarrow G \ H \square$$

Its interpretation as an edition principle is a bit trickier, but it can be understood as a form of *sharing* of information. Indeed, it roughly says that a subgraph G can be erased if it already occurs “higher” on SA. Also this does precisely the opposite of copy-pasting, which is known in software engineering as *factorization*⁹.

Compared to sequent calculus, it can be seen as a deep generalization of the *contraction* rule, the base case where $H\square = \square$ giving $GG \rightarrow G$.

The applicability of the next two rules depends on the polarity of the subgraph’s area:

Insertion Any graph G may be inserted in a negative area:

$$\rightarrow G$$

This is akin to a *weakening* rule, stating that if a proposition is known to be true, one might add (useless) hypotheses at will. The closest equivalent we found in the deep inference literature is indeed the weakening rule $w\downarrow$ of ISp in [184].

Deletion Any graph G occurring in a positive area may be erased:

$$G \rightarrow$$

This is exactly the dual of Insertion, stating that if a proposition is known to be true, then one might as well refrain from asserting it. It is the only *non-analytic* rule of the system when reading rules from conclusion to premiss, since G does not already appear in the right-hand side. It is thus strongly related to the *cut* rule of sequent calculus, which it can simulate together with the Deiteration rule.

7: Even though computers did not exist yet in Peirce’s time! In fact, Martin Irvine argues in [100] that Peirce anticipated many developments in computer science and information technologies, such as the use of electrical switches to compute boolean functions, whose invention is usually attributed to Claude Shannon.

8: This might also be related to the notion of *justified move* in game semantics, where the nesting of cuts in the context $H\square$ corresponds to a sequence of alternating moves between Player and Opponent.

9: This is closely related to the kind of factorization at work in bubble calculi. In particular, the fact that the factorizing occurrence is higher and usually outside of a cut is very reminiscent of the *outward* flow rules of system B (those whose name ends with \uparrow in Figure ??); and the deduplicating effect makes Deiteration even closer to the variant of the same rules in B_{inv} (Figure ??).

[184]: Tiu (2006), ‘A Local System for Intuitionistic Logic’

The last rule is more of a *space management* principle that works as an *isotopy*, i.e. a bidirectional topological deformation:

Double-cut A *double-cut* may be inserted or erased around any graph G :



The bidirectional arrow \leftrightarrow expresses that the rule can be applied in both directions. Logically, this corresponds to the classical equivalence $\neg\neg A \simeq A$, where in particular the deletion direction $\neg\neg A \supset A$ is not true intuitionistically. Topologically, the double-cut forms a *ring*, that separates G from the rest of SA while preserving its polarity. Then the two directions of the rules can be understood as the following dual *homotopies*:

Contraction The ring is created by cutting SA around G , and then *contracting* the inner area where G resides on itself. This effectively “pulls apart” G from the rest of the sheet, leaving apparent in the empty space of the ring whatever lies behind SA. Peirce thought of positive and negative areas as being the *recto* and *verso* of SA, respectively. Thus in the positive version of the rule (on the left), the ring would represent negative empty space on the verso of SA.

Expansion The ring is erased by *expanding* the inner area where G resides towards the outer border of the ring. Unfolding the metaphor to its conclusion, the inner area is then “glued back” to the rest of SA¹⁰.

Figure ?? shows a derivation of Peirce’s law with the rules of Alpha. Note that the direction of arrows has been reversed compared to the above presentation: as usual, we prefer to read rules from conclusion to premiss, starting from the goal to prove — here the graph associated to the formula $((a \supset b) \supset a) \supset a$ — that we reduce to the empty goal, represented by the empty SA. Also, the reader unfamiliar with EG might find it hard to convince herself that all the steps followed in the derivation are sound logically. We suggest her to either build a *syntactic* intuition for the rules by practicing them on various tautologies of propositional logic, or to wait until we give a formal *semantic* proof of soundness in Section ??.

8.3 Graphs as multisets

As noted by various authors¹¹, the nesting of cuts on SA induces a *tree* structure on graphs: each cut constitutes a node, whose children are either leaves corresponding to atomic propositions residing in the area of the cut, or nodes corresponding to nested cuts. Empty cuts have no children, and thus also form leaves of the tree. Then SA may be seen either as a forest of atoms and cuts, or as a rooted tree whose root represents SA, and is distinguished from cut nodes. This can be captured by the following grammar:

$$SA ::= G \quad G, H, K ::= g_1, \dots, g_n \quad g, h, k ::= a \mid [G]$$

10: This is reminiscent of the *absorption* rules $\{a, a-, a+\}$ of system B, as is very clear in their graphical presentation (Figure ??).

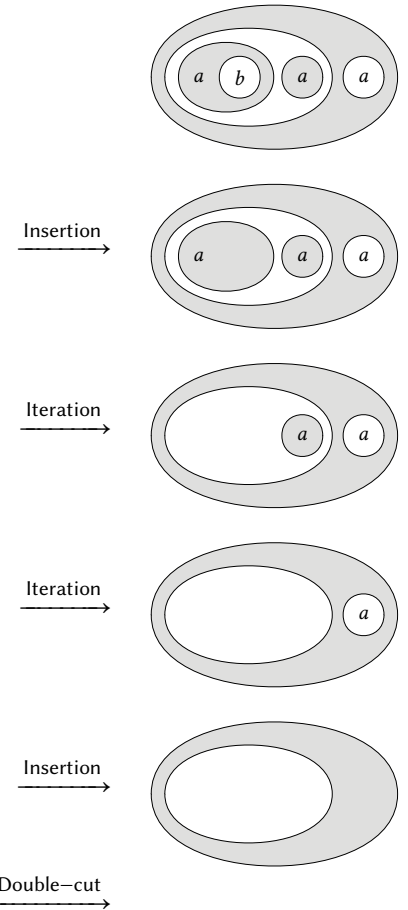


Figure 8.3: A derivation of Peirce’s law in Alpha

11: See for instance the Tree Existential Graphs of Roberts and Pronovost [162], or Section 2.2 in [16].

Example 8.3.1 The graph of Figure ?? may be written as either one of the following expressions:

$$[a, [[b], c]] \quad [a, [c, [b]]] \quad [[[b], c], a] \quad [[c, [b]], a]$$

To abstract from the specific order in which nodes are sequenced in this notation, and thus represent faithfully the isotropy of SA, we define α -graphs as (recursive) *finite multisets*:

Definition 8.3.1 (α -graph) *Given a denumerable set of atomic propositions \mathcal{A} , the sets of α -nodes N_α and α -graphs G_α are defined mutually inductively as follows:*

- **(Spot)** *If $a \in \mathcal{A}$, then $a \in N_\alpha$;*
- **(Area)** *If $G \subset N_\alpha$ is a finite multiset, then $G \in G_\alpha$;*
- **(Enclosure)** *If $G \in G_\alpha$, then $[G] \in N_\alpha$.*

The terminology written in parentheses is the one used by Peirce to denote the same concepts in [150]. Note the similarity with the definitions of bubbles (enclosures) and solutions (areas) (Definition ??). The main difference between α -graphs and solutions, is that in the former formulas (ions) are restricted to atoms (spots), and they are not *polarized* (see Remark ??).

[150]: Peirce (1906), ‘Prolegomena to an Apology for Pragmaticism’

The five rules of Alpha can now be formalized as multiset rewriting rules on α -graphs. But first, we need a notion of *context* in which rules apply:

Definition 8.3.2 (α -graph context) *An α -graph context $G\Box$ is an α -graph which contains exactly one occurrence of the special node \Box called the hole. The hole can always be filled (substituted) with any other graph H or context $K\Box$, producing a new graph $G[H]$ or context $G[K\Box]$. In particular, filling with the empty graph \emptyset will yield a graph $G\Box$, which is just $G\Box$ with its hole removed.*

Then to reason by induction on contexts, we need to define formally how to measure their *depth*. It turns out the only way to increase the depth of an α -graph is to insert *cuts*, and thus the depth of a context coincides with its *parity*, i.e. the number of cuts enclosing its hole:

Definition 8.3.3 (Depth) *The depth of a context $G\Box$ is defined recursively by*

$$\begin{aligned} |H, \Box| &= 0 \\ |H, [G\Box]| &= |G\Box| + 1 \end{aligned}$$

Definition 8.3.4 (Parity) *The parity of a context $G\Box$ is defined by $\text{par}(G\Box) = |G\Box|$.*

Definition 8.3.5 (Polarity) *We say that a context $G\Box$ is positive if $\text{par}(G\Box)$ is even, and negative otherwise. We denote positive and negative contexts respectively by $G^+\Box$ and $G^-\Box$.*

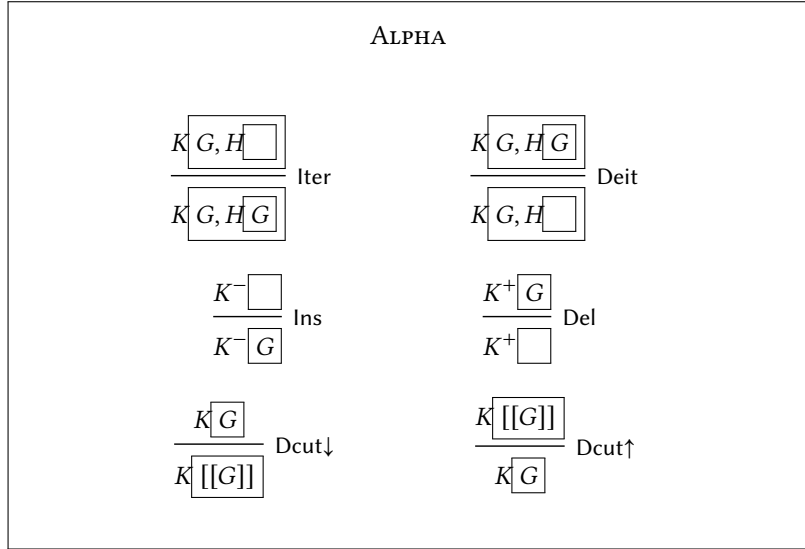


Figure 8.4: Inductive presentation of the rules of Alpha

The inductive version of the rules of Alpha is given in Figure ??, as a set of unary inference rules on α -graphs: when read *top-down*, they correspond to usual inferences from premiss to conclusion, as we first introduced them in Section ?. But as already mentioned there, we will rather emphasize their *bottom-up* reading: then they express the different ways in which one may choose to simplify a goal.

Definition 8.3.6 (Derivation) *We write $G \rightarrow H$ to indicate a rewrite step in Alpha, that is an instance of some rule from Figure ?? with H as premiss and G as conclusion. A derivation $G \rightarrow^n H$ is a sequence of rewrite steps $G_0 \rightarrow G_1 \dots \rightarrow G_n$ with $G_0 = G$, $G_n = H$ and $n \geq 0$. Generally the length n of the derivation does not matter, and we just write $G \rightarrow^* H$.*

Definition 8.3.7 (Proof) *A proof of an α -graph G is a derivation $G \rightarrow^* \emptyset$.*

8.4 Illative atomicity

Insertions and Omissions A remarkable feat of Peirce's rules, on which he insisted very much, is that they are only expressed in terms of *insertions* and *omissions* of graphs on SA. He thought that those were the *smallest* steps in which reasoning could be dissected, making his system extremely appropriate for *analytical* purposes. This is summarized in the following excerpt [150, p. 533]:

In the first place, the most perfectly analytical system of representing propositions must enable us to separate illative transformations into indecomposable parts. Hence, an illative transformation from any proposition, A, to any other, B, must in such a system consist in first transforming A into AB, followed by the transformation of AB into B. For an omission and an insertion appear to be indecomposable transformations and the only indecomposable transformations.

[150]: Peirce (1906), 'Prolegomena to an Apology for Pragmatism'

We already considered this question of decomposing logical inferences into their most elementary operations, when reflecting on the graphical presentation of BJ at the end of Section ?? . In this setting, the most basic insertions and omissions we could find were not logically *sound*, whereas in Alpha they are. This is quite promising, and prompts us to reevaluate our conception of *illative atomicity*, understood precisely as the definition of what it means for an inference step to be (the most) *elementary*.

Note that this should be distinguished from the notion of *analyticity*, as popularized by Gentzen with the *subformula property* in sequent calculus: the latter is concerned with the analysis of *propositions* into their constituents through inference rules, while here we are interested in the analysis of the inference rules themselves¹². This is a philosophically debatable question, because inference rules are usually posited as axioms in a deductive system, and are thus by definition the smallest constituents of proofs. The only other logician we know of who attempted to give a non-trivial account of illative atomicity is J.-Y. Girard. In fact it can be argued that it is the principal motivation behind most of his works starting from linear logic, which became explicit in ludics with his slogan “From the rules of logic to the logic of rules” [67].

12: We will give a positive answer to the question of analyticity in Alpha at the end of Section ??.

Linearity There is an intriguing remark by Peirce in [150, pp. 536–537] about the atomicity of the rules presented thus far, that seems to have gone unnoticed in the literature on EG. Indeed, Peirce argues that the principle of Double-cut “cannot be assumed as an undeduced Permission” — i.e. a primitive rule of the system, because the area inside the inner cut becomes identified with the area outside the outer cut when the double cut is removed, which “is not strictly an Insertion or a Deletion”. Another way to view this, is that it is the only *linear* rule of the system, in the sense that the premiss and conclusion contain exactly the same atomic graphs. Contrast this with linear logic, which instead takes linearity as the criterion for illative atomicity, as exemplified by the linear decomposition of implication $A \supset B \triangleq !A \multimap B$. This might be the consequence of an opposite treatment given to *negation*: while in EG it is the only primitive constructor of the system — remember that the only way to increase the depth of a graph is with a cut, in LL negation is the only defined notion through De Morgan dualities. Thus EG are closer (at least syntactically) to *type theories*, which also take a negative operation (the arrow or dependent product type) as their sole primitive construct.

Interactivity and Locativity Peirce then suggests a “more scientific way”, where the principle of Double-cut is subsumed by a restricted variant of the principle of Iteration and Deiteration. His description of this “more scientific” (de)iteration principle is based on a relation of *local justification* (our terminology) between two areas of a graph, that captures the fact that the deeper occurrence of G in the Iter and Deit rules (Figure ??) is justified by the other occurrence by virtue of their respective *locations*. Later in the text, Peirce emphasizes the importance of this locative aspect of argumentation [150, pp. 544–545]:

[...] when an Argument is brought before us, there is brought to our notice a process whereby the Premisses bring forth the Conclusion, not informing the Interpreter of its Truth,

but appealing to him to assent thereto. This Process of Transformation, which is evidently the kernel of the matter, is no more built out of Propositions than a motion is built out of position.

Once again, game-theoretical ideas and the concept of space (Remark ??) are prominent in this excerpt: Truth is not primitive, but rather a side effect of the interaction between an Interpreter (Opponent) being lead to agree with the Graphist (Player), whenever the latter performs a transformation on the graph under discussion. The soundness of such a transformation guarantees that this will work for *any* Interpreter/Opponent, leading to what is known as a *winning strategy* in game semantics. Since illative transformations only consist of Insertions and Deletions, whose validity depends solely on the positions where they occur in the graph, it ensues that the components of an argumentation can be reduced to “motions” (moves) that relate pure locations.

It is then interesting to notice that the quest for illative atomicity, who led Peirce to discover these interactive and locative aspects of logic, also led Girard to identify these properties as fundamental, in his recent works on ludics [67] and transcendental syntax [55]. We tend to share the vision put forth by Boris Eng in his thesis [55, §24.4], that logic is mostly about *space* and the *shape* of objects, while *time* and *dynamics* pertain more to the realm of computation. In this view, Peirce’s systems of EG are a logico-computational complex where each aspect can clearly be identified: the Process of Illative Transformation is an interactive computation among the Graphist and Interpreter, whose logical nature is determined by the spatial constraints of the Permissions, that are expressible thanks to the topology induced by cuts on SA^{13} .

The more scientific way Let us now go back to the modified (de)iteration principle proposed by Peirce. With our formalization of graphs as multisets, we can give a more rigorous formulation than the original natural language description given by Peirce¹⁴. In this setting, a location in a graph is represented by the hole of a context, thus the relation of local justification between two areas is defined on contexts:

Definition 8.4.1 (Local justification) *Given two contexts $G\Box$ and $H\Box$, we say that $H\Box$ is locally justified by $G\Box$, written $G\Box \succeq_0 H\Box$, if and only if one of the following conditions holds for some $K\Box$, $G_0\Box$, $H_0\Box$ such that $G\Box = K[G_0\Box]$ and $H\Box = K[H_0\Box]$:*

1. $G_0\Box = H_0\Box = K_0, \Box$ for some K_0 ;
2. $G_0\Box = K_0, [K_1], \Box$ and $H_0\Box = K_0, [K_1, \Box]$ for some K_0, K_1 ;
3. $G_0\Box = K_0, [K_1, [K_2]], \Box$ and $H_0\Box = K_0, [K_1, [K_2, \Box]]$ for some K_0, K_1, K_2 .
4. $G_0\Box = K_0, [[K_1, \Box]]$ and $H_0\Box = K_0, \Box, [[K_1]]$ for some K_0, K_1 .

These four conditions are exactly the formal counterpart of those given by Peirce in [150]. They might be more easily understood by looking at their graphical representation in Figure ??: the red and blue dots denote respectively the locations of the holes in the justified context $H\Box$ and justifying context $G\Box$, as suggested by the arrow between them. In particular, it becomes clear that it is Condition 4 that will account for the

13: Both Peirce and Girard also shared the ambition to develop a comprehensive philosophical foundation for logic, as part of a more general theory of *meaning*: for Peirce it was his *semeiotic*, stemming from his overarching doctrine of *pragmaticism* [23]; for Girard it was the theory of programming languages and their semantics.

14: Although we limit ourselves to propositional logic in Alpha, while in [150] Peirce also accounts for the lines of identity of Beta handling predicate logic, to be introduced in Section ??.

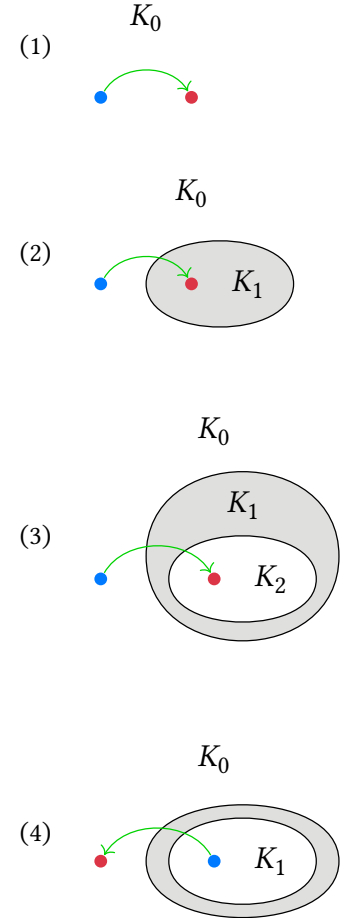


Figure 8.5: Graphical representation of the four conditions of local justification

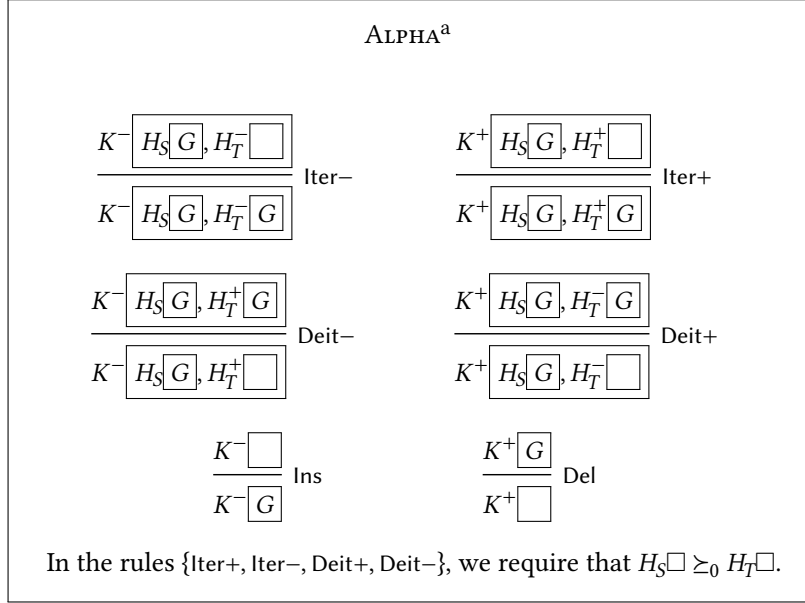


Figure 8.6: The illatively atomic system Alpha^a

principle of Double-cut. Then the new rules of iteration Iter+, Iter- and deiteration Deit+, Deit- are given in the so-called *atomic* variant Alpha^a of Alpha in Figure ??, which now only comprises rules that truly are insertions and omissions of *arbitrary* graphs¹⁵. The atomic (de)iteration rules are a restriction of the original ones in two respects:

Locality Following Definition ??, the depth of the justified context $H_T \boxed{}$ can be at most 2 in the atomic rules, while it is unbounded in the original rules. This does not hinder their expressivity however: global (de)iterations can be simulated by successive applications of local ones, by erasing intermediate copies with the Ins and Del rules. This is because the *global justification* relation \succeq associated with the original rules coincides with the transitive closure of the local relation \succeq_0 , modulo the 4th condition for double-cuts¹⁶.

Polarity In the atomic iteration (resp. deiteration) rules, the justified context must be positive (resp. negative), while it can have an arbitrary polarity in the original rules. This is expressed by splitting each of the latter into two rules, one where the outer context $K \boxed{}$ is positive (Iter+, Deit+), and one where it is negative (Iter-, Deit-). Again, this does not alter their deductive power: every iteration (resp. deiteration) in a negative (resp. positive) context can be trivially performed by an instance of the Ins (resp. Del) rule. Thus atomic rules eliminate a redundancy of Alpha, where many insertions/omissions could be interpreted as instances of either Iter/Deit or Ins/Del. They also eliminate the possibility for a conclusion to justify a hypothesis, as remarked in Section ?? when commenting on the principle of Iteration, making them closer to the rules of sequent calculus¹⁷.

In the rest of this chapter, we settle on the more standard system Alpha, and leave a more detailed and rigorous study of Alpha^a for future work. But the above informal arguments should convince the reader that there is little doubt that Alpha^a is both sound and complete if and only if Alpha is, which is the object of the following two sections.

15: The terminology “atomic” might be a bit confusing: here we think of *illative* atomicity in Peirce’s sense, not the fact that the graphs manipulated by rules are atomic, which might be termed *structural* atomicity. There seems to be a symmetric tradeoff when comparing EG to the calculus of structures: in the former, one maximizes illative atomicity by minimizing linearity and structural atomicity; while in the latter, one maximizes structural atomicity and linearity by minimizing illative atomicity. This will become explicit in Section ??, when simulating the calculus of structures SKS in Alpha.

16: Our notation for justification relations actually comes from [130], where the authors define the same notion informally for an intuitionistic variant of EG.

17: We suspect however that the more general (de)iteration rules are still relevant from a computational point of view.

8.5 Soundness

We are now going to prove formally the *soundness* of each rule of Alpha, by showing that if $G \rightarrow H$ and H is *true*, then so is G . In classical propositional logic, one can easily evaluate the truth of any formula A , given a truth-valuation $v : \mathcal{A} \rightarrow \{0, 1\}$ for the atoms of A . The same applies to α -graphs:

Definition 8.5.1 (α -graph evaluation) *Given a valuation $v : \mathcal{A} \rightarrow \{0, 1\}$ and a graph G , the evaluation $v(G)$ of G is defined by mutual recursion as follows:*

$$v(G) = \begin{cases} 1 & \text{if } G = \emptyset \\ \min_{g \in G} v(g) & \text{otherwise} \end{cases}$$

$$v([G]) = 1 - v(G)$$

This follows the standard way to evaluate conjunctions and negations.

To factorize the proof of soundness, we first prove a few lemmas for the *invertible* rules of Alpha, that is those who satisfy $v(G) = v(H)$ for every valuation v if $G \rightarrow H$.

Lemma 8.5.1 (Iteration) *For every graph G , context $H \square$ and valuation v , we have*

$$v(G, H \square) = v(G, H \square G)$$

Proof. By recurrence on $|H \square|$.

Base case Suppose $H \square = H', \square$. Then we have

$$\begin{aligned} v(G, H') &= \min_{g \in G \cup H'} v(g) \\ &= \min_{g \in G \cup H' \cup G} v(g) \\ &= v(G, H', G) \end{aligned}$$

Recursive case Suppose $H = H', [H_0 \square]$. Then we have

$$\begin{aligned} v(G, H', [H_0 \square]) &= \min(v(H'), v(G, [H_0 \square])) \\ &= \min(v(H'), v(G, [H_0 \square G])) \quad (\text{IH}) \\ &= v(G, H', [H_0 \square G]) \end{aligned}$$

□

Lemma 8.5.2 (Double-cut) *For every graph G and valuation v , we have*

$$v([[G]]) = v(G)$$

Proof.

$$v([[G]]) = 1 - (1 - v(G)) = \begin{cases} 1 - (1 - 0) = 0 & \text{if } v(G) = 0 \\ 1 - (1 - 1) = 1 & \text{if } v(G) = 1 \end{cases}$$

In both cases we have $v([[G]]) = v(G)$. \square

Since all rules apply in an arbitrary deep context $K\Box$, we will benefit from the following *functoriality* lemmas:

Lemma 8.5.3 (Variance) *For every context $K\Box$, graphs G, H and valuation v such that $v(G) \leq v(H)$, we have:*

1. $v(K\Box G) \leq v(K\Box H)$ if $K\Box$ is positive;
2. $v(K\Box H) \leq v(K\Box G)$ if $K\Box$ is negative.

Proof. By recurrence on $|K\Box|$.

Base case ($|K\Box| = 0$)

1. Suppose $K\Box = K', \Box$. Then we have

$$\begin{aligned} v(K', G) &= \min(v(K'), v(G)) \\ &\leq \min(v(K'), v(H)) \quad (\text{Hypothesis}) \\ &= v(K', H) \end{aligned}$$

2. We have $|K\Box| > 0$ since $K\Box$ is negative. Contradiction.

Recursive case ($|K\Box| > 0$)

1. Suppose $K\Box = K', [K_0^- \Box]$. Then by IH we have $v(K_0^- [H]) \leq v(K_0^- [G])$, and thus $1 - v(K_0^- [G]) \leq 1 - v(K_0^- [H])$. Therefore

$$\begin{aligned} v(K', [K_0^- [G]]) &= \min(v(K'), 1 - v(K_0^- [G])) \\ &\leq \min(v(K'), 1 - v(K_0^- [H])) \\ &= v(K', [K_0^- [H]]) \end{aligned}$$

2. Suppose $K\Box = K', [K_0^+ \Box]$. Then by IH we have $v(K_0^+ [G]) \leq v(K_0^+ [H])$, and thus $1 - v(K_0^+ [H]) \leq 1 - v(K_0^+ [G])$. Therefore

$$\begin{aligned} v(K', [K_0^+ [H]]) &= \min(v(K'), 1 - v(K_0^+ [H])) \\ &\leq \min(v(K'), 1 - v(K_0^+ [G])) \\ &= v(K', [K_0^+ [G]]) \end{aligned}$$

\square

Corollary 8.5.4 (Functoriality) *If $v(G) = v(H)$ then $v(K\Box G) = v(K\Box H)$.*

Theorem 8.5.5 (Soundness) *If $G \rightarrow H$, then $v(H) \leq v(G)$ for every valuation v .*

Proof. By inspection of each rule.

Iter, Deit We have $v\left(K\left[G, H\left[\square\right]\right]\right) = v\left(K\left[G, H\left[G\right]\right]\right)$ by Lemma ?? and functoriality.

Dcut \downarrow , Dcut \uparrow We have $v\left(K\left[G\right]\right) = v\left(K\left[\left[G\right]\right]\right)$ by Lemma ?? and functoriality.

Ins, Del This follows from the fact that $v(G) \leq 1 = v(\emptyset)$ and Lemma ??.

□

8.6 Completeness

To show the completeness of Alpha, it is standard in the literature on EG to simulate an existing proof system for classical propositional logic, that is itself known to be complete. For instance in [161], completeness is shown by simulating the Hilbert-style system P of Church, which only comprises 3 axioms for the (functionally complete) fragment $\{\supset, \neg\}$. We propose in this section the first proof (that we know of) by simulation of a *deep inference* system, more specifically the calculus of structures SKS first introduced in [21]. This should provide a good overview of the similarities and differences between the two systems, and in particular of how they exemplify two distinct approaches to *symmetry* in a deep inference setting.

[21]: Brünnler et al. (2001), ‘A Local System for Classical Logic’

As the name indicates, the objects manipulated by inference rules in calculi of structures are so-called *structures*. In the case of SKS, they correspond to formulas in *negation normal form* built from atoms and units $\{\top, \perp\}$, i.e. where connectives are restricted to the fragment $\{\wedge, \vee\}$, and negation is pushed to atoms by relying on De Morgan’s laws.

Definition 8.6.1 (Structure) *The structures of SKS are generated by the following grammar:*

$$S, T, U, V, W ::= a \mid \bar{a} \mid \top \mid \perp \mid S \wedge T \mid S \vee T$$

Definition 8.6.2 (De Morgan dual) *The De Morgan dual of a structure S is defined recursively as follows:*

$$\begin{array}{ll} \bar{\bar{a}} = a & \bar{\bar{a}} = a \\ \overline{\top} = \perp & \overline{\perp} = \top \\ \overline{S \wedge T} = \bar{S} \vee \bar{T} & \overline{S \vee T} = \bar{S} \wedge \bar{T} \end{array}$$

It is customary in CoS to further quotient the set of structures with additional equations between them, which account for various algebraic properties of connectives such as associativity, commutativity and unitality. Here we will rely instead on the formulation of SKS given by Tubella

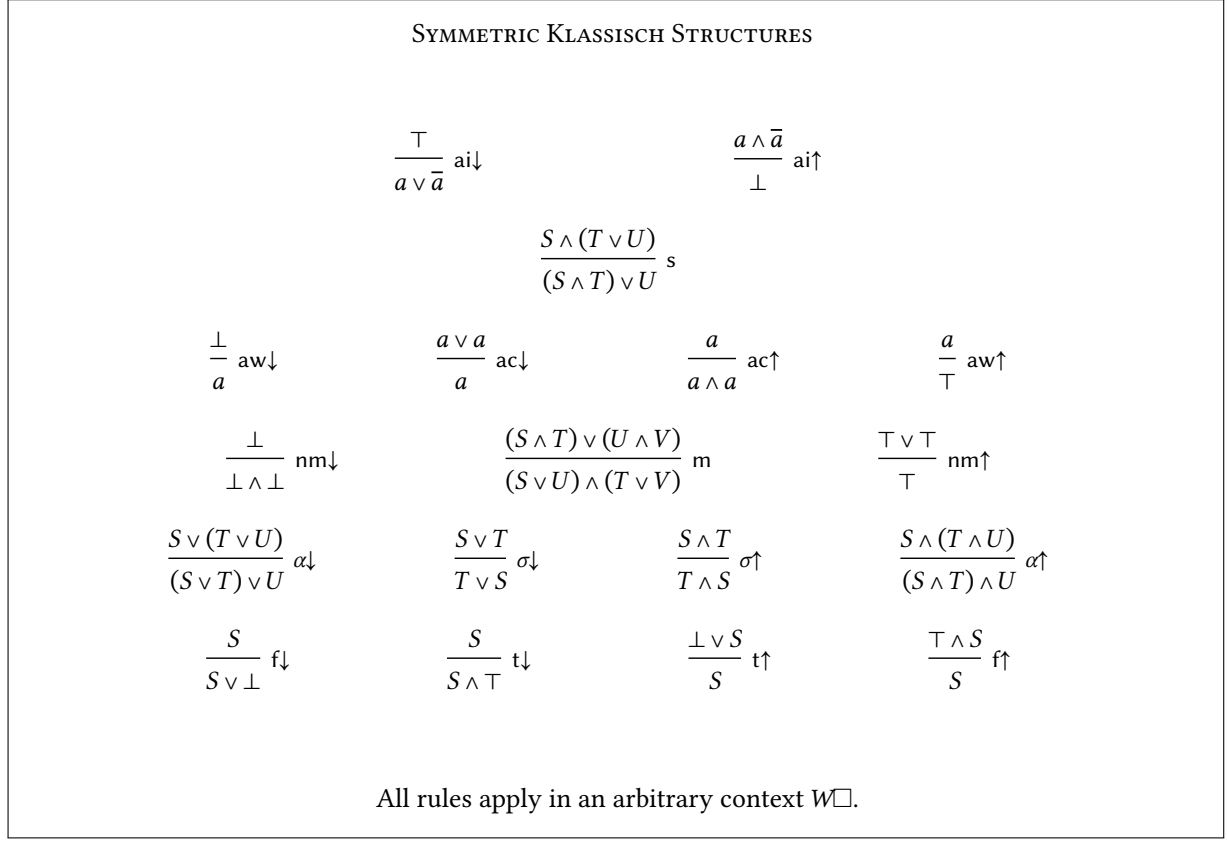


Figure 8.7: Inference rules of SKS

and Straßburger in [185], where all equations are incorporated in the system as explicit rules.

The full set of rules of SKS is given in Figure ?? . All rules are implicitly applicable in any *context* $W\Box$ of arbitrary depth, with the usual notion of context as a structure with a hole.

Definition 8.6.3 (Depth) *The depth $|S|$ of a structure context $S\Box$ is defined recursively as follows:*

$$\begin{aligned}
 |\Box| &= 0 \\
 |S\Box \wedge T| &= |T \wedge S\Box| = |S\Box \vee T| = |T \vee S\Box| = |S\Box| + 1
 \end{aligned}$$

Remark 8.6.1 Contexts for structures are always *positive*, since negation is pushed down to atoms. This is the opposite situation from that of Alpha, where negation is the *only* construct that can increase the depth of a graph. This explains why some rules in Alpha need explicit indications for the polarity of the context in which they apply.

The rules of SKS satisfy two notable properties:

Symmetry Every rule r has a *dual* rule \bar{r} : $U\boxed{S} \xrightarrow{r} U\boxed{T}$ if and only if $U\boxed{\bar{T}} \xrightarrow{\bar{r}} U\boxed{\bar{S}}$. For rules whose name ends with \downarrow , the dual is the rule with the same name ending with \uparrow . This corresponds to all rules except the *switch* rule s and the *medial* rule m which are self-dual,

i.e. $\bar{s} = s$ and $\bar{m} = m$. In Alpha, duality is captured in the *polarity* of contexts rather than through De Morgan's laws:

Fact 8.6.1 (Duality) $K^+[G] \xrightarrow{r} K^+[H]$ if and only if $K^-[\bar{H}] \xrightarrow{\bar{r}} K^-[\bar{G}]$, where

$$\begin{array}{ll} \overline{\text{Iter}} = \text{Deit} & \overline{\text{Deit}} = \text{Iter} \\ \overline{\text{Ins}} = \text{Del} & \overline{\text{Del}} = \text{Ins} \\ \overline{\text{Dcut}\downarrow} = \text{Dcut}\uparrow & \overline{\text{Dcut}\uparrow} = \text{Dcut}\downarrow \end{array}$$

Remark 8.6.2 Contrary to De Morgan duality, the notion of polarity of a context also exists in intuitionistic logic, and is in fact used in the same way to obtain dual rules in the intuitionistic calculus of structures SISa of Tiu [184]. This constitutes one more argument in favor of the view defended by Minghui and Pietarinen in [130], that Peirce had a *pre-intuitionistic* conception of negation. It also echoes our observation in Remark ??, that the choice of negation and conjunction as primitives is to be connected with the eminently constructive works of Girard and Melliès, in particular the non-involutive tensorial negation of the latter. The issue of finding seeds of intuitionism in Peirce's work will be discussed more in depth in Section ??.

Locality Every rule is *local*, in the sense that it does not require the inspection of expressions of arbitrary size (Definition 2.1.1 in [185]). This is almost the opposite in Alpha: to the exception of the rules of double-cut (which are best seen as a structural equivalence like those of CoS), all rules depend heavily on the creation, duplication or deletion of subgraphs of arbitrary size. This is exemplified by the derivation of Peirce's law in Figure ??, where not a single rule is instantiated on atoms. In fact it is quite hard to see how to build a derivation of Peirce's law that performs only local transformations.

In light of this, it becomes surprising that we *will* be able to simulate SKS in Alpha. Indeed, it means that there is a set $\text{Alpha}_{\text{SKS}}$ of perfectly local rules on graphs, corresponding to the translation of the rules of SKS, and which is entirely derivable in Alpha. Thus by restricting oneself to the rules of $\text{Alpha}_{\text{SKS}}$ (and forgetting that they are derived with non-local rules), one gets a fully local subsystem of Alpha!

To formulate the simulation, we need to translate the structures of SKS into equivalent α -graphs. This is easily done by exploiting the functional completeness of $\{\wedge, \neg\}$ (see Section ??):

Definition 8.6.4 (Structure translation) *The translation S^\bullet of a structure S as an α -graph is defined recursively as follows:*

$$\begin{array}{ll} a^\bullet = a & \bar{a}^\bullet = [a] \\ \top^\bullet = \emptyset & \perp^\bullet = [] \\ (S \wedge T)^\bullet = S^\bullet, T^\bullet & (S \vee T)^\bullet = [[S^\bullet], [T^\bullet]] \end{array}$$

[130]: M
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As per Remark ??, the translation of a structure context (where the hole is translated as itself) will always be positive:

Fact 8.6.2 For every context $S\Box$, $S\Box^\bullet$ is positive.

Proof. By a straightforward recurrence on $|S\Box|$. \square

It is easy to show that a structure and its translation as a graph are semantically equivalent, i.e. $v(S) = v(S^\bullet)$ for any valuation v . Thus to get the completeness of Alpha, it is sufficient to simulate the translation of each rule of SKS. But first, we need to ensure that Alpha satisfies a property of *contextual closure*: this will allow us to ignore the implicit context $W\Box$ in the rules of Figure ??.

Lemma 8.6.1 (Positive closure) *If $G \rightarrow H$, then $K^+[G] \rightarrow K^+[H]$.*

Proof. Since all rules of Alpha apply in a context of unbounded depth, we know that there are some graphs G_0, H_0 and context $K'\Box$ such that $G = K'[G_0]$ and $H = K'[H_0]$. Then either $K'\Box$ is positive, and $\text{par}(K^+[K'\Box]) = \text{par}(K^+\Box) + \text{par}(K'\Box)$ is even since it is the sum of two even numbers; or $K'\Box$ is negative, and $\text{par}(K^+[K'\Box])$ is odd since it is the sum of an even and an odd number. In both cases $K^+[K'\Box]$ has the same polarity as $K'\Box$, and thus the same rule can be applied. \square

Theorem 8.6.2 (Completeness) *If $U\Box \rightarrow U\Box$, then $U^\bullet\Box \rightarrow^* U^\bullet\Box$.*

Proof. We show that $S^\bullet \rightarrow^* T^\bullet$ by simulating each rule of Figure ??. The closure with $U\Box^\bullet$ follows from Fact ?? and Lemma ??.

To make the notation lighter, we implicitly apply the translation $(-)^{\bullet}$ on substructures. We also add some coloring to put clearly in evidence the subgraphs manipulated by rules. Assuming that the rules are read from bottom to top:

(De)iteration In the rules Iter and Deit, the justifying occurrence is squared in blue. In the Iter (resp. Deit) rule, the erased (resp. space for the inserted) copy is highlighted in blue.

Insertion/Deletion In the rule Ins (resp. Del), the erased (resp. space for the inserted) subgraph is highlighted in red.

Double-cut In the rule Dcut \downarrow (resp. Dcut \uparrow), the space around which the double-cut is erased (resp. inserted) is highlighted in gray.

We start with the identity rules $\{i\downarrow, i\uparrow\}$:

$$\frac{\top}{a \vee \bar{a}} i\downarrow \mapsto \frac{\frac{\frac{\frac{\frac{\top}{\top}}{a \vee \bar{a}} i\downarrow}{\top} \text{Dcut}\downarrow}{\frac{\top}{\top}} \text{Ins}}{\frac{\top}{\top}} \text{Iter} \text{Dcut}\downarrow \quad \frac{a \wedge \bar{a}}{\perp} ai\uparrow \mapsto \frac{\frac{a, [a]}{[a], [a]} \text{Deit}}{\frac{a, [a]}{[a], [a]} \text{Del}}$$

Then onto weakening $\{aw\downarrow, aw\uparrow\}$ and contraction $\{ac\downarrow, ac\uparrow, nm\downarrow, nm\uparrow\}$:

$$\begin{aligned} \frac{\perp}{a} aw\downarrow &\mapsto \frac{\frac{\frac{\perp}{a} aw\downarrow}{\perp} \text{Ins}}{\frac{\perp}{a} aw\downarrow} \text{Dcut}\uparrow & \frac{a}{\top} aw\uparrow &\mapsto \frac{a}{\top} \text{Del} \\ \frac{a \vee a}{a} ac\downarrow &\mapsto \frac{\frac{\frac{a \vee a}{a} ac\downarrow}{a \vee a} \text{Deit}}{\frac{a \vee a}{a} ac\downarrow} \text{Dcut}\uparrow & \frac{a}{a \wedge a} ac\uparrow &\mapsto \frac{a}{a \wedge a} \text{Iter} \\ \frac{\perp}{\perp \wedge \perp} nm\downarrow &\mapsto \frac{\frac{\perp}{\perp \wedge \perp} nm\downarrow}{\perp \wedge \perp} \text{Iter} & \frac{\top \vee \top}{\top} nm\uparrow &\mapsto \frac{\frac{\top \vee \top}{\top} nm\uparrow}{\top \vee \top} \text{Deit} \end{aligned}$$

For the switch rule s , we give two dual derivations: the first uses the rules Deit and Ins to move U into the cuts enclosing T , while the second uses the rules Del and Iter to move S out of the cuts of T .

$$\begin{aligned} \frac{S, [[T], [U]]}{[[S, [[T], [U]]]]} \text{Dcut}\downarrow & \quad \frac{S, [[T], [U]]}{[[S, [[T], [U]]]]} \text{Iter} \\ \frac{\frac{\frac{S, [[T], [U]]}{[[S, [[T], [U]]]]} \text{Dcut}\downarrow}{[[S, [[T], [U]]]]} \text{Ins}}{\frac{S, [[T], [U]]}{[[S, [[T], [U]]]]} \text{Deit}} & \quad \frac{\frac{S, [[T], [U]]}{[[S, [[T], [U]]]]} \text{Iter}}{\frac{S, [[T], [U]]}{[[S, [[T], [U]]]]} \text{Del}} \end{aligned}$$

Similarly for the medial rule m , which is the other self-dual rule of SKS, we have two dual derivations:

$$\begin{array}{c}
\frac{[[S, T], [U, V]]}{[[S, T], [U, [[V]]]]} \text{Dcut}\downarrow \\
\frac{[[S, T], [U, [[V]]]]}{[[S, [[T]]], [U, [[V]]]]} \text{Dcut}\downarrow \\
\frac{[[S, [[T]]], [U, [[V]]]]}{[[S, [[T]]], [U, [[T]], [V]]]} \text{Ins} \\
\frac{[[S, [[T]]], [U, [[T]], [V]]]}{[[S, [[T]], [V]], [U, [[T]], [V]]]} \text{Ins} \\
\frac{[[S, [[T]], [V]], [U, [[T]], [V]]], [[T], [V]]}{[[S, [[T]], [V]], [U, \boxed{], [[T], [V]]]} \text{Ins} \\
\frac{[[S, [[T]], [V]], [U, \boxed{], [[T], [V]]]}{[[S, \boxed{], [U]], [[T], [V]]]} \text{Deit} \\
\frac{[[S, T], [U, V]]}{\boxed{[[S, T], [U, V]]}, \boxed{[[S, T], [U, V]]}} \text{Iter} \\
\frac{\boxed{[[S, T], [U, V]]}, \boxed{[[S, T], [U, V]]}}{[[S, T], [U, V]], [[S, T], [\boxed{V}]]} \text{Del} \\
\frac{[[S, T], [U, V]], [[S, T], [\boxed{V}]]}{[[S, T], [U, V]], [[\boxed{T}], [V]]} \text{Del} \\
\frac{[[S, T], [U, V]], [[\boxed{T}], [V]]}{[[S, T], [U, \boxed{], [[T], [V]]]} \text{Del} \\
\frac{[[S, T], [U, \boxed{], [[T], [V]]]}{[[S, \boxed{], [U]], [[T], [V]]} \text{Del}
\end{array}$$

The other rules correspond to equations on structures: α for *associativity*, σ for *commutativity*, and f and t for *unitality*. Note that all rules involving \wedge and \top are trivially simulated by the isotropy of SA. Simulating the other rules only requires the double-cut rules, substantiating our claim (based on Peirce's own view, see Section ??) that the latter should be seen as expressing a structural equivalence, rather than as *bona fide* inference rules.

$$\begin{array}{ccc}
\frac{S \vee (T \vee U)}{(S \vee T) \vee U} \alpha\downarrow & \mapsto & \frac{\frac{[[S], [[T], [U]]]}{[[S], [T], [U]]} \text{Dcut}\uparrow}{[[[S], [T]], [U]]} \text{Dcut}\downarrow \\
\frac{S \vee T}{T \vee S} \sigma\downarrow & \mapsto & [[S], [T]] \\
\frac{S}{S \vee \perp} \text{f}\downarrow & \mapsto & \frac{\frac{S}{[[S]]} \text{Dcut}\downarrow}{[[S], [[]]]} \text{Dcut}\downarrow \\
\frac{S}{S \wedge \top} \text{t}\downarrow & \mapsto & S \\
\frac{S \wedge (T \wedge U)}{(S \wedge T) \wedge U} \alpha\uparrow & \mapsto & S, T, U \\
\frac{S \wedge T}{T \wedge S} \sigma\uparrow & \mapsto & S, T \\
\frac{\top \wedge S}{S} \text{f}\uparrow & \mapsto & S \\
\frac{\perp \vee S}{S} \text{t}\uparrow & \mapsto & \frac{\frac{[[[]], [S]]}{[[S]]} \text{Dcut}\uparrow}{S} \text{Dcut}\uparrow
\end{array}$$

□

A powerful result of Brünnler and Tiu [21], is that the whole up-fragment of SKS (all rules whose name ends with \uparrow) is *admissible*: if a structure S has a *proof* $S \rightarrow^* \top$, then it also has a proof $S \xrightarrow{\text{KS}}^* \top$ in KS, defined as SKS without the up-fragment¹⁸. Dually, the whole down-fragment (all rules whose name ends with \downarrow) is “*co-admissible*”: if a structure S has a *refutation* $\perp \rightarrow^* S$, then it also has a refutation $\perp \xrightarrow{\overline{\text{KS}}}^* S$ in $\overline{\text{KS}}$, defined as SKS without the down-fragment.

18: The name KS comes from SKS, with the first ‘S’ standing for “symmetric” dropped.

This duality reflects nicely in our simulation: we were careful to always give derivations for up-rules that mirror closely those for down-rules, modulo the use of the double-cut principle. Roughly, if the simulation of $S \xrightarrow{r} T$ has the shape $S^\bullet \xrightarrow{r_1} \dots \xrightarrow{r_n} T^\bullet$, then the simulation of $\bar{T} \xrightarrow{\bar{r}} \bar{S}$ has the shape $\bar{T}^\bullet \xrightarrow{\bar{r}_1} \dots \xrightarrow{\bar{r}_n} \bar{S}^\bullet$ (see Fact ??). An important consequence is that the deletion rule Del is never used in the simulation of KS, if one chooses the appropriate derivation among the two provided for the switch and medial rules s and m. Thus deletion is admissible in Alpha, a result that seems to be novel in the literature on EG.

Corollary 8.6.3 (Admissibility of Deletion)

If $G \rightarrow^* \emptyset$, then $G \xrightarrow{\text{Alpha} \setminus \{\text{Del}\}}^* \emptyset$.

Dually, the insertion rule Ins is never used in the simulation of $\overline{\text{KS}}$, implying the co-admissibility of insertion. In fact there is a curious dissymmetry, in that the rule Dcut \downarrow of *double-cut* insertion also never appears in the simulation of $\overline{\text{KS}}$, while Dcut \uparrow is used multiple times in the simulation of KS:

Corollary 8.6.4 (Co-admissibility of Insertion)

$$\text{If } [] \rightarrow^* G, \text{ then } [] \xrightarrow{\text{Alpha} \setminus \{\text{Ins}, \text{Dcut}\}}^* G.$$

Corollary ?? is what allows us to conclude that Alpha is an *analytic* system, in a sense very close to that of Gentzen. Because we do not have a notion of logical connective nor tree-shaped derivations, we must reduce the subformula property to *atomic* graphs. Then it is easy to see that all rules of Alpha except Del satisfy this property:

Definition 8.6.5 (Subgraph) *A graph G is a subgraph of a graph H , written $G < H$, if there exists a context $K[]$ such that $H = K[G]$.*

Fact 8.6.3 If $G \xrightarrow{\text{Alpha} \setminus \{\text{Del}\}} H$ and $a < H$, then $a < G$.

Corollary 8.6.5 (Analyticity) *If G is provable in Alpha, then it has a proof $G \rightarrow G_1 \rightarrow \dots \rightarrow G_n \rightarrow \emptyset$ where for all i and a such that $a < G_i$, $a < G$.*

8.7 Beta graphs

Before working on EG, Peirce had already developed a deep understanding of the logic of relations of arbitrary arity, inventing the notions of variables and quantifiers 30 years before the standard Russell-Whitehead syntax for predicate logic appeared in 1910 [23]. This all stemmed from his extensive study of *relation algebras*, first investigated by De Morgan in 1860. However in his system Beta of EG, Peirce gives a very different account of the logic of relations, both in the graphical representation of relational statements, and the illative transformations that govern them. In the following, we illustrate informally the principles of Beta, and how they are able to capture what is identified nowadays in symbolic logic as *purely relational* first-order theories (that is, without constant nor function symbols) equipped with a primitive equality predicate.

Syntax

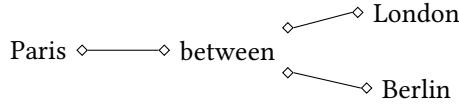
Spots In the propositional system Alpha, atomic graphs represent sentences that can be asserted or denied (or equivalently, assigned a truth value), but they do not exhibit any internal structure syntactically: they might as well be depicted just as (distinguished) points on SA. As most logicians of his time, Peirce was directly influenced by the *term logic* of Aristotle, where assertions are decomposed into a *subject* to which applies some *predicate*. However, while Aristotle's notion of predicate has a metaphysical flavor, Peirce's notion is purely grammatical. For instance, Aristotle rejected the sentence “The person sitting down is Socrates” as a genuine predication, because Socrates is an *individual*, and in his view predicates could only be so-called *universals* like “humans” or “mortals” [168]. In Beta there is no such restriction, and the previous sentence can

[168]: Smith (2022), ‘Aristotle’s Logic’

be represented by the following graph:

$$\text{The person sitting down} \diamond \text{---} \diamond \text{Socrates} \quad (8.1)$$

Here both “The person sitting down” and “Socrates” are modelled as unary predicates. The little diamonds, called *hooks* by Peirce, represent placeholders for the arguments (subjects) of each predicate, and the data of a predicate together with its hooks is called a *spot*¹⁹. Any predicate of arity n can then be represented by a spot with n hooks disposed freely around its periphery. For instance, the sentence “Paris is between London and Berlin” can be expressed by the graph



where “between” is modelled as a ternary predicate.

Lines of Identity To assert that there exists an individual who is both the person sitting down and Socrates in graph (??), we connect the two hooks with a so-called *line of identity* (LoI hereafter). In Peirce’s view, each point in a LoI denotes an individual of the universe represented by SA. Since scribing anything on SA means asserting its truth in the universe, then it suffices to reduce the truth of an individual to its existence, in order to interpret the marking of LoI as having existential force. This is actually the origin of the “existential” qualificative in the denomination “existential graph”. Note that no information is given but the individual’s existence: in particular, two distinct points on SA might or might not denote two distinct individuals, just as two distinct variables x and y might or might not refer to the same object. It is the *continuity* of a LoI that signifies, in an iconic way, the identity of every point/individual constituting, and connected by the line. Hence the following graph

$$\text{The person sitting down} \diamond \text{---} \text{---} \diamond \text{Socrates}$$

expresses that both the person sitting down and Socrates exist, but we do not know whether they are the same individual.

First-order logic “The person sitting down is Socrates” might be equivalently expressed in a first-order language as the formula

$$\exists x. \text{PersonSittingDown}(x) \wedge \text{Socrates}(x) \quad (8.2)$$

LoI can then be seen as encoding the concept of *existential quantification* over a single *variable* x , where the occurrences of x correspond to the extremities of the line connected to the hooks. As in Alpha, the conjunctive aspect of the sentence is accounted for by the fact that the two spots are juxtaposed in the same area on SA.

Now if one considers a first-order theory with a predicate symbol = satisfying the usual axioms for equality, then our sentence can alternatively

19: The use of diamonds to depict hooks is our own addition, Peirce never drew them explicitly.

be expressed by the following formula:

$$\exists x.\exists y.\text{PersonSittingDown}(x) \wedge \text{Socrates}(y) \wedge x = y \quad (8.3)$$

In Peirce's original notation, there is no way to distinguish between these two formulations, and they would both be represented by graph (??). However in [88], in order to have a rigorous interpretation of the syntax of Beta in category theory, the authors propose to analyze LoI into essentially two distinct icons, *binders* and *teridentities*²⁰, from which every LoI can be reconstructed:

Binder As we have just seen, one function of LoI is to *quantify* over individuals. For now we have only considered LoI located at the top-level of SA, i.e. in a *positive* area, where they are given *existential* force. If we were to negate the graph (??) by enclosing it in a cut, we would get a graph expressing the negation of formula (??), which by De Morgan duality is equivalent to

$$\forall x.\neg\text{PersonSittingDown}(x) \vee \neg\text{Socrates}(x)$$

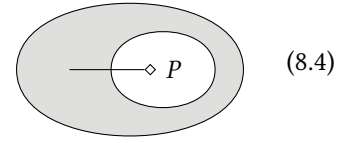
More generally, it is well-known that in classical logic, *universal* quantification can be defined symbolically by $\forall x.P(x) \triangleq \neg\exists x.\neg P(x)$, and hence that any formula in the usual language of FOL has a classically equivalent formula in the fragment $\{\neg, \wedge, \exists\}$. This is precisely how Peirce expresses universal quantification in Beta, as illustrated for a unary predicate P by the graph (??) of Figure ?? . But in order to interpret correctly this graph, one needs to adopt what Peirce calls an *endoporeutic*²¹ reading of EG, where they are inspected starting from the top-level of SA, and then descending (recursively) into their various cuts. In particular, the location of a LoI should be identified with its *outermost* end, as illustrated in graph ??; if we were to associate it instead with its innermost end as in graph (??), then we would swap the positions of \exists and \neg in the associated statement, giving the non-equivalent formula $\neg\exists x.P(x)$.

From these observations, we get that the type of quantification performed by a LoI is fully captured by its location: existential in a positive area, universal in a negative area. This leads us to analyze the syntax of LoI into two components: so-called *binders* that encode *quantifiers* as distinguished heavy dots on SA like those of Figure ??²²; and two-ended *wires* that connect binders to the hooks of predicates, encoding the *identity* between a bound variable x and an occurrence of x .

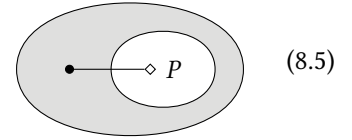
Remark 8.7.1 The graph of universal quantification (??) bears a striking similarity to that of implication, as illustrated in Figure ?? . While the similarity also exists for the symbolic encoding of these connectives in the fragment $\{\neg, \wedge, \exists\}$ captured by Beta, the graphical representation makes this fact more apparent. In constructive type theories, both universal quantification $\forall x.B$ and implication $A \supset B$ are seen as instances of a more general construct, the *dependent product type* $\Pi x : A.B$. Thus retrospectively, one might interpret the above observation as another manifestation of Peirce's pre-intuitionistic conception of logic.

[88]: Haydon et al. (2020), 'Compositional Diagrammatic First-Order Logic'

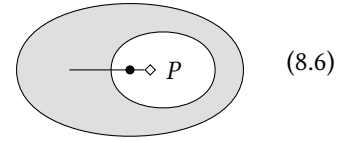
20: This is our own terminology, chosen mainly for historical reasons. In [88], binders and teridentities correspond respectively to the generators of the monoid-comonoid pair of a Frobenius algebra.



(8.4)



(8.5)



(8.6)

Figure 8.8: Universal quantification $\forall x.P(x)$ in Beta

21: From the greek *endon* ('within') and *poros* ('passage, pore') [151], literally "that lets through within". This physically-flavored terminology is reminiscent of the intuition we developed within our own bubble calculus and illustrated in Figure ??, even though we were not aware of the existence of EG at the time!

22: Peirce liked to insist that LoI should be drawn as *heavy* lines, to distinguish them from the normal lines used to depict cuts.

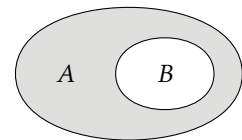
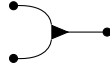


Figure 8.9: Implication $A \supset B$ in Alpha

Teridentity Binders and wires are sufficient to express unary predicates applied to distinct bound variables, but they cannot identify multiple occurrences of the *same* variable, and thus cannot account for graph (??). To palliate this, we can introduce a new construct called *teridentity*, that we propose to represent as a black triangle ►. The three vertices of the triangle should be seen as three plugs on which one can connect wires, so that the graph

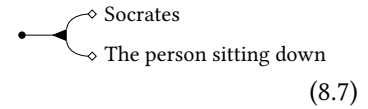


can be interpreted as the formula $\exists x.\exists y.\exists z.x = y \wedge y = z$. Rather than a way to express equality between variables, we think it is more useful however to have an *operational* understanding of teridentities: their real purpose is to *duplicate* wires (e.g. by splitting them), or dually to *merge* two wires into a single one. This gives a constructive way to explain the notion of *occurrence* of a variable²³. Then formulas (??) and (??) can be represented faithfully and respectively by the graphs (??) and (??) of Figure ??.

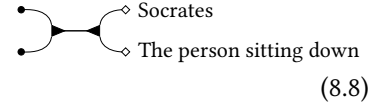
LoI (or their decomposition into the above constructs) constitute the only icons introduced in Beta compared to Alpha.

Iconic atomicity The fact that Peirce took LoI to be a primitive, unanalyzed icon can be seen as a consequence (or a cause?) of his view that only *closed* sentences should be considered. Indeed in an early exposition of EG (Ms 493), he proposed a way to show, if necessary, that “a complete assertion is not intended” [161, p. 49]. That is, he devised a syntax equivalent in purpose to that of *free variables* in predicate calculus. Our analysis into wires that connect hooks, binders and teridentities allows this, and more generally makes the syntax of graphs closer to predicate calculus. But in later expositions, Peirce always required every hook to be filled with a LoI, that is every variable to be quantified.

Now, it is unclear which of those presentations is the more “analytical” or primitive, when restricting oneself to closed (or in Peirce’s terminology, complete) assertions. Indeed, consider that we give the force of quantification to wires, as Peirce does with LoI: then one can replace every binder by a dangling wire, rendering binders useless in the syntax. Also since empty hooks and teridentities are forbidden, they will always be filled with wires. Then couldn’t we just reduce the full syntax of LoI to wires? A remarkable insight of Peirce, is that one cannot build the concept of teridentity from two-ended wires, but that the converse is possible, as illustrated in Figure ???. This is most clearly (and speculatively) understood by seeing LoI as made out of *pipes* rather than wires. Indeed, just gluing one extremity of a two-ended pipe P to the exterior of another pipe Q will not make P and Q communicate; and there is no reason to interpret the joining, or (infinitesimally) close juxtaposition of two lines on SA at one point, as doing more than the gluing of two pipes²⁴. One solution would be to first drill a hole in Q, before glueing P on it. Another is to have *branching* pipes as the basic building blocks for our plumbing, i.e. teridentities. This is how we interpret and justify metaphorically the following enigmatic quote from Peirce [161, p. 116]:



(8.7)



(8.8)

Figure 8.10: Decomposing lines of identity

23: A very similar metaphor is brought up by Girard in [68], where the fact that a variable can have infinitely many occurrences is seen precisely as a consequence of the possibility to split or “debit” indefinitely a wire into smaller wires.

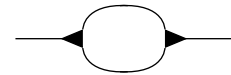



Figure 8.11: Building a two-ended wire from two teridentities

24: If one wants to keep the wire metaphor, joining two LoI can be interpreted as just putting in contact two wires. Then electrical current can flow from one wire to the other, but the problem resides elsewhere, at the *illative* level: indeed nothing prevents us from separating back the two wires, or connecting two initially disjoint wires. But in a negative (resp. positive) context, the former (resp. latter) action corresponds to forgetting a possibly necessary equality hypothesis between two variables (resp. identifying two possibly distinct individuals), which is not valid logically speaking. To prevent this, one needs to do more than just put the two wires in contact with each other (juxtaposition), i.e. solder them together (teridentity).

Teridentity is not mere identity. It is identity and identity, but this ‘and’ is a distinct concept [from that denoted by the juxtaposition of graphs on SA], and is precisely that of teridentity.

Then every LoI can be built out of teridentities, which Peirce expressed like so [161, p. 117]:

Every line of identity ought to be considered as bristling with microscopic points of teridentity; so that _____ when magnified shall be seen to be .

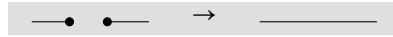
Rules

A remarkable fact about Beta is that it does not need any new illative principle compared to Alpha. Rather, it simply generalizes those of Alpha to account for LoI²⁵.

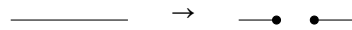
Iteration/Deiteration When a spot is iterated, every hook of the new copy must be connected to the same hook of the original copy with a LoI. Conversely, when a spot is deiterated, every LoI of the deleted copy must be retracted to the corresponding hook of the original copy. This applies in particular to any binder seen as a unary spot, which allows to extend (resp. retract) any LoI inside (resp. outside) a cut:



Insertion/Deletion Every pair of binders residing in the same negative area can be connected and replaced by a wire (Insertion):



Dually, every wire in a positive area can be severed in two, capping off the newly created ends with two binders (Deletion):



By reading the rules from right to left — i.e. in *proof search* mode, Insertion and Deletion on LoI can be understood as capturing respectively the operations of *anti-unification* and *unification* on two variables. That is:

Unification adding a wire between two disconnected binders x and y is equivalent in purpose to substituting x for y (resp. y for x) in every spot/predicate connected by a LoI to y (resp. x);

Anti-unification while severing a wire connected to a binder z in two parts capped by binders x and y amounts to partitioning the set of spots connected to z in two sets $\{P_i\}$ and $\{Q_j\}$, and substituting x for z in every P_i , and y for z in every Q_j .

Unification and anti-unification are the heart of many (semi-)decision procedures implemented in automated and interactive theorem provers; thus it is remarkable that they constitute a core illative principle of Beta.

25: Thus in a sense, the first-order individuals denoted by LoI behave in the exact same way as the propositions denoted by the graphs of Alpha. This can be interpreted as a manifestation of Peirce’s *psycho-physical monism* [23], that blurs the distinction between the psychological level of propositions (concepts) and the physical level of individuals (objects) enforced in the language of predicate logic, and inherited from Aristotle’s conception of predication. Independently, Girard has recently been pushing the idea further in his transcendental syntax programme, by proposing to see individuals as particular kinds of *linear* propositions (see [55, §84.3]). And what is more linear than a line?

Remark 8.7.2 In the original Beta system, Peirce enforces the usual model-theoretic assumption that the universe of discourse must be non-empty — i.e. contain at least one individual, through an *axiom* permitting to “scribe a heavy dot or unattached line on SA” [161, p. 47]. In fact together with the axiom allowing to assert the blank SA, which was implicit in our notion of proof for Alpha (Definition ??), these are the only axiom in all systems of EG. This is yet another striking similarity with Girard’s philosophy, who attempted to get rid of axioms in logic starting with ludics — although in many of his writings, he actively criticizes the non-empty model assumption.

Figure ?? gives a proof of the famous syllogism from Aristotle in Beta, by reducing the graph associated to the formula

$$\begin{aligned} & \forall x. \text{Socrates}(x) \wedge \text{Human}(x) \wedge (\forall y. \text{Human}(y) \supset \text{Mortal}(y)) \supset \\ & \exists z. \text{Socrates}(z) \wedge \text{Mortal}(z) \end{aligned} \quad (8.9)$$

to the empty SA. Again, we invert the direction of arrows in inference steps, to follow the proof search reading of rules. Note that in many steps, we add or remove some teridentities and binders without further justification: these correspond to splits, merges and rewirings of LoI, and a more rigorous set of equations describing these operations can be found in [88, Section 3: “The algebra of lines of identity”].

The essence of the syllogism lies in the instantiation of the universally quantified variable y by x in formula (??), captured by the Deletion step in Figure ?. Thus contrary to Alpha, it seems that Deletion is not admissible in Beta anymore. Because of the *subterm property* of first-order logic [40], this should not break analyticity: indeed we should only need Deletion on LoI, which connects already existing binders. However one still needs to find out the binders that must be connected, which we conjecture to be a major factor in the undecidability of first-order logic.

[40]: Degtyarev et al. (2001), ‘The Inverse Method’



Figure 8.12: A proof of a famous syllogism in Beta

8.8 Gardens

Ergonomy of LoI Overall, the example of Figure ?? demonstrates how Beta is particularly well-suited to analyze the fine structure of relational reasoning: be it at the level of *statements*, with the complex circuits resulting from the composition of LoI; or at the level of *proofs*, with a decomposition of such a simple syllogism into 8 distinct inferential steps. While this is satisfying from the standpoint of meta-logical investigation originally pursued by Peirce, this syntax seems to be too cumbersome to form the basis for a practical theorem proving interface, where the user would perform illative transformations through direct manipulation of graphs. In the words of Peirce himself [150, p. 544]:

There are a number of deduced liberties of transformation, by which even much more complicated inferences than a syllogism can be performed at a stroke. For that sort of problem, however, which consists in drawing a conclusion or assuring oneself of its correctness, this System is not particularly adapted.

Variables Still, the complexity of Beta from a UX perspective stems mostly from the tedious management of LoI. Our analysis into binders and teridentities gives us a hint towards the solution: since we now have binders, why not just replace the complex circuits of teridentities by *variables*? The process is simple:

1. Take any complex LoI connected to n binders and m hooks;
2. Among the n binders, choose one that occurs in the outermost area of SA, and give it a fresh name x ;
3. Replace the m wires connected to the hooks by m occurrences of x ;
4. Erase all remaining wires and teridentities.

Thus for instance, both the first and second graphs in Figure ?? would be represented by the graph of Figure ??. In fact, Peirce already had the idea to use a name-based syntactic device similar to, and arguably more primitive than variables, which he called *selectives*, in order to avoid the ambiguity of LoI crossing cuts [150, p. 531]:

A Ligature crossing a Cut is to be interpreted as unchanged in meaning by erasing the part that crosses to the Cut and attaching to the two Loose Ends so produced two Instances of a Proper Name nowhere else used; such a Proper name (for which a capital letter will serve) being termed a *Selective*.

The idea of connecting two locations by marking them with the same symbol is quite natural, and is implemented for instance in *footnotes* — or in this thesis, *sidenotes* — with the help of *numbers* rather than capital letters. Footnotes are a good example, because contrary to variables, they share with selectives a *linearity* property, that exactly *two* occurrences of the symbol must be present. This is necessary to simulate accurately a two-ended wire, and it is not surprising that the same device has been used recently (under the name of *ports*) to give an algebraic syntax to *interaction nets* [49], a model of computation inspired by *linear logic* and its graphical, string-diagram like syntax of *proof nets* [66].

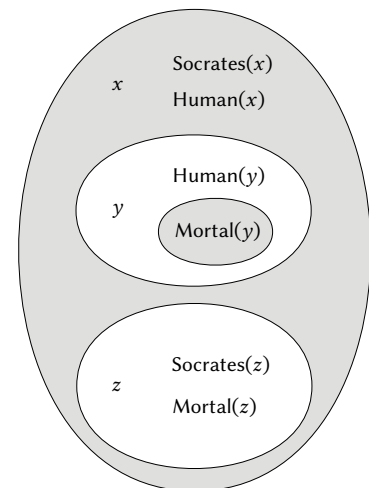


Figure 8.13: Using variables in EG

[49]: Dorman et al. (2013), 'A Hierarchy of Expressiveness in Concurrent Interaction Nets'

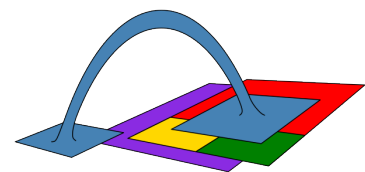


Figure 8.14: A depiction of Peirce's Bridge for lines of identity

Source: https://commons.wikimedia.org/wiki/File:4CT_Inadequacy_Explanation.svg

Bridges After introducing selectives, Peirce further remarks on the next page:

In order to avoid the intersection of Lines of Identity, either a Selective may be employed, or a *Bridge*, which is imagined to be a bit of paper ribbon.

Thus he already identified the problem of readability stemming from having too many wires crossing each other, a well-known concern in the design of graphical programming languages²⁶. The proposed alternative solution of having so-called *bridges* is quite interesting, in that it makes the syntax of EG *three-dimensional*, in order to preserve the continuity of lines. A nice illustration of the bridge is given in Figure ?? . We found this picture in the Wikipedia article of the *four color theorem* [191], which is no coincidence according to Burch [23]:

Peirce began to research the four-color map conjecture, to work on the graphical mathematics of de Morgan's associate A. B. Kempe, and to develop extensive connections between logic, algebra, and topology, especially topological graph theory. Ultimately these researches bore fruit in his existential graphs [...]

Multisets The Wikipedia article on Alfred Kempe also mentions the following interesting fact [190]:

Kempe (1886) revealed a rather marked philosophical bent, and much influenced Charles Sanders Peirce. Kempe also discovered what are now called multisets, although this fact was not noted until long after his death [107][78].

As it turns out, we can also give a multiset formalization of the syntax of graphs in Beta extending that of Section ??, and based on the previous idea of replacing teridentities by variables. Every area will now be equipped with a set of binders, in addition to the multiset of nodes (i.e. atoms and cuts). Anticipating our flower metaphor of Chapter ??, we call sets of binders *sprinklers*, which can be imagined as watering spots on their hooks by sending water through the (now invisible) LoI, seen as hoses. Naturally, the pair formed by a sprinkler and a multiset of nodes is called a *garden*.

26: This is to be opposed to critics of the syntax of EG such as Quine, who devised a notation similar to LoI, and deemed it “too cumbersome for practical use” [161, p. 125].

[107]: Kempe (1886), ‘A memoir on the theory of mathematical form’

[78]: Grattan-Guinness (2000), *The Search for Mathematical Roots, 1870-1940: Logics, Set Theories and the Foundations of Mathematics from Cantor through Russell to Godel*

Definition 8.8.1 (β -graph) *Given a denumerable set of variables \mathcal{V} and a denumerable set of predicate symbols \mathcal{P} together with their arities $\text{ar} : \mathcal{P} \rightarrow \mathbb{N}$, the sets of β -nodes \mathbf{N}_β , β -gardens Γ_β and β -graphs \mathbf{G}_β are defined mutually inductively as follows:*

- ▶ **(Spot)** *If $p \in \mathcal{P}$ with $\text{ar}(p) = n$, then $p(x_1, \dots, x_n) \in \mathbf{N}_\beta$;*
- ▶ **(Graph)** *If $G \subset \mathbf{N}_\beta$ is a finite multiset, then $G \in \mathbf{G}_\beta$.*
- ▶ **(Garden)** *If $x \in \mathcal{V}$ is a finite set and $G \subset \mathbf{N}_\beta$ a finite multiset, then $x \cdot G \in \Gamma_\beta$;*
- ▶ **(Enclosure)** *If $\gamma \in \Gamma_\beta$, then $[\gamma] \in \mathbf{N}_\beta$.*

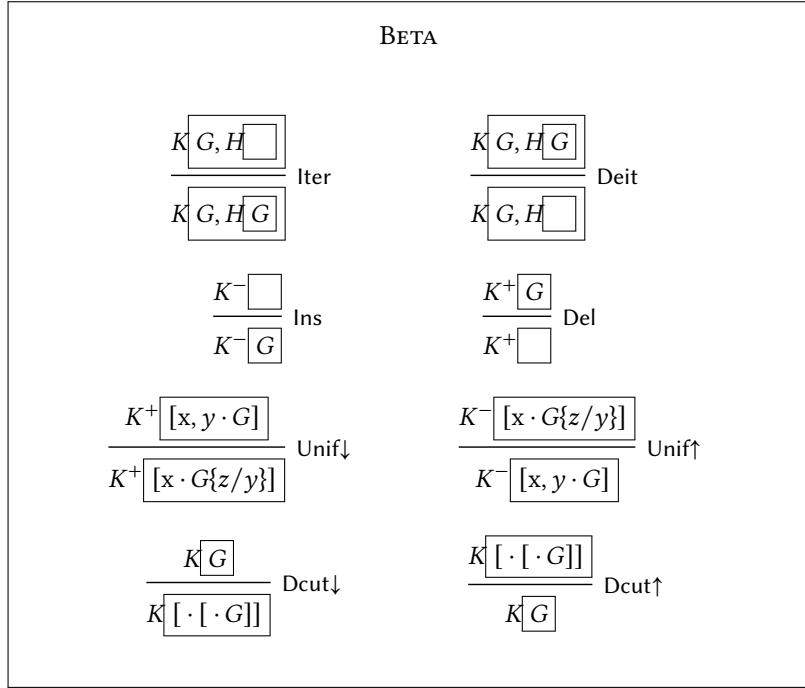


Figure 8.15: Inductive presentation of the rules of Beta

Example 8.8.1 The graph of Figure ?? can be written in textual notation as the following expression:

$$\begin{aligned} &[x \cdot \text{Socrates}(x), \text{Human}(x), \\ &[y \cdot \text{Human}(y), [\cdot \text{Mortal}(y)]], \\ &[z \cdot \text{Socrates}(z), \text{Mortal}(z)]] \end{aligned}$$

Note that the ‘ \cdot ’ operator for constructing gardens has lower precedence than the ‘ $,$ ’ operator for juxtaposition of graphs. Thus the expression $x \cdot \text{Socrates}(x), \text{Human}(x)$ is to be read as $x \cdot (\text{Socrates}(x), \text{Human}(x))$, and not $(x \cdot \text{Socrates}(x)), \text{Human}(x)$ (which would be ill-typed anyway).

Inference rules As already suggested earlier, the garden syntax for β -graphs quotients the LoI syntax: the first Deiteration step in Figure ?? cannot be performed in the garden syntax, because its premiss and conclusion are represented by the same graph. In fact, both Iteration and Deiteration are automatically handled by the notion of *scope* for binders, that results from the endoporeutic reading of graphs. Then it only remains to account for Insertion and Deletion on LoI, which is done by capturing our intuition relating these principles to *unification* in the rules $\text{Unif}\downarrow$ and $\text{Unif}\uparrow$ of Figure ??, respectively. Thus the inductive version of Beta is obtained by simply adding these two rules to those of Alpha introduced in Figure ??.

Figure ?? gives a derivation of Aristotle’s syllogism in this system. Even though we do not apply the Deit rule anymore compared to the graphical proof of Figure ??, we need two additional instances of $\text{Unif}\uparrow$ on z and x , that would correspond to two instances of Del on the associated LoI.

$$\begin{aligned} &\frac{\frac{\frac{}{[\cdot [\cdot]]} \text{Dcut}\downarrow}{[x \cdot [\cdot]]} \text{Unif}\uparrow}{[x \cdot \text{Socrates}(x), \text{Mortal}(x), [\cdot]]} \text{Ins} \\ &\frac{[x \cdot \text{Socrates}(x), \text{Mortal}(x), [\cdot \text{Socrates}(x), \text{Mortal}(x)]]}{[x \cdot \text{Socrates}(x), \text{Mortal}(x), [z \cdot \text{Socrates}(z), \text{Mortal}(z)]]} \text{Unif}\uparrow \\ &\frac{[x \cdot \text{Socrates}(x), [\cdot [\cdot \text{Mortal}(x)]], [z \cdot \text{Socrates}(z), \text{Mortal}(z)]]}{[x \cdot \text{Socrates}(x), \text{Human}(x), [\cdot [\cdot \text{Mortal}(x)]], [z \cdot \text{Socrates}(z), \text{Mortal}(z)]]} \text{Dcut}\downarrow \\ &\frac{[x \cdot \text{Socrates}(x), \text{Human}(x), [\cdot [\cdot \text{Mortal}(x)]], [z \cdot \text{Socrates}(z), \text{Mortal}(z)]]}{[x \cdot \text{Socrates}(x), \text{Human}(x), [y \cdot \text{Human}(y), [\cdot \text{Mortal}(y)]], [z \cdot \text{Socrates}(z), \text{Mortal}(z)]]} \text{Ins} \\ &\frac{[x \cdot \text{Socrates}(x), \text{Human}(x), [y \cdot \text{Human}(y), [\cdot \text{Mortal}(y)]], [z \cdot \text{Socrates}(z), \text{Mortal}(z)]]}{[x \cdot \text{Socrates}(x), \text{Human}(x), [y \cdot \text{Human}(y), [\cdot \text{Mortal}(y)]], [z \cdot \text{Socrates}(z), \text{Mortal}(z)]]} \text{Unif}\uparrow \end{aligned}$$

Figure 8.16: A proof in the inductive syntax of Beta

Remark 8.8.1 As in Alpha, β -graphs G, H, K and their one-holed contexts $G\Box, H\Box, K\Box$ are multisets of β -nodes. But now they do not correspond anymore to *areas* in the graphical notation, which are instead captured by gardens γ, δ, χ . In particular, this entails a subtle difference from Peirce's formulation of Beta: because rules apply to graphs and not gardens, one cannot have binders at the top-level of SA, they must be enclosed in at least one cut. Thus to be able to reason on (the garden version of) the graph (??), we must first enclose it in a double-cut, giving the graph

$$[\cdot [x \cdot \text{TheSittingPerson}(x), \text{Socrates}(x)]]$$

While this choice might seem confusing, it makes the formulation of rules more uniform with that of Alpha, and will ease the transition to the flower calculus in Chapter ??.

Note that the rules $\text{Unif}\downarrow$ and $\text{Unif}\uparrow$ rely on the usual notion of capture-avoiding substitution:

Definition 8.8.2 (β -graph substitution) *The capture-avoiding substitution of a variable y for a variable x in a β -graph G , written $G\{y/x\}$, is defined by mutual recursion as follows:*

$$\begin{aligned} p(x_1, \dots, x_n)\{y/x\} &= p(z_1, \dots, z_n) \text{ with } z_i = \begin{cases} y & \text{if } x_i = x \\ x_i & \text{otherwise} \end{cases} \\ g_1, \dots, g_n\{y/x\} &= g_1\{y/x\}, \dots, g_n\{y/x\} \\ (z \cdot G)\{y/x\} &= \begin{cases} z \cdot G\{y/x\} & \text{if } x \notin z \\ z \cdot G & \text{otherwise} \end{cases} \\ [\gamma]\{y/x\} &= [\gamma\{y/x\}] \end{aligned}$$

Also, this system supports free variables, and there is no need to forbid them like Peirce did in his original LoI-based syntax.

In a certain flower garden, each flower was either red, yellow, or blue, and all three colors were represented. A statistician once visited the garden and made the observation that whatever three flowers you picked, at least one of them was bound to be red. A second statistician visited the garden and made the observation that whatever three flowers you picked, at least one was bound to be yellow. Two logic students heard about this and got into an argument. The first student said: "It therefore follows that whatever three flowers you pick, at least one is bound to be blue, doesn't it?" The second student said: "Of course not!". Which student was right, and why?

Raymond Smullyan, *The Flower Garden*, 1985

We introduce the *flower calculus*, a novel proof system for intuitionistic predicate logic based on syntactic objects called *flowers*. We start by explaining how flowers stem from considerations in graphical logic, and more specifically from an intuitionistic variant of the *existential graphs* of C. S. Peirce proposed by A. Oostra. Then we present our inductive syntax for flowers, reminiscent at the same time of the nested sequents of deep inference proof theory, and the geometric/coherent formulas of categorical logic. A salient feature of our calculus inherited from EG, is that it is *fully iconic*: it dispenses completely with the traditional notion of symbolic formula, operating instead as a rewriting system on flowers containing only atomic predicates. We also propose a notion of proof geared towards analyticity results à la Gentzen, suggesting new rules absent from other works on intuitionistic EG. This allows us to prove admissibility theorems for many rules, including Peirce's deletion rule which is a variant of Gentzen's cut rule. These results are obtained as a consequence of our soundness and completeness proofs with respect to Kripke semantics, in the spirit of the *normalization-by-evaluation* technique. Furthermore, the kernel of rules targetted by completeness is fully invertible, a desirable property in both automated and interactive proof search. This is illustrated by our implementation of the Flower Prover, an early prototype of GUI for ITP that uses the rules of the flower calculus both for direct manipulation of flowers in its frontend, and automated simplification of goals in its backend.

The chapter is organized as follows: in Section ??, we retrace the origin of Oostra's syntax for intuitionistic EG (hereafter "IEG") as a natural generalization of the *scroll*, an icon for implication introduced by Peirce that inspired the very creation of EG. In Section ??, we explain how flowers are really just a fun and metaphorical way to draw IEG, and proceed to give them an inductive, multiset-based syntax as in Section ??. In Section ??, we introduce the full set of inference rules of the flower calculus as well as our notion of proof, and prove a few syntactic properties, including two deduction theorems. In Section ??, we give a direct Kripke semantics to flowers, avoiding the need for translations to and from formulas. In Section ??, we show that the rules of the flower calculus are valid with respect to our Kripke semantics, and in Section ?? we identify a complete

fragment of the system where all rules are both *analytic* and *invertible*. This entails the admissibility of all rules outside of this fragment, and as a consequence the analyticity of the system. We exploit these properties in Section ?? by describing an algorithm for fully automated proof search in the propositional fragment; unfortunately, the current version of the algorithm is neither terminating nor complete. Then in Section ?? we give an overview of the Flower Prover, a prototype of GUI in the Proof-by-Action paradigm whose actions map directly to the rules of the flower calculus, and which integrates nicely with (a restricted version of) our search procedure. We conclude in Section ?? by a comparison with some related works, and a discussion of future works and applications that we envision.

9.1 Intuitionistic existential graphs

The Scroll In Section ??, we presented the syntax of existential graphs (EG) as stemming from two fundamental icons: the *sheet of assertions* (SA), with its ability to represent the conjunction of assertions through *juxtaposition*, and *cuts* in SA that signify the denial or negation of assertions. However as noted in Remark ??, the first interpretation of juxtaposition proposed by Peirce was that of *disjunction*, in his system of *entitative graphs*. According to him, the illative transformations of EG are a necessary consequence of the *conjunctive* interpretation of juxtaposition, as witnessed by the following excerpt [150, p. 533]:

[150]: Peirce (1906), ‘Prolegomena to an Apology for Pragmatism’

If you carefully examine the above conventions, you will find that they are simply the development, and excepting in their insignificant details, the inevitable result of the development of the one convention that if any Graph, A, asserts one state of things to be real and if another graph, B, asserts the same of another state of things, then AB, which results from setting both A and B upon the sheet, shall assert that both states of things are real.

He goes on to notice:

This was not the case with my first system of Graphs, described in Vol. VII of The Monist, which I now call Entitative Graphs. But I was forced to this principle by a series of considerations which ultimately arrayed themselves into an exact logical deduction of all the features of Existential Graphs.

Thus the conjunctive reading of juxtaposition itself stemmed from “a series of considerations” that “forced” Peirce to adopt it. While in this article he does not give the full “exact logical deduction of all the features of Existential Graphs”, he exposes in some details the initial and determining insight that kickstarted the whole development: the discovery of the icon called the *scroll*. Again, I will let Peirce speak for himself [150, pp. 533–534]:

Accordingly, since logic has primarily in view argument, and since the conclusiveness of an argument can never be weakened by adding to the premisses or by subtracting from the conclusion, I thought I ought to take the general form of

argument as the basal form of composition of signs in my diagrammatization; and this necessarily took the form of a “scroll”, that is [...] a curved line without contrary flexure and returning into itself after once crossing itself, and thus forming an outer and an inner “close”.

Figure ?? shows Peirce’s drawing of the scroll as it appears in [150, Fig. 5]. He defines its intended meaning like so [150, p. 534–535]:

I shall call the outer boundary the Wall; and the inner, the Fence. In the outer I scribed the Antecedent, in the inner the Consequent, of a Conditional Proposition *de inesse*. [...] [Thus the meaning of Figure ?? is] that if both A and B are true, then both C and D are true. [...] a Conditional *de inesse* (unlike other conditionals) only asserts that either the antecedent is false or the consequent is true.

This shows the classical view of Peirce on EG, who interprets the scroll as signifying the *conditional de inesse* — also called nowadays *material implication*, and defined here in its disjunctive form, expressed symbolically by $A \supset B \triangleq \neg A \vee B$. This is no coincidence that Peirce based his most fundamental icon on implication: according to Lewis [113, p. 79], he was the one who introduced the “illative relation” of implication into symbolic logic in the first place, by giving it a distinguished symbol, and studying extensively the algebraic laws that govern it (including Peirce’s law).

Blank Antecedent A first principle that Peirce derives from the scroll is the following [150, p. 534]:

[...] any insertion [is] permitted in the outer close, and any omission from the inner close. By applying the former clause of this rule to [Figure ??], we see that this scroll with the outer close void, justifies the assertion that if no matter what be true, C is in any case true; so that the two walls of the scroll, when nothing is between them, fall together, collapse, disappear, and leave only the contents of the inner close standing, asserted, in the open field.

This first form of “collapsing of walls” is called the *Rule of Blank Antecedent* in [130], and corresponds symbolically to the equivalence $\top \supset A \simeq A$. The reader might be tempted to see the “former clause” that permits any insertion in the outer close as a special case of the Insertion principle of Alpha (Section ??). However, we stress again that Peirce first identified this clause as a feature of the scroll, seen as the diagrammatic embodiment of the “general form of argument” mentioned in a previous excerpt. The principle of Insertion only followed as a subsequent generalization, stemming from the analysis of the scroll into two nested cuts [150, p. 535]:

[...] and you will further see that a scroll is really nothing but one oval within another.

To emphasize this point, we will from now on depict scrolls as two nested cuts joined at a single point highlighted in orange, as illustrated in Figure ??.

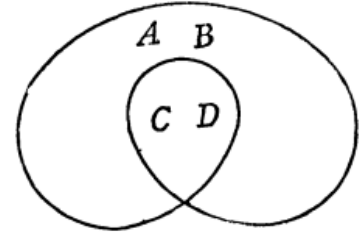


Figure 9.1: Peirce’s scroll

[113]: Lewis (1920), ‘A Survey of Symbolic Logic’

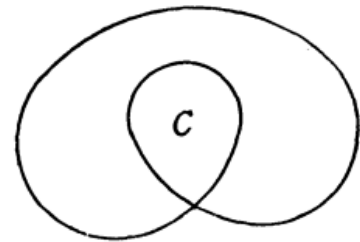


Figure 9.2: Peirce’s scroll with a blank antecedent

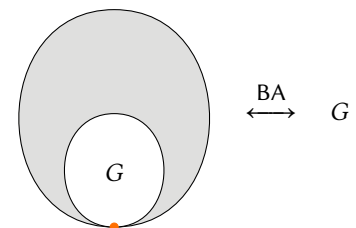


Figure 9.3: The rule of Blank Antecedent

Remark 9.1.1 It is interesting to note that the rule of Blank Antecedent is not seen as primitive by Peirce, but as a consequence of a *dynamic potential* of the scroll: namely, the ability to insert anything in the outer close, at will. This is another manifestation of Peirce’s concern for the question of *illative atomicity*, and is to be related to the elimination of the Double-cut rule discussed in Section ??.

Currying Peirce was aware of the phenomenon of *currying*, expressed symbolically by the equivalence $A \supset B \supset C \simeq A \wedge B \supset C$, as witnessed by the following passage [150, p. 535]:

Now, Reader, if you will just take pencil and paper and scribe the scroll expressing that if A be true, then it is true that if B be true C and D are true [Figure ??], and compare this with [Figure ??], which amounts to the same thing in meaning, you will see that scroll walls with a void between them collapse even when they belong to different scrolls.

It is remarkable that he comes to this conclusion by a topological argument, noting that this second form of “collapsing of walls”, now involving two different scrolls, follows from the scroll beeing composed of two nested cuts. If we reject this interpretation by requiring that the Fence (the inner oval) stays glued to the Wall (the outer oval), then one cannot derive currying through the rule of double-cut, precisely because the system only permits to collapse a Wall and a Fence continuously joined in the same scroll, by the weaker rule of Blank Antecedent. Fear not however, as one can still derive the currying and uncurrying laws in this intuitionistic setting, but through the additional use of the insertion and deiteration rules, as depicted in Figure ?? and Figure ?. Yet we find that Peirce’s insight on the topological explanation of currying in the classical setting remains noteworthy.

Remark 9.1.2 Note that in Figure ?? and Figure ??, we give *direct* proofs that rewrite the premiss of the argument into its conclusion, rather than *goal-directed* proofs (Definition ??) that rewrite a goal into the empty SA, as we usually did in Chapter ?. Direct proofs are closer to Peirce’s usage of the illative transformations — and thus to what can be found in most of the literature on EG, and have the advantage of being more economical in space by leaving the goal implicit. One can easily go from a direct proof to a goal-directed one as shown by the *deduction theorem* of Sowa [170, Section 6], which also applies in the intuitionistic setting by substituting the rule of Double-cut with the rule of Blank Antecedent.

The n -ary scroll In [141], A. Oostra proposes to take the above remark seriously, by reifying the scroll as a primitive icon of EG (“*rizo*” in Spanish), that exists alongside the cut (“*corte*”), and is distinguished from it. In fact he goes further than this, and proposes to generalize both the cut and the scroll into an n -ary construction called the *curl* (“*bucle*”), where n is the number of inner closes, called *loops* (“*lazos*”). Figure ?? shows an example of curl with five loops. In [130], the curl is simply called *n -ary scroll*, and is analyzed into the outer area (that enclosed by the Wall)

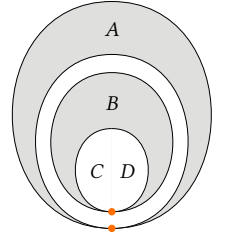


Figure 9.4: Currying as scroll nesting

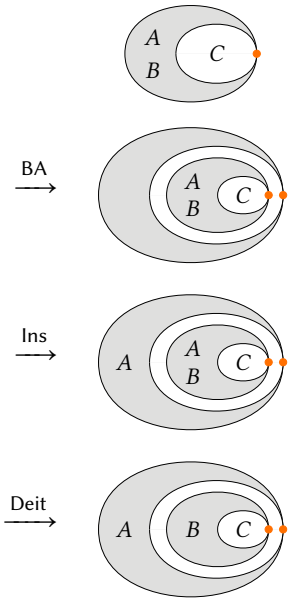


Figure 9.5: Intuitionistic proof of currying

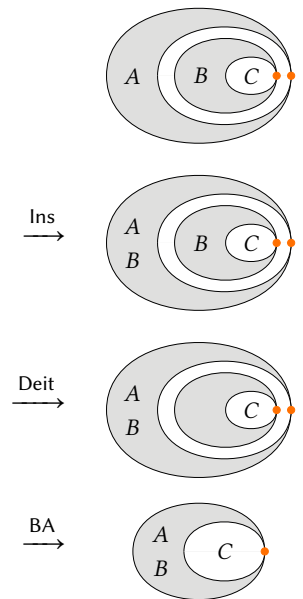


Figure 9.6: Intuitionistic proof of uncurrying

called the *outloop*, and the inner areas (those enclosed by the n Fences, i.e. the loops of Oostra) called the *inloops*. Then cuts and scrolls are indeed special cases of n -ary scrolls, respectively with $n = 0$ and $n = 1$.

Like the unary scroll, the n -ary scroll is to be read as an implication whose antecedent is the content of the outloop, and consequent the content of the inloops. The generalization then consists in taking the *disjunction* of the contents of all inloops: this reflects nicely the etymological meaning of the word “disjunction”, since the inloops enclose *disjoint* areas of the outloop to which they are attached. Then the 5-ary scroll of Figure ?? is read as the formula $a \supset b \vee c \vee d \vee e \vee f$; and the 0-ary scroll obtained by removing all inloops from the latter as $a \supset \perp$, since a 0-ary disjunction is naturally evaluated to its neutral element \perp . This coincides with the intuitionistic reading of negation $\neg A \triangleq A \supset \perp$, and is thus consistent with the interpretation of cuts as negations.

Continuity With this interpretation of the n -ary scroll, the Alpha encodings of disjunction and implication as nested cuts are no longer valid, because they are not intuitionistically equivalent to the associated binary and unary scrolls. This is illustrated in Figure ??, where the closeness in meaning is reflected iconically (but not symbolically) in the fact that the graphs only differ in the *continuity* (or lack thereof) between inloops and their outloop. Indeed, contrary to nested cuts, any n -ary scroll can be drawn by a *continuous* movement of the pen, producing a self-intersecting curve as described by Peirce in [150]. This might be related to other manifestations of the notion of continuity in the semantics of intuitionistic logic, such as the well-known Stone-Tarski interpretation of formulas as topological spaces [176], and the interpretation of proofs as continuous maps in the *denotational semantics* of Dana Scott [2]. Before the advent of Oostra’s IEG, Zalamea gave a detailed analysis of Peirce’s philosophy of the *continuum*, how it relates to modern developments in mathematics, and how it is embodied in existential graphs [197]. Actually according to Oostra [142, p. 162], “the possibility of developing intuitionistic existential graphs was first suggested by Zalamea in the 1990s [195][196]”.

Coherent formulas More generally, a n -ary scroll with atoms $G :=$

a_1, \dots, a_m in its outloop and $\Delta := \begin{pmatrix} a_{1,1} & \dots & a_{1,p_1} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \dots & a_{n,p_n} \end{pmatrix}$ in its inloops, where each row H_j in Δ encodes an inloop, can be interpreted as the formula

$$\bigwedge_{i=1}^m a_i \supset \bigvee_{j=1}^n \bigwedge_{k=1}^{p_n} a_{j,k}$$

If one adds *binders* to the mix (see Section ??) by having $\gamma := x \cdot G$ as

outloop, and $\Xi := \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \cdot \Delta$ as inloops, then the interpretation is extended

into the formula

$$\forall x. \left(\bigwedge_{i=1}^m a_i \supset \bigvee_{j=1}^n \exists x_j. \bigwedge_{k=1}^{p_n} a_{j,k} \right)$$

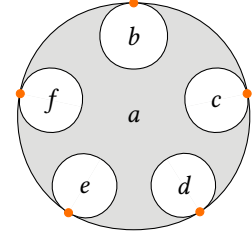


Figure 9.7: A curl with five loops

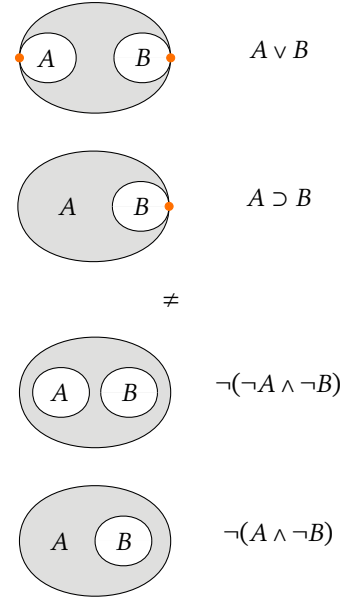
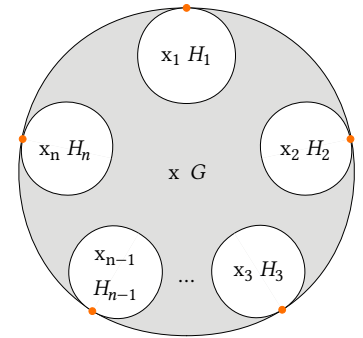


Figure 9.8: Continuity, disjunction and implication in IEG

[2]: Abramsky et al. (1995), ‘Domain Theory’

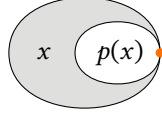
[142]: Oostra (2022), ‘Advances in Peircean Mathematics: The Colombian School’



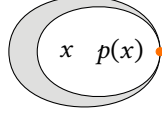
$$\forall x. \left(\bigwedge G \supset \bigvee_{j=1}^n \exists x_j. \bigwedge H_j \right)$$

Figure 9.9: Formula interpretation of the n -ary scroll

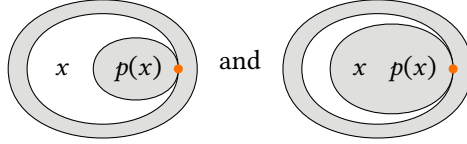
as depicted in Figure ?? . Typically, the particular case where $\gamma := x \cdot \emptyset$ and $\Xi := (\emptyset) \cdot (p(x))$ encodes the graph



expressing the universal quantification $\forall x.p(x)$, and the case where $\gamma := \emptyset \cdot \emptyset$ and $\Xi := (x) \cdot (p(x))$ the graph



expressing the existential quantification $\exists x.p(x)$. The interpretation is invariant under polarity, meaning that for instance the graphs



obtained by enclosing the previous graphs in a cut are interpreted with the same quantifiers, as the formulas $\neg\forall x.p(x)$ and $\neg\exists x.p(x)$. In Beta, we would have exploited the classical equivalences $\neg\forall x.A \simeq \exists x.\neg A$ and $\neg\exists x.A \simeq \forall x.\neg A$ (justified by the double-cut principle) in order to interpret them as $\exists x.\neg p(x)$ and $\forall x.\neg p(x)$, emphasizing the idea that positive and negative binders encode respectively \exists and \forall . But this is not possible anymore with the intuitionistic interpretation of n -ary scrolls, where the \exists/\forall duality is replaced by the inloop/outloop distinction. In fact, we are tempted to further qualify this distinction of *adjunction*, following a classical result of Lawvere in the context of categorical logic [111].

Lawvere is also known for some contributions to the study of *geometric logic* [110], a subset of the formulas of FOL first discovered by Skolem [167] that is capable of expressing many mathematical theories, and has close connections to *topos theory*. Quite remarkably, the interpretation of n -ary scrolls coincides exactly with the class of *coherent formulas*, which are the formulas of geometric logic where infinitary disjunctions are restricted to finitary ones. There is a difference however: the full syntax of IEG allows for arbitrary *nestings* of n -ary scrolls inside eachother, i.e. the multisets G and H_j in Figure ?? can contain n -ary scrolls in addition to atoms; while coherent formulas are restricted to atoms.

Coherent formulas have some nice properties, which might also apply to IEG to some extent. We only mention two important ones:

Completeness Every first-order theory has a coherent conservative extension, making coherent formulas (and thus non-nested n -ary scrolls) in principle as expressive as arbitrary first-order formulas [53].

[111]: Lawvere (1970), ‘Quantifiers and Sheaves’

[110]: Lawvere (1975), ‘Continuously Variable Sets; Algebraic Geometry = Geometric Logic’

[167]: Skolem (1920), ‘Logisch-Kombinatorische Untersuchungen Über Die Erfüllbarkeit Oder Bewiesbarkeit Mathematischer Sätze Nebst Einem Theorem Über Dichte Mengen’

[53]: Dyckhoff et al. (2015), ‘Geometrization of First-Order Logic’

Automation Coherent formulas benefit from faster proof-search procedures compared to arbitrary formulas, making automation more tractable computationally. They also allow the direct encoding of many reasoning problems, thanks to their use of the full set of connectives and quantifiers of FOL; and avoiding complex encodings (as can be found e.g. in SMT solvers) is crucial in *interactive* theorem proving, where the user and the computer manipulate the same formulas in goals [14]. This has been exploited already in some domain-specific theorem provers, like the Larus prover that automatically generates illustrated proofs in geometry¹ [101].

Remark 9.1.3 Thus with IEG, one becomes able to reason *geometrically* on geometric formulas that speak about geometry: another beautiful incarnation of the reflexivity at work in Peirce's iconic logic.

[14]: Bezem et al. (2005), 'Automating Coherent Logic'

1: Incidentally, projective geometry was one of the motivating applications that led Skolem to identify the class of coherent formulas [14].

[101]: Janičić et al. (2023), 'Automated generation of illustrated proofs in geometry and beyond'

9.2 Flowers

Blooming As we have seen, the (n -ary) scroll is a powerful icon, because it captures the distinction between classical and intuitionistic logic as being a matter of *continuity* between the space of inputs/hypotheses (outloop) and the spaces of outputs/conclusions (inloops), reflecting an intuition discovered much later in the denotational semantics of the λ -calculus. However as a diagrammatic component to be operated upon through direct manipulation, it has one notable flaw, also shared with the classical cut-based syntax: it quickly induces heavy nestings of curves in the plane, making even a simple graph like that of Figure ?? hard to read for an untrained eye.

Before devising an alternative syntax, one should ask: what are the essential features of the scroll that we want to preserve? Following the previous observations, we identified two of them:

Continuity the scroll is a self-intersecting continuous curve, which can be drawn in one stroke of the pen;

Polarity this curve delineates two kinds of areas: inloops that have the same polarity as the area on which the scroll is scribed, and the outloop which has the opposite polarity.

Fortunately, these two properties are preserved when turning inloops *inside-out*, as illustrated in Figure ?. This might be because the very process of turning inside-out can be seen as a continuous movement in three-dimensional space, where the inloops are rotated around their intersection points with the outloop. In this way, we have effectively divided the amount of curve-nesting in scrolls by two. And as an added bonus, the new icon is reminiscent of a *flower*, as if it had bloomed from its curled bud; or as if the pistol cylinder from Figure ?? had transformed into a *pistil*, and its bullet chambers into *petals*².

From that point onwards, we decided to fully embrace the flower metaphor: first in our drawing style as witnessed in Figure ??, but also in our syntactic terminology, to be introduced in the next pages. Negative outloops are now drawn as *yellow* pistils for a more colorful experience, and inloops

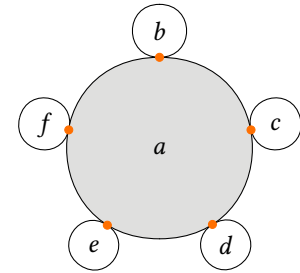


Figure 9.10: Turning a 5-ary scroll inside-out

2: As the saying goes: make love, not war.

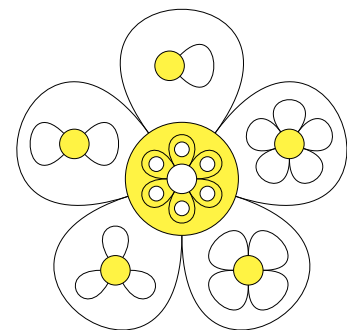


Figure 9.11: Nested flowers

as transparent petals, i.e. of the same color as the area on which they are scribed. We also drop the requirement that petals should intersect their pistil at a single point, for purely aesthetic reasons.

Multisets As we did for classical EG in Section ?? and Section ??, we are now going to distill the syntactic essence of flowers into an inductive, (multi)set-based data structure. This will allow for a more compact textual notation, that is better suited to proof-theoretical study.

In Section ??, we explained how the graphs of Beta allow to represent purely relational statements, without function symbols. Since functions are just deterministic relations, one can in principle formalize any first-order theory in this syntax³. However it is much more convenient to have a dedicated syntax for functions, and we will thus introduce them as is usually done in predicate calculus.

3: Conversely, every relation can be faithfully encoded as its characteristic function, which is the basis for the formalization of mathematics in *type theories*.

Definition 9.2.1 (First-order signature) *A first-order signature is a triplet $\Sigma = (\mathcal{F}, \mathcal{P}, \text{ar})$, where \mathcal{F} and \mathcal{P} are respectively the countable sets of function and predicate symbols of Σ , and $\text{ar} : \mathcal{F} \cup \mathcal{P} \rightarrow \mathbb{N}$ gives an arity to each symbol.*

In the following, we assume given a denumerable set of variables \mathcal{V} and a first-order signature Σ .

Definition 9.2.2 (Terms) *The set of terms \mathbb{T} is defined inductively as follows:*

- **(Variable)** If $x \in \mathcal{V}$ then $x \in \mathbb{T}$;
- **(Application)** If $f \in \mathcal{F}$ and $\vec{t} \in \mathbb{T}^{\text{ar}(f)}$, then $f(\vec{t}) \in \mathbb{T}$.

Definition 9.2.3 (Flowers) *The sets of flowers \mathbb{F} and gardens \mathbb{G} are defined mutually inductively as follows:*

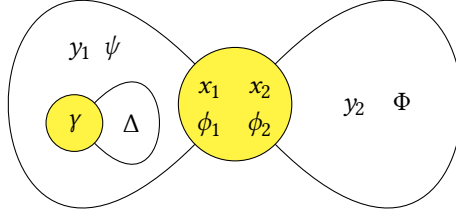
- **(Atom)** If $p \in \mathcal{P}$ and $\vec{t} \in \mathbb{T}^{\text{ar}(p)}$, then $p(\vec{t}) \in \mathbb{F}$;
- **(Garden)** If $x \subset \mathcal{V}$ is a finite set and $\Phi \subset \mathbb{F}$ a finite multiset, then $x \cdot \Phi \in \mathbb{G}$;
- **(Flower)** If $\gamma \in \mathbb{G}$ and $\Delta \subset \mathbb{G}$ is a finite multiset, then $\gamma \triangleright \Delta \in \mathbb{F}$.

Any finite set $x \subset \mathcal{V}$ of variables is called a *sprinkler*, finite multiset $\Phi \subset \mathbb{F}$ of flowers a *bouquet*, and finite multiset $\Gamma \subset \mathbb{G}$ of gardens a *corolla*. We will often write gardens as $x_1, \dots, x_n \cdot \phi_1, \dots, \phi_m$, where the x_i are called *binders*; and non-atomic flowers as $\gamma \triangleright \delta_1; \dots; \delta_n$, where γ is the *pistil*, and the δ_i are called *petals*. We write $\{E_i\}_i^n$ to denote a finite (multi)set of size n with elements E_i indexed by $1 \leq i \leq n$. We also omit writing the empty (multi)set, accounting for it with blank space as is done in sequent notation or in EG; in particular, \cdot stands for the empty garden $\emptyset \cdot \emptyset$, $\gamma \triangleright$ for the flower with no petals $\gamma \triangleright \emptyset$, and $\gamma \triangleright \cdot$ for the flower with one empty petal.

Note that the order of precedence of operators is $, < \cdot < ; < \triangleright$ so that for instance, the string

$$x_1, x_2 \cdot \phi_1, \phi_2 \triangleright y_1 \cdot \psi, (\gamma \triangleright \Delta); y_2 \cdot \Phi$$

is parsed as the flower



Also to improve readability, we will most of the time omit the garden dot ‘ \cdot ’ when the sprinkler is empty, writing Φ instead of $\cdot \Phi$.

Remark 9.2.1 In some places the choice of letter for meta-variables will be important to disambiguate the kind of syntactic object we denote. Table ?? summarizes our chosen notational conventions in this respect.

As usual, we introduce a *depth* measure that will allow us to reason inductively on the structure of flowers:

Definition 9.2.4 (Depth) *The depth $|-|$ of a flower or garden is defined mutually recursively as follows:*

$$\begin{aligned} |p(\vec{t})| &= 0 \\ |x \cdot \Phi| &= \max_{\phi \in \Phi} |\phi| \\ |\gamma \triangleright \Delta| &= 1 + \max(|\gamma|, \max_{\delta \in \Delta} |\delta|) \end{aligned}$$

We now proceed with routine definitions for handling variables and substitutions of terms in flowers.

Definition 9.2.5 (Free variables) *The sets of free variables $\text{fv}(-)$ of a term, flower, bouquet or garden are defined mutually recursively as follows:*

$$\begin{aligned} \text{fv}(x) &= \{x\} & \text{fv}(\Phi) &= \bigcup_{\phi \in \Phi} \text{fv}(\phi) \\ \text{fv}(f(\vec{t})) &= \bigcup_{t \in \vec{t}} \text{fv}(t) & \text{fv}(x \cdot \Phi) &= \text{fv}(\Phi) \setminus x \\ \text{fv}(p(\vec{t})) &= \bigcup_{t \in \vec{t}} \text{fv}(t) & \text{fv}(x \cdot \Phi \triangleright \Delta) &= \text{fv}(x \cdot \Phi) \cup \bigcup_{\gamma \cdot \Psi \in \Delta} \text{fv}(x, \gamma \cdot \Psi) \end{aligned}$$

We say that a term, flower, bouquet or garden is closed when its set of free variables is empty.

Remark 9.2.2 Note that the scope of a binder located in a pistil extends both to the pistil *and* to all its attached petals, whereas for a binder located in a petal it is limited to said petal. This is reflected in the above definition of free variables for (non-atomic) flowers, and is visually explained by the nesting of curves in an n -ary scroll.

Kind	Letters
Variables (\mathcal{V})	x, y, z
Terms (\mathcal{T})	t, u, v
Flowers (\mathcal{F})	ϕ, ψ, ξ
Gardens (\mathcal{G})	γ, δ
Sprinklers	x, y, z
Term vectors	$\vec{t}, \vec{u}, \vec{v}$
Substitutions	σ, τ
Bouquets	Φ, Ψ, Ξ
Corollas	Γ, Δ
Contexts	$\Phi\Box, \Psi\Box, \Xi\Box$
Theories	\mathcal{T}, \mathcal{U}

Figure 9.12: Notational conventions for meta-variables

Definition 9.2.6 (Bound variables) *The sets of bound variables $\text{bv}(-)$ of a flower, bouquet or garden are defined mutually recursively as follows:*

$$\begin{aligned} \text{bv}(p(\vec{t})) &= \emptyset & \text{bv}(x \cdot \Phi) &= x \cup \text{bv}(\Phi) \\ \text{bv}(\Phi) &= \bigcup_{\phi \in \Phi} \text{bv}(\phi) & \text{bv}(\gamma \sqsupset \Delta) &= \text{bv}(\gamma) \cup \bigcup_{\delta \in \Delta} \text{bv}(\delta) \end{aligned}$$

To avoid reasoning about α -equivalence, we adopt in this work the so-called *Barendregt convention* that all variable binders are distinct, both among themselves and from eventual free variables. Formally, we assume that for any bouquet Φ , the two following conditions hold:

1. computing $\text{bv}(\Phi)$ as a multiset gives the same result as computing it as a set;
2. $\text{bv}(\Phi) \cap \text{fv}(\Phi) = \emptyset$.

To define substitutions, we introduce a general notion of *function update*, which will be useful for the semantic evaluation of flowers in Section ??.

Definition 9.2.7 (Function update) *Let A, B be two sets, $f, g : A \rightarrow B$ two functions and $R \subseteq A$ some subset of their domain. The update of f on R with g is the function defined by:*

$$(f|_R g)(x) = \begin{cases} g(x) & \text{if } x \in R \\ f(x) & \text{otherwise} \end{cases}$$

— $|_R$ — is left-associative, that is $f|_R g|_S h = (f|_R g)|_S h$. Also if f or g is the identity function 1 we omit writing it, i.e. $f|_R = f|_R 1$ and $|_R g = 1|_R g$.

Fact 9.2.1 (Associativity) $f|_R g|_S h = f|_{R \cup S} (g|_S h)$.

Fact 9.2.2 (Commutativity) If $R \cap S = \emptyset$ then $f|_R g|_S h = f|_S h|_R g$.

Fact 9.2.3 (Agreement) If $f(x) = g(x)$ for all $x \in R$ then $h|_R f = h|_R g$.

Fact 9.2.4 (Idempotency) $f|_R f = f$.

Definition 9.2.8 (Substitution) *A substitution is a function $\sigma : \mathcal{V} \rightarrow \mathbb{T}$ with a finite support $\text{supp}(\sigma) = \{x \mid \sigma(x) \neq x\}$. By abuse of notation, we will write $\sigma : x \rightarrow \mathbb{T}$ to denote a substitution σ whose support is x . The domain of substitutions is extended to terms, flowers, bouquets and gardens mutually recursively as follows:*

$$\begin{aligned} \sigma(f(t_1, \dots, t_n)) &= f(\sigma(t_1), \dots, \sigma(t_n)) \\ \sigma(p(t_1, \dots, t_n)) &= p(\sigma(t_1), \dots, \sigma(t_n)) \\ \sigma(\phi_1, \dots, \phi_n) &= \sigma(\phi_1), \dots, \sigma(\phi_n) \\ \sigma(x \cdot \Phi) &= x \cdot \sigma|_x(\Phi) \\ \sigma(x \cdot \Phi \sqsupset \delta_1; \dots; \delta_n) &= \sigma(x \cdot \Phi) \sqsupset \sigma|_x(\delta_1); \dots; \sigma|_x(\delta_n) \end{aligned}$$

Definition 9.2.9 (Capture-avoiding substitution) *We say that a substitution $\sigma : x \rightarrow \mathbb{T}$ is capture-avoiding in a bouquet Φ if $\text{fv}(\sigma(x)) \cap \text{bv}(\Phi) = \emptyset$ for every $x \in x$.*

9.3 Calculus

Contexts Equipped with an inductive syntax, we can now express formally the inference rules of our flower calculus, just as we did for Alpha (Section ??) and Beta (Section ??). There, graphs and their contexts were defined as multisets of nodes, which have now turned into bouquets of flowers:

Definition 9.3.1 (Context) *A bouquet context $\Phi\Box$ is a bouquet which contains exactly one occurrence of the special flower \Box called the hole. The hole can always be filled (substituted) with any other bouquet Ψ or context $\Xi\Box$, producing a new bouquet $\Phi[\Psi]$ or context $\Phi[\Xi\Box]$. In particular, filling with the empty bouquet will yield a bouquet $\Phi[\Box]$, which is just $\Phi\Box$ with its hole removed. A flower context $\phi\Box$ is a bouquet context of size 1.*

Definition 9.3.2 (Depth) *The depth $|\Phi\Box|$ of a bouquet context $\Phi\Box$ is defined recursively as follows:*

$$\begin{aligned} |\Psi, \Box| &= 0 \\ |\Psi, (x \cdot \Phi\Box \triangleright \Delta)| &= 1 + |\Phi\Box| \\ |\Psi, (\gamma \triangleright x \cdot \Phi\Box; \Delta)| &= 1 + |\Phi\Box| \end{aligned}$$

Contrarily to EG (Definition ??), the parity of a context does not coincide with its depth, since petals increase depth but preserve polarity:

Definition 9.3.3 (Parity) *The parity $\text{par}(\Phi\Box)$ of a context $\Phi\Box$ is defined recursively by:*

$$\begin{aligned} \text{par}(\Psi, \Box) &= 0 \\ \text{par}(\Psi, (x \cdot \Phi\Box \triangleright \Delta)) &= \text{par}(\Phi\Box) + 1 \\ \text{par}(\Psi, (\gamma \triangleright x \cdot \Phi\Box; \Delta)) &= \text{par}(\Phi\Box) \end{aligned}$$

Definition 9.3.4 (Polarity) *We say that a context $\Phi\Box$ is positive if $\text{par}(\Phi\Box)$ is even, and negative otherwise. We denote positive and negative contexts respectively by $\Phi^+\Box$ and $\Phi^-\Box$.*

Pollination In order to formulate the equivalent of the (de)iteration rules of EG for flowers, we introduce a *pollination* relation that captures the availability of a flower in a given context, akin to the *justification* relation of Section ??:

Definition 9.3.5 (Pollination) *We say that a flower ϕ can be pollinated in a context $\Phi\Box$, written $\phi \succ \Phi\Box$, when there exists a bouquet Ψ with*

$\phi \in \Psi$ and contexts $\Xi\Box$ and $\Xi_0\Box$ such that either:

- **(Cross-pollination)** $\Phi\Box = \Xi\Box \Psi, \Xi_0\Box$;
- **(Self-pollination)** $\Phi\Box = \Xi\Box x \cdot \Psi \triangleright y \cdot \Xi_0\Box; \Delta$ for some x, y, Δ .

A bouquet Ψ can be pollinated in $\Phi\Box$, written $\Psi \succ \Phi\Box$, if $\psi \succ \Phi\Box$ for all $\psi \in \Psi$.

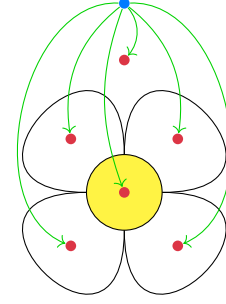
We now employ the metaphor of *pollination* to speak about (de)iteration in flowers. This is illustrated in Figure ??, where the blue dot marks the location of the justifying/pollinating occurrence of ϕ , and the red dots all the areas that it (locally) justifies/pollinates, and thus where ϕ can be (de)iterated⁴. We distinguish two cases of *cross-pollination* and *self-pollination*, as botanists do when describing the reproduction of flowers. This distinction does not exist in classical EG, because pistils and petals are both identified as instances of cuts⁵. If we were to replace binders by LoI (lines of identity, see Section ??), then the pollination relation would also prescribe in which areas LoI can be extended/iterated, providing an explanation for the scope of binders (Remark ??).

Rules As has become standard in this thesis, we define the flower calculus as a *rewriting system* on bouquets, presented in Figure ?? as a set of unary deep inference rules: when read *top-down*, they correspond to usual inferences from premiss to conclusion, and will be justified by the soundness theorem of Section ?. But the more interesting direction, and the one around which the calculus has been designed, is when you read the rules *bottom-up*: then they are indeed rewrite rules, telling you the different ways in which you can choose to simplify a goal. This is how the *graphical* version of the rules is presented in Figure ?? and Figure ??.

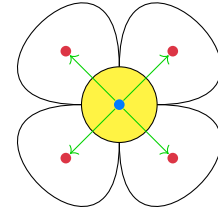
Let us now describe the rules in more detail, starting with the fragment that is a direct adaptation of the rules of Beta (Figure ??):

Blank Antecedant (epis) It allows to enclose any bouquet in a petal attached to an (e)mpty (pis)til. This is one direction of the rule BA of (Figure ??), which is a weaker, intuitionistic version of the classical rule Dcut \uparrow of Alpha and Beta. The other direction (rule epis \downarrow in Figure ??) is actually admissible, which might be related to the co-admissibility of Dcut \downarrow in Alpha (Corollary ??).

(De)iteration (poll \downarrow , poll \uparrow) Renamed (*poll*)ination rules, they correspond to the rules Iter and Deit of Alpha and Beta, but reformulated with the pollination relation (Definition ??). In fact in their textual presentation of Figure ??, they are more general than (de)iteration rules, because Definition ?? allows the pollinating bouquet Φ to be *scattered* in the context $\Xi\Box$, i.e. its flowers need not be located in the same area. On the contrary in the graphical presentation of Figure ??, they are less general since only one flower can be pollinated at a time, rather than an entire bouquet of flowers residing in the same area. But it is easy to see that all these variants are equivalent in deductive power, since the pollination of a bouquet (however scattered) can always be simulated by the successive pollinations of each of its flowers.



Cross-pollination



Self-pollination

Figure 9.13: Pollination in flowers

4: Figure ?? summarizes visually the flow of information in flowers, just like Figure ?? summarized the flow of information in EG, and Figure ?? in bubbles. From a UI point of view, all these figures can be understood as kind of “cheatsheets”, that indicate with arrows the allowed drag-and-drop moves for importing a statement (the source of the DnD) into a new context (the destination of the DnD).

5: The same phenomenon is at work in *subformula linking* (Chapter ??): self-pollination and cross-pollination correspond respectively to the *backward* \otimes and *forward* \circledast linking operators, which are collapsed into a single interaction operator $*$ in the original formulation of subformula linking for classical linear logic [26].

$$\frac{\Phi}{\cdot \triangleright \cdot \Phi} \text{ epis}\downarrow$$

Figure 9.14: Converse of epis rule

Insertion/Deletion (grow, crop, pull, glue) They correspond to the rules Ins and Del of Alpha and Beta, but have doubled in number to account for the syntactic distinction between pistils and petals. More precisely, rules *grow* and *crop* allow to insert and delete entire flowers, while rules *pull* and *glue* deal with petals. As for pollination rules, manipulating single flowers/petals (graphical version) or entire bouquets/corollas (textual version) does not change the deductive power of the rules.

Unification (ipis, ipet, apis, apet) Rules *ipis* and *ipet* allow to (i)stantiate a sprinkler located respectively in a (pis)til (\forall) and a (pet)al (\exists) with an arbitrary substitution, while rules *apis* and *apet* do the opposite operation of (a)bstracting a set of terms by introducing a sprinkler. They correspond respectively to a generalization of the rules $\text{Unif}\uparrow$ and $\text{Unif}\downarrow$ of Beta, where the variable substitution $\{z/y\}$ becomes an arbitrary substitution σ . Once again, we have twice the amount of rules to account for the pistil/petal distinction, which is not surprising since in the LoI syntax of EG, they are special cases of Insertion/Deletion. Note that for the instantiation rules *ipis*/*ipet* to be invertible, we duplicate the whole flower/petal where the sprinkler occurs, mirroring what is done in multi-conclusion sequent calculi (see Figure ??).

The last two rules mainly handle the behavior of disjunctive and absurd statements, i.e. flowers with respectively $n \geq 2$ and $n = 0$ petals, and are closer to sequent-style introduction/elimination rules:

Disjunction Introduction (epet) It allows to erase any flower with an (e)mpty (pet)al. According to Oostra [142, p. 109], Peirce already identified *epet* as a component of his decision procedure for Alpha (it is simply called “Operation 1” in [142]). This is no coincidence, since we precisely came up with this rule when trying to design a decision procedure for flowers (see Section ??).

Disjunction/Falsity Elimination (srep) It corresponds to a n -ary generalization of the left introduction rule for disjunction in sequent calculus, the 0-ary case capturing falsity elimination (*ex falso quodlibet*). The binary case is also used in the IEG system of [130], together with its converse. The name *srep* is short for (s)elf-(re)production, which is more clearly visualized in the graphical version of the rule in Figure ?. Through the Curry-Howard correspondence, it can be related to the *pattern-matching generator* found in modern editors of some functional programming languages, such as the Hazel structure editor and the Agda proof assistant [194].

The rules of the flower calculus have an interesting property: they are mostly *arity-agnostic*, i.e. they work uniformly on flowers, bouquets and gardens with any number of petals, flowers and binders. In particular, this means that the same rules can be used to capture provability in almost any *fragment* of intuitionistic predicate logic, understood as any subset $\mathfrak{F} \subset \mathbf{F}$ of the set of all flowers⁶. Table ?? shows how all the usual symbolic connectives can be expressed by *cardinality* constraints on set-based syntactic constructs: $<$, \leq , $=$, \geq , $>$ correspond respectively to a cardinality smaller, smaller or equal, equal, greater or equal, and greater than 1; and $-$ denotes the absence of constraint. These constraints are then taken

[194]: Yuan et al. (2023), ‘Live Pattern Matching with Typed Holes’

6: The only exception seems to be the rule (*ipis*) (resp. *ipet*), whose duplication of flowers (resp. petals) prevents \forall from being expressible (i.e. provable) without \wedge (resp. \vee). This can be fixed by simply removing the duplication and polarizing the context of application as for the rule *apis* (resp. *apet*), at the cost of making the rule non-invertible.

Connective		\top	\wedge	\perp	\neg	\supset	\vee	\forall	\exists
Corolla		\geq	$=$	$<$	$<$	$=$	$>$	$=$	$=$
Bouquets	Pistil	$-$	$<$	$<$	$=$	\leq	$<$	$<$	$<$
	Petals	$<$	$>$	$-$	$-$	$=$	$=$	$=$	$=$
Sprinklers	Pistil	$-$	$<$	$<$	$<$	$<$	$<$	\geq	$<$
	Petals	$<$	$<$	$-$	$-$	$<$	$<$	$<$	\geq

Table 9.1: Fragments of intuitionistic logic as cardinality constraints on flowers

conjunctively for a single connective (column-wise); and they can be freely mixed *disjunctively* (row-wise), in order to capture any fragment corresponding to a subset of connectives.

Proofs Our notions of derivation and proof are essentially the same as the ones given for EG in Section ??, except that we distinguish from the outset between two kinds of derivations, stemming from our partitioning of the rules into two sets: the *natural* rules denoted by \otimes , and the *cultural* rules denoted by $\otimes\prec$. In particular, every \otimes -rule is both *analytic* (i.e. every atom in the premiss already appears in the conclusion) and *invertible* (this will be shown in Section ??); and we will prove in Section ?? that all $\otimes\prec$ -rules are *admissible*.

Definition 9.3.6 (Derivation) *Given a set of rules R , we write $\Phi \rightarrow_R \Psi$ to indicate a rewrite step in R , that is an instance of some $r \in R$ with Ψ as premiss and Φ as conclusion. We just write $\Phi \rightarrow \Psi$ to mean $\Phi \rightarrow_{\otimes \cup \otimes\prec} \Psi$. A derivation $\Phi \rightarrow_R^n \Psi$ is a sequence of rewrite steps $\Phi_0 \rightarrow_R \Phi_1 \dots \rightarrow_R \Phi_n$ with $\Phi_0 = \Phi$, $\Phi_n = \Psi$ and $n \geq 0$. Generally the length n of the derivation does not matter, and we just write $\Phi \rightarrow_R^* \Psi$. Finally, natural derivations are closed under arbitrary contexts: for every context $\Xi[\]$, $\Phi \rightarrow_{\otimes} \Psi$ implies $\Xi[\Phi] \rightarrow_{\otimes} \Xi[\Psi]$. We write $\Phi \rightarrow_{\otimes} \Psi$ to denote a local natural step, i.e. a direct instance of a natural rule in the empty context.*

The following lemma is the flower calculus equivalent of Lemma ?? for EG:

Lemma 9.3.1 (Positive closure) *If $\Phi \rightarrow \Psi$, then $\Xi^+[\Phi] \rightarrow \Xi^+[\Psi]$.*

Proof. In the case of a natural step $\Phi \rightarrow_{\otimes} \Psi$, this is immediate by definition. Otherwise we have a cultural step $\Xi'[\Phi_0] \rightarrow_{\otimes\prec} \Xi'[\Psi_0]$. Then either $\Xi'[\]$ is positive, and $\text{par}(\Xi^+[\Xi'[\]]) = \text{par}(\Xi^+[\]) + \text{par}(\Xi'[\])$ is even since it is the sum of two even numbers; or $\Xi'[\]$ is negative, and $\text{par}(\Xi^+[\Xi'[\]])$ is odd since it is the sum of an even and an odd number. In both cases $\Xi^+[\Xi'[\]]$ has the same polarity as $\Xi'[\]$, and thus the same rule can be applied. \square

Now we can define our usual “goal-oriented” notion of proof:

Definition 9.3.7 (Proof) *A proof of a bouquet Φ is a derivation $\Phi \rightarrow^* \emptyset$.*

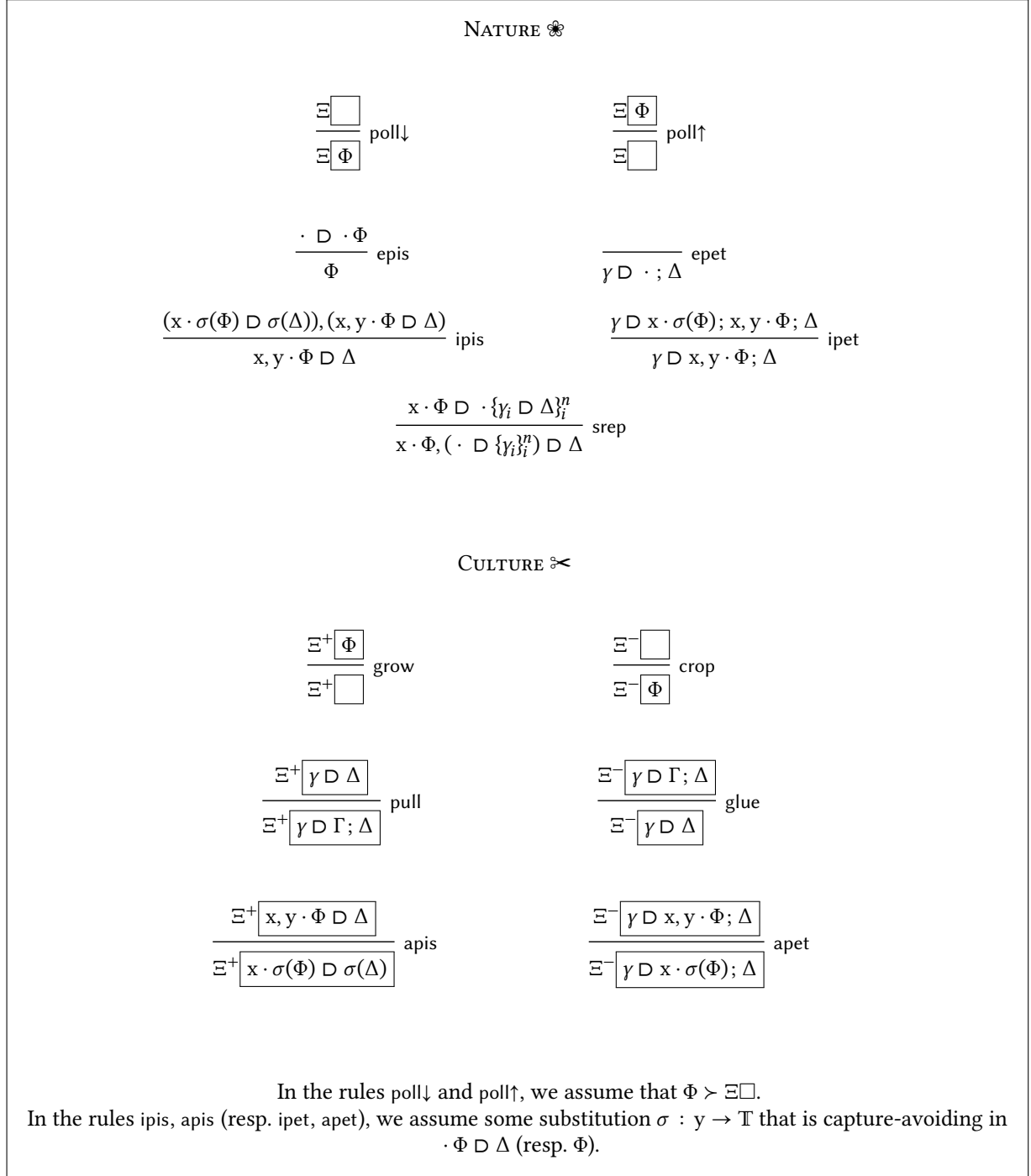


Figure 9.15: Rules of the flower calculus

In Peircean terms, the empty bouquet is the blank sheet of assertion, which as we have seen in Section ?? can be interpreted as the icon of *absolute truth*. Then in our proof construction paradigm, proving a bouquet amounts to erasing it completely from the sheet of assertion, thus reducing it to absolute truth.

If we want to speak about *relative truth* $\Psi \vdash \Phi$, i.e. Φ is true under the assumption that Ψ is, we can simply rely on the existence of a derivation $\Phi \rightarrow^* \Psi$ in the full flower calculus. This will be justified by *strong*

soundness and completeness theorems, relying on the following strong deduction theorem:

Theorem 9.3.2 (Strong deduction) $\Phi \rightarrow^* \Psi$ if and only if $\Psi \sqsupset \Phi \rightarrow^* \emptyset$.

Proof. Suppose that $\Phi \rightarrow^* \Psi$. Then we have:

$$\begin{array}{ll} \Psi \sqsupset \Phi & \rightarrow^* \quad \Psi \sqsupset \Psi \quad (\text{Hypothesis} + \text{Lemma ??}) \\ & \rightarrow_{\text{poll}\downarrow} \Psi \sqsupset \cdot \\ & \rightarrow_{\text{epet}} \emptyset \end{array}$$

In the other direction, suppose that $\Psi \sqsupset \Phi \rightarrow^* \emptyset$. Then we have:

$$\begin{array}{ll} \Phi & \rightarrow_{\text{epis}} \sqsupset \Phi \\ & \rightarrow_{\text{grow}} (\Psi \sqsupset \Phi), (\sqsupset \Phi) \\ & \rightarrow_{\text{poll}\uparrow} (\Psi \sqsupset \Phi), ((\Psi \sqsupset \Phi) \sqsupset \Phi) \\ & \rightarrow^* (\Psi \sqsupset \Phi) \sqsupset \Phi \quad (\text{Hypothesis} + \text{Lemma ??}) \\ & \rightarrow_{\text{grow}} \Psi, ((\Psi \sqsupset \Phi) \sqsupset \Phi) \\ & \rightarrow_{\text{poll}\downarrow} \Psi, ((\sqsupset \Phi) \sqsupset \Phi) \\ & \rightarrow_{\text{srep}} \Psi, (\sqsupset (\Phi \sqsupset \Phi)) \\ & \rightarrow_{\text{poll}\downarrow} \Psi, (\sqsupset (\Phi \sqsupset \cdot)) \\ & \rightarrow_{\text{epet}} \Psi, (\sqsupset \cdot) \\ & \rightarrow_{\text{epet}} \Psi \end{array}$$

□

Contrary to full derivability, natural derivability $\Phi \rightarrow_{\otimes}^* \Psi$ is too weak to satisfy a strong deduction theorem. This can be intuited from the proof of Theorem ??, by noticing that the converse direction relies on the \Leftarrow -rule *grow*, a close analog to the cut rule in sequent calculus. Also as already mentioned, the natural rules of the flower calculus are both *invertible* and *complete* for provability. A consequence of invertibility is that natural derivability is only able to relate logically equivalent bouquets – in fact not even all of them. That is, as soon as $\Psi \sqsupset \Phi$ is provable but the converse $\Phi \sqsupset \Psi$ is not, it will necessarily follow that $\Phi \rightarrow_{\otimes}^* \Psi$, thus contradicting the strong deduction theorem.

A trivial way to circumvent this is to define directly $\Psi \vdash \Phi$ as $\Psi \sqsupset \Phi \rightarrow^* \emptyset$. In fact this is closer to what one would find in sequent calculus, where hypothetical proofs are closed derivations of hypothetical sequents, not open derivations. The difference is that sequents capture only the first-order implicative structure of logic⁷, while flowers capture the full structure of intuitionistic predicate logic. This allows for a nice generalization of the notion of hypothetical provability, which will be useful in the completeness proof of Section ??.

7: As opposed to *higher-order*, i.e. negatively nested implications.

Definition 9.3.8 (Hypothetical provability) *Given two bouquets Φ, Ψ , we say that Φ is hypothetically provable from Ψ in a fragment R of rules, written $\Psi \vdash_R \Phi$, if for every context $\Xi \square$ such that $\Psi \succ \Xi \square$, $\Xi \square \rightarrow_R^* \Xi \square$. We write $\Psi \vdash \Phi$ to denote hypothetical provability in the full flower calculus.*

Lemma 9.3.3 (Reflexivity) *For any bouquet Φ , $\Phi \vdash_{\clubsuit} \Phi$.*

Proof. For any context $\Xi \square$ such that $\Phi \succ \Xi \square$, one has the following derivation:

$$\Xi \boxed{\Phi} \rightarrow_{\text{poll}\downarrow} \Xi \square$$

□

There is a subtle but important shift here with respect to the standard notions of hypothetical provability, as found in Gentzen systems or type theories: while in these settings it is characterized as the existence of a proof for a *single* hypothetical judgment $\Gamma \Rightarrow C$ which constrains the space of derivations, here we have the stronger requirement that there exist proofs for a *class* of judgments $\Xi \boxed{\Phi}$, whose hypothetical shape comes from the condition that $\Psi \succ \Xi \square$. In practice, the pollination rules $\{\text{poll}\downarrow, \text{poll}\uparrow\}$ and the epis rule make this equivalent to the existence of a proof for $\Psi \sqsupset \Phi$. But we conjecture that the epis rule might be admissible modulo the addition of the distributivity rule crep^8 of Figure ??.

Thus our stronger notion of hypothetical provability makes more sense in the variant $\clubsuit \setminus \{\text{epis}\} \cup \{\text{crep}\}$ of the flower calculus, although it will still be useful in this work to make meta-theoretical proofs slightly shorter. For now we allow the epis rule, which renders the deduction theorem trivial:

Theorem 9.3.4 (Deduction) *For any pair Φ, Ψ of bouquets, $\Psi \vdash_{\clubsuit} \Phi$ if and only if $\vdash_{\clubsuit} \Psi \sqsupset \Phi$.*

Proof. Let $\Xi \square$ be some context. If $\Psi \vdash_{\clubsuit} \Phi$, then in particular $\Xi' \boxed{\Phi} \rightarrow_{\clubsuit}^* \Xi' \square$ for $\Xi' \square := \Xi \boxed{\Psi \sqsupset \Phi}$. Thus we have:

$$\Xi \boxed{\Psi \sqsupset \Phi} \rightarrow_{\clubsuit}^* \Xi \boxed{\Psi \sqsupset \cdot} \rightarrow_{\text{epet}} \Xi \square$$

In the other direction, let Ξ be some context such that $\Psi \succ \Xi \square$. If $\vdash_{\clubsuit} \Psi \sqsupset \Phi$, then in particular $\Xi \boxed{\Psi \sqsupset \Phi} \rightarrow_{\clubsuit}^* \Xi \square$. Thus we have:

$$\Xi \boxed{\Phi} \rightarrow_{\text{epis}} \Xi \boxed{\sqsupset \Phi} \rightarrow_{\text{poll}\uparrow} \Xi \boxed{\Psi \sqsupset \Phi} \rightarrow_{\clubsuit}^* \Xi \square$$

□

8: crep stands for cross-reproduction, mirroring the distinction between cross-pollination and self-pollination, but with respect to the self-reproduction rule srep .

$$\frac{\gamma \sqsupset \{x_i \cdot \Phi_i, \Psi_i^n\}}{(\gamma \sqsupset \{x_i \cdot \Phi_i\}_i^n), \Psi} \text{crep}$$

Figure 9.16: Cross-reproduction rule

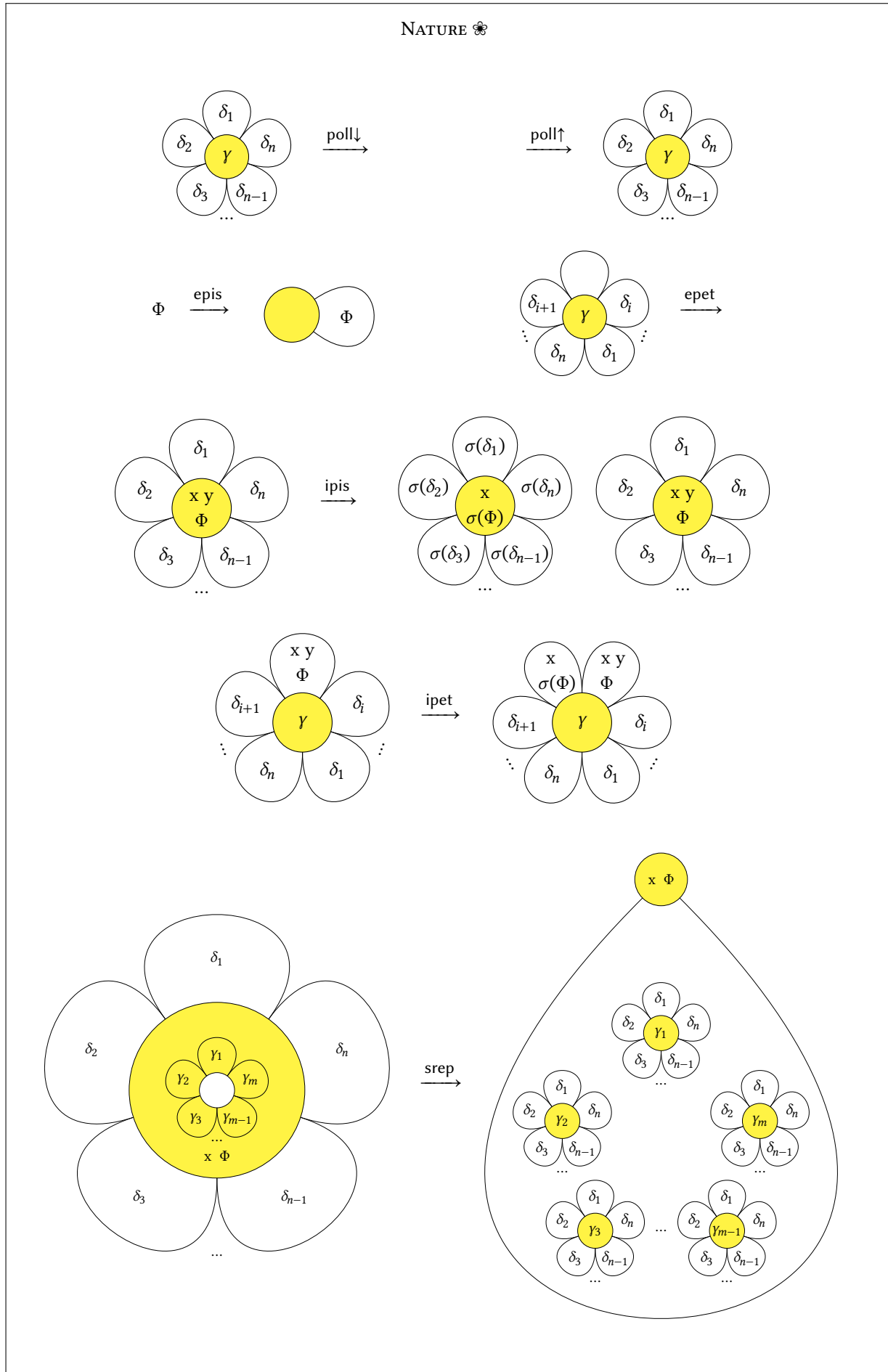


Figure 9.17: Graphical presentation of the natural rules

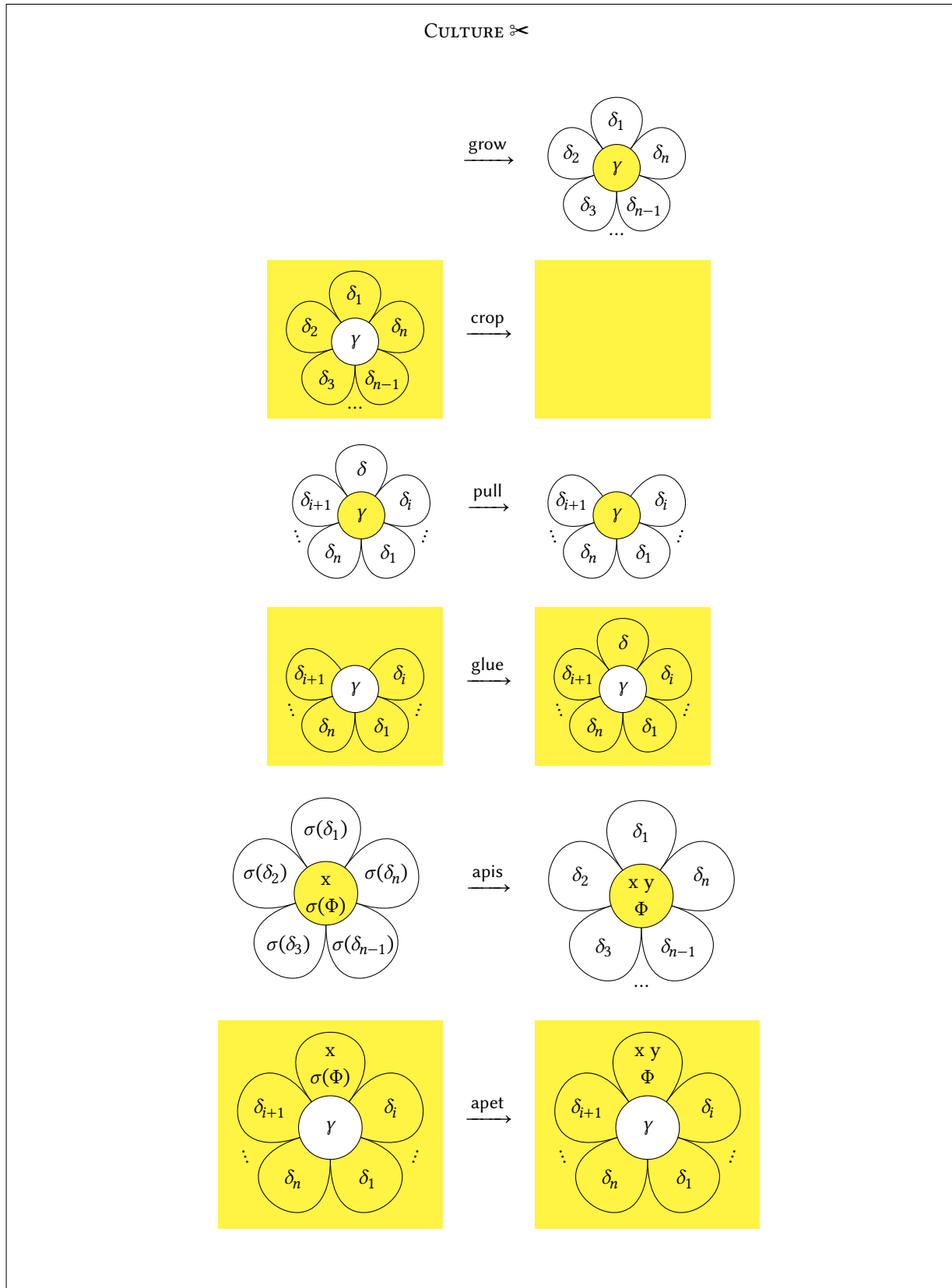


Figure 9.18: Graphical presentation of the cultural rules

9.4 Kripke semantics

In Section ??, in order to prove the soundness of system B, we gave a bi-intuitionistic (resp. classical) semantics to bubbles in Heyting-Brouwer (resp. Boolean) algebras, and in Section ?? we interpreted α -graphs with simple boolean truth values. For flowers, we use a third kind of models that is standard in the literature on intuitionistic logic: Kripke structures. Our goal is not to fill as many pages as possible by introducing new definitions in each chapter, but rather to find the simplest semantics for our purposes with the specific proof system at hand. In the case of the flower calculus, there are a few reasons that led us to the choice of Kripke structures, detailed hereafter by order of importance:

Generalization of EG As mentioned in Section ??, the syntax of intuitionistic EG (and thus of flowers) subsumes that of Peirce’s classical EG, by seeing the cut as a 0-ary scroll (or a flower with no petals). Similarly, it is well-known that Kripke structures enable a natural generalization of truth valuations, where classical valuations are those limited to “unary” structures with a single possible world⁹.

Quantifiers It is easy to accomodate quantifiers in Kripke structures, by interpreting terms as individuals in the domains of the structure’s worlds. In contrast, extensions of algebraic semantics that account for quantifiers like polyadic and cylindric algebras are more involved, and less studied in the literature.

Cut-free completeness Rather than just completeness, we are interested more specifically in the completeness of the natural fragment \clubsuit of the flower calculus, where all rules are *analytic*. In Gentzen systems, this corresponds to the well-known questions of *proof normalization* (natural deduction) and *cut admissibility* (sequent calculus). Gentzen originally proved cut admissibility through a syntactic procedure of *cut-elimination*, which is very hard to transpose in our deep inference setting, especially since there is no known internal cut-elimination procedure in the (sparse) literature on deep inference systems for full intuitionistic logic. In fact, the requirement that the procedure be *internal* is useful when studying the computational content of proofs, but too strong for our logical study of analyticity. Thus our first attempt was to devise an *external* syntactic procedure, based on the simulation of a cut-free sequent calculus as in [184]; and we do have a working, verified implementation of this procedure in Coq [44]. However, we realized *a posteriori* that this only proves a weak form of completeness, in the sense that we only guarantee that a true flower is provable if it is the direct translation of a symbolic formula. But formulas are based on binary connectives and unary quantifiers, and are thus less expressive syntactically than flowers and their n -ary constructs.

To palliate this limitation, we turned to a more *semantic* (and not so-well known) strand of analyticity proofs, which nowadays tends to be labelled *normalization-by-evaluation* [1]. The idea is to prove completeness of the analytic fragment of the proof system with respect to some semantic models (in our case, $\models \phi$ implies $\vdash_{\clubsuit} \phi$), and then compose with the soundness of the full system with respect to the same models ($\vdash \phi$ implies $\models \phi$), giving the desired admissibility

9: It is tempting to draw a parallel between *possible worlds* and the *petals* of flowers, where the accessibility relation \leq between worlds might be reflected to some extent in the pollination relation illustrated in Figure ?? (or more accurately, in a justification relation between contexts in the style of Definition ??). In particular, transitivity of \leq could correspond to the possibility of cross-pollinating a petal by first cross-pollinating the pistil to which it is attached, and then performing self-pollination. An analogy between possible worlds and intuitionistic disjunction is also proposed by Girard in [70], although as usual he demonstrates his (free) criticism towards Kripke semantics.

[184]: Tiu (2006), ‘A Local System for Intuitionistic Logic’

[1]: Abel (2013), ‘Normalization by Evaluation: Dependent Types and Impredicativity’

result ($\vdash \phi$ implies $\vdash_{\otimes} \phi$). And in the case of intuitionistic logics, the models used are most of the time Kripke structures¹⁰ [93][92][99].

We now recall the standard definitions, starting with the interpretation of constants in *first-order structures*:

Definition 9.4.1 (First-order structure) *A first-order structure is a pair $(M, \llbracket \cdot \rrbracket)$ where M is a non-empty set, and $\llbracket \cdot \rrbracket$ is a map called the interpretation that associates to each function symbol $f \in \mathcal{F}$ a function $\llbracket f \rrbracket : M^{\text{ar}(f)} \rightarrow M$, and to each predicate symbol $p \in \mathcal{P}$ a relation $\llbracket p \rrbracket \subseteq M^{\text{ar}(p)}$.*

Definition 9.4.2 (Kripke structure) *A Kripke structure is a triplet $\mathcal{K} = (W, \leq, (M_w)_{w \in W})$, where W is the set of worlds, \leq is a pre-order on W called accessibility, and $(M_w)_{w \in W}$ is a family of first-order structures indexed by W . Furthermore, we require the following monotonicity conditions to hold whenever $w \leq w'$:*

- ▶ $M_w \subseteq M_{w'}$;
- ▶ for every $f \in \mathcal{F}$, $\llbracket f \rrbracket_w \subseteq \llbracket f \rrbracket_{w'}$;
- ▶ for every $p \in \mathcal{P}$, $\llbracket p \rrbracket_w \subseteq \llbracket p \rrbracket_{w'}$.

Then we need a way to interpret arbitrary terms with free variables in any given world w of a Kripke structure, which is done through the concept of *w-evaluation*:

Definition 9.4.3 (*w-evaluation*) *Given a Kripke structure \mathcal{K} and a world w in \mathcal{K} , a w -evaluation is a function $e : \mathcal{V} \rightarrow M_w$. The interpretation map of M_w is extended to terms and substitutions with respect to any evaluation e as follows:*

$$\begin{aligned} \llbracket x \rrbracket_e &= e(x) \\ \llbracket f(\vec{t}) \rrbracket_e &= \llbracket f \rrbracket_w(\llbracket \vec{t} \rrbracket_e) \\ \llbracket \sigma \rrbracket_e(x) &= \llbracket \sigma(x) \rrbracket_e \end{aligned}$$

The crux of Kripke semantics is the *forcing* relation, that captures the truth-conditions of statements in Kripke structures. While it is usually defined on formulas, here we adapt the definition to flowers, which in our opinion makes it simpler and more uniform since flowers can be seen as built from essentially one big constructor:

Definition 9.4.4 (Forcing) *Given some Kripke structure \mathcal{K} , the forcing relation $w \Vdash \phi[e]$ between a world w , a flower ϕ and a w -evaluation e is defined by recurrence on $|\phi|$ as follows:*

- (Atom)** $w \Vdash p(\vec{t})[e]$ iff $\llbracket \vec{t} \rrbracket_e \in \llbracket p \rrbracket_w$;
- (Flower)** $w \Vdash x \cdot \Phi \sqsupset \{x_i \cdot \Phi_i\}_i^n[e]$ iff for every $w' \geq w$ and every w' -evaluation e' , if $w' \Vdash \Phi[e|_x e']$ then there is some $1 \leq i \leq n$ and w' -evaluation e'' such that $w' \Vdash \Phi_i[e|_x e' |_{x_i} e'']$.
- (Bouquet)** $w \Vdash \Phi[e]$ iff $w \Vdash \phi[e]$ for every $\phi \in \Phi$.

10: We know of two exceptions: the first is the (complex) uniform completeness proof for various logics proposed by Okada [139] and based on *phase spaces*, which are the closest one can get to a truth-based (or Tarskian) semantics for *linear logic* [66]. The second is the recent completeness proof of Frumin for the logic of Bunched Implications (BI) [59], a cousin of linear logic at the heart of *separation logic*, which is a very popular framework in contemporary deductive program verification. It is based on so-called *BI algebras*, a kind of Heyting algebra with additional structure for the linear part of the logic. We should also mention the recent normalization proof for cubical type theory given by Sterling in his thesis [174], based on a categorical and topos-theoretic generalization of Kripke structures.

[93]: Hermant (2005), ‘Semantic Cut Elimination in the Intuitionistic Sequent Calculus’

[92]: Herbelin et al. (2009), ‘Forcing-Based Cut-Elimination for Gentzen-Style Intuitionistic Sequent Calculus’

[99]: Ilik (2010), ‘Constructive Completeness Proofs and Delimited Control’

The following lemmas will be useful for the soundness proof of the next section:

Lemma 9.4.1 (Monotonicity) *If $w \leq w'$ and $w \Vdash \phi[e]$ then $w' \Vdash \phi[e]$.*

Proof. By a straightforward recurrence on $|\phi|$. \square

Lemma 9.4.2 (Mirroring) *$w \Vdash \sigma(\phi)[e]$ iff $w \Vdash \phi[e|_x \llbracket \sigma \rrbracket_e]$ for $\sigma : x \rightarrow \mathbb{T}$ capture-avoiding in ϕ and $x \cap \text{bv}(\phi) = \emptyset$.*

Substitution $\varsigma : \mathcal{V} \rightarrow \mathbb{T}$
Evaluation $e : \mathcal{V} \rightarrow M_w$

Proof. By recurrence on $|\phi|$.

(Base case) Suppose $\phi = p(\vec{t})$. We show that $\llbracket \sigma(\vec{t}) \rrbracket_e \in \llbracket p \rrbracket_w$ iff $\llbracket \vec{t} \rrbracket_{e|_x \llbracket \sigma \rrbracket_e} \in \llbracket p \rrbracket_w$ by proving that $\llbracket t \rrbracket_{e|_x \llbracket \sigma \rrbracket_e} = \llbracket \sigma(t) \rrbracket_e$ for any term t by recurrence on $|t|$.

- If $t = x$, then either:
 - * $x \in x$, and $\llbracket x \rrbracket_{e|_x \llbracket \sigma \rrbracket_e} = \llbracket \sigma \rrbracket_e(x) = \llbracket \sigma(x) \rrbracket_e$; or
 - * $x \notin x$, and $\llbracket x \rrbracket_{e|_x \llbracket \sigma \rrbracket_e} = e(x) = \llbracket x \rrbracket_e = \llbracket \sigma(x) \rrbracket_e$.
- If $t = f(\vec{t})$, then

$$\begin{aligned} \llbracket f(\vec{t}) \rrbracket_{e|_x \llbracket \sigma \rrbracket_e} &= \llbracket f \rrbracket_w(\llbracket \vec{t} \rrbracket_{e|_x \llbracket \sigma \rrbracket_e}) \\ &= \llbracket f \rrbracket_w(\llbracket \sigma(\vec{t}) \rrbracket_e) \quad (\text{IH}) \\ &= \llbracket f(\sigma(\vec{t})) \rrbracket_e \\ &= \llbracket \sigma(f(\vec{t})) \rrbracket_e \end{aligned}$$

(Recursive case) Suppose $\phi = y \cdot \Phi \sqsupset \{z_i \cdot \Psi_i\}_i^n$. We show that $w \Vdash y \cdot \sigma(\Phi) \sqsupset \{z_i \cdot \sigma(\Psi_i)\}_i^n[e]$ implies $w \Vdash y \cdot \Phi \sqsupset \{z_i \cdot \Psi_i\}_i^n[e|_x \llbracket \sigma \rrbracket_e]$, the argument working in both directions. Let $w' \geq w$ and e' a w' -evaluation such that $w' \Vdash \Phi[e|_x \llbracket \sigma \rrbracket_e|_y e']$. Since σ is capture-avoiding in ϕ , we know that $\text{fv}(\sigma(x)) \cap y = \emptyset$, and thus $\llbracket \sigma \rrbracket_e(x) = \llbracket \sigma(x) \rrbracket_e = \llbracket \sigma(x) \rrbracket_{e|_y e'} = \llbracket \sigma \rrbracket_{e|_y e'}(x)$ for any $x \in x$. Hence by Fact ?? $w' \Vdash \Phi[e|_x \llbracket \sigma \rrbracket_{e|_y e'}|_y e']$, and since by hypothesis $x \cap y = \emptyset$ we obtain $w' \Vdash \Phi[e|_y e'|_x \llbracket \sigma \rrbracket_{e|_y e'}]$ by Fact ??. Then by IH we get $w' \Vdash \sigma(\Phi)[e|_y e']$, and thus by hypothesis $w' \Vdash \sigma(\Psi_i)[e|_y e'|_{z_i} e'']$ for some $1 \leq i \leq n$ and w' -evaluation e'' . Again by IH we get $w' \Vdash \Psi_i[e|_y e'|_{z_i} e''|_x \llbracket \sigma \rrbracket_{e|_y e'|_{z_i} e''}]$, and since σ is capture-avoiding in ϕ we have $\text{fv}(\sigma(x)) \cap z_i = \emptyset$ for any $x \in x$, and thus $w' \Vdash \Psi_i[e|_y e'|_{z_i} e''|_x \llbracket \sigma \rrbracket_e]$ by Fact ??. Finally by hypothesis $x \cap z_i = \emptyset$, thus we can conclude that $w' \Vdash \Psi_i[e|_x \llbracket \sigma \rrbracket_e|_y e'|_{z_i} e'']$ by Fact ??. \square

Lastly, we define the notion of *semantic entailment* $\Phi \models \Psi$ on bouquets, mirroring the syntactic entailment $\Phi \vdash \Psi$ of the last section:

Definition 9.4.5 (Semantic entailment) *Let \mathcal{K} be a Kripke structure, and Φ, Ψ some bouquets. We say that Φ semantically entails Ψ in \mathcal{K} , written $\Phi \models_{\mathcal{K}} \Psi$, when $w \Vdash \Phi[e]$ implies $w \Vdash \Psi[e]$ for every world $w \in W$ and w -evaluation e . This entailment is valid if it holds for any Kripke*

Figure 9.19: The syntax-semantics mirror

structure \mathcal{K} , and in that case we simply write $\Phi \models \Psi$. We say that Φ is semantically equivalent to Ψ , written $\Phi \models \Psi$, when $\Phi \models \Psi$ and $\Psi \models \Phi$.

Fact 9.4.1 (Reflexivity) $\Phi \models \Phi$.

Fact 9.4.2 (Transitivity) If $\Phi \models \Psi$ and $\Psi \models \Xi$, then $\Phi \models \Xi$.

9.5 Soundness

We now show that every rule of the flower calculus is *sound* with respect to our Kripke semantics for flowers, and thus that $\vdash \phi$ implies $\models \phi$ for every ϕ . We start with the pervasive *functoriality* lemma at the basis of every deep inference system¹¹:

Lemma 9.5.1 (Functoriality) *If $\Phi \models \Psi$, then for any Ξ either $\Xi[\Phi] \models \Xi[\Psi]$ if Ξ is positive, or $\Xi[\Psi] \models \Xi[\Phi]$ if Ξ is negative.*

11: Other instances in this thesis are Lemma ??, Lemma ??, Lemma ??, and Corollary ??.

Proof. By recurrence on $|\Xi|$. □

Weakening lemmas are also standard in proof theory and type theory. Here they are purely semantic, but they will participate in the admissibility of the weakening rules {grow, crop, pull, glue}:

Lemma 9.5.2 (Weakening) $\Phi \models \emptyset$.

Proof. Trivial by Definition ??. □

Lemma 9.5.3 (Co-weakening) $\gamma \supset \Delta \models \gamma \supset \Gamma; \Delta$.

Proof. Let $\gamma = x \cdot \Phi$, w a world in some Kripke structure \mathcal{K} , $w' \geq w$, e a w -evaluation and e' a w' -evaluation such that $w \Vdash \gamma \supset \Delta[e]$ and $w' \Vdash \Phi[e|_x e']$. Then by hypothesis there must exist some $y \cdot \Psi \in \Delta$ and w' -evaluation e'' such that $w' \Vdash \Psi[e|_x e'|_y e'']$, and thus we can conclude. □

The less obvious rules in terms of soundness are the *pollination* rules {poll↓, poll↑}, because of the arbitrary context Ξ and reliance on the pollination relation. The following lemma can be compared to Lemma ?? for the (de)iteration rules in EG:

Lemma 9.5.4 (Cross-pollination) $\Phi, \Xi[\Phi] \models \Phi, \Xi[\]$.

Proof. Let w a world in some Kripke structure \mathcal{K} , and e a w -evaluation. We show that $w \Vdash \Phi, \Xi[\Phi][e]$ iff $w \Vdash \Phi, \Xi[\][e]$ by recurrence on $|\Xi|$.

(Base case) Suppose $\Xi\Box = \Xi', \Box$. Then we trivially have $w \Vdash \Phi, \Xi', \Phi[e]$ iff $w \Vdash \Phi, \Xi'[e]$ by Definition ??.

(Recursive case) We distinguish two cases:

(Pistil) Suppose $\Xi\Box = \Xi', (x \cdot \Xi_0\Box \triangleright \Delta)$.

1. Suppose $w \Vdash \Phi, \Xi\Box[e]$. Then $w \Vdash \Phi[e]$, $w \Vdash \Xi'[e]$ and $w \Vdash x \cdot \Xi_0\Box \triangleright \Delta[e]$. Thus it remains to show that $w \Vdash x \cdot \Xi_0\Box \triangleright \Delta[e]$. Let $w' \geq w$ and e' a w' -evaluation such that $w' \Vdash \Xi_0\Box[e|_x e']$. By IH we have $\Phi, \Xi_0\Box \models \Phi, \Xi_0\Box$, and thus by Lemma ?? $x \cdot \Phi, \Xi_0\Box \triangleright \Delta \models x \cdot \Phi, \Xi_0\Box \triangleright \Delta$. By Lemma ?? and Lemma ?? we have $w \Vdash x \cdot \Phi, \Xi_0\Box \triangleright \Delta[e]$, and thus $w \Vdash x \cdot \Phi, \Xi_0\Box \triangleright \Delta[e]$. Then since $w' \Vdash \Xi_0\Box[e|_x e']$, and since by Lemma ?? (and the fact that $x \cap \text{fv}(\Phi) = \emptyset$) we have $w' \Vdash \Phi[e|_x e']$, we can conclude that there are some $y \cdot \Psi \in \Delta$ and w' -evaluation e'' such that $w' \Vdash \Psi[e|_x e'|_y e'']$.
2. $\Phi, \Xi\Box \models \Phi, \Xi\Box$ holds by the same argument in the other direction.

(Petal) Suppose $\Xi\Box = \Xi', (x \cdot \Psi \triangleright y \cdot \Xi_0\Box; \Delta)$.

1. Suppose $x \Vdash \Phi, \Xi\Box[e]$. Then $w \Vdash \Phi[e]$, $w \Vdash \Xi'[e]$ and $w \Vdash x \cdot \Psi \triangleright y \cdot \Xi_0\Box; \Delta[e]$. Thus it remains to show that $w \Vdash x \cdot \Psi \triangleright y \cdot \Xi_0\Box; \Delta[e]$. Let $w' \geq w$ and e' a w' -evaluation such that $w' \Vdash \Psi[e|_x e']$. Then we can deduce that there exists a w' -evaluation e'' such that either:
 - * $w' \Vdash \Psi'[e|_x e'|_y e'']$ for some $y' \cdot \Psi' \in \Delta$, and we conclude immediately;
 - * or $w' \Vdash \Xi_0\Box[e|_x e'|_y e'']$. By Lemma ?? (and the fact that $x \cap \text{fv}(\Phi) = \emptyset$ and $y \cap \text{fv}(\Phi) = \emptyset$) we have $w' \Vdash \Phi[e|_x e'|_y e'']$, and thus $w' \Vdash \Phi, \Xi_0\Box[e|_x e'|_y e'']$. Then by IH we have $w' \Vdash \Phi, \Xi_0\Box[e|_x e'|_y e'']$, and thus we can conclude in particular that $w' \Vdash \Xi_0\Box[e|_x e'|_y e'']$.
2. $\Phi, \Xi\Box \models \Phi, \Xi\Box$ holds by the same argument in the other direction.

□

Then we also need to account for *self-pollination*:

Lemma 9.5.5 (Pollination) *If $\Phi \succ \Xi\Box$, then $\Xi\Box \models \Xi\Box$.*

Proof. We show that $\phi \succ \Xi\Box$ implies $\Xi\Box \models \Xi\Box$ for any flower ϕ and context $\Xi\Box$: then assuming that $\Phi = \phi_1, \dots, \phi_n$, we get

$$\underbrace{\Xi\Box[\phi_1, \dots, \phi_n] \models \Xi\Box[\phi_2, \dots, \phi_n] \models \dots \models \Xi\Box}_{n \text{ times}}$$

and conclude by Fact ??.

By Definition ??, there are a bouquet Ψ and two contexts $\Xi', \Xi_0\Box$ such that one of the two following cases holds:

(Cross-pollination) $\Xi \square = \Xi' \boxed{\Psi, \phi, \Xi_0 \square}$. Then $\phi, \Xi_0 \boxed{\phi} \models \phi, \Xi_0 \square$ by Lemma ??, and we conclude by Lemma ??.

(Self-pollination) $\Xi \square = \Xi' \boxed{x \cdot \Psi, \phi \sqsupset y \cdot \Xi_0 \square; \Delta}$ for some x, y, Δ . Let w a world in some Kripke structure \mathcal{K} and e a w -evaluation. We show that $w \Vdash x \cdot \Psi, \phi \sqsupset y \cdot \Xi_0 \boxed{\phi}; \Delta [e]$ iff $w \Vdash x \cdot \Psi, \phi \sqsupset y \cdot \Xi_0 \square; \Delta [e]$, and conclude by Lemma ??.

1. Suppose that $w \Vdash x \cdot \Psi, \phi \sqsupset y \cdot \Xi_0 \boxed{\phi}; \Delta [e]$, and let $w' \geq w$ and e' a w' -evaluation such that $w' \Vdash \Psi, \phi [e|_x e']$. Then we can deduce that there exists a w' -evaluation e'' such that either:
 - $w' \Vdash \Psi' [e|_x e' |_{y'} e'']$ for some $y' \cdot \Psi' \in \Delta$, and we conclude immediately;
 - or $w' \Vdash \Xi_0 \boxed{\phi} [e|_x e' |_{y'} e'']$. Since $\text{fv}(\phi) \cap y = \emptyset$ we have $w' \Vdash \phi [e|_x e' |_{y'} e'']$, and thus $w' \Vdash \phi, \Xi_0 \boxed{\phi} [e|_x e' |_{y'} e'']$. Then by Lemma ?? we have $w' \Vdash \phi, \Xi_0 \square [e|_x e' |_{y'} e'']$, and thus we can conclude in particular that $w' \Vdash \Xi_0 \square [e|_x e' |_{y'} e'']$.
2. $x \cdot \Psi, \phi \sqsupset y \cdot \Xi_0 \square; \Delta \models x \cdot \Psi, \phi \sqsupset y \cdot \Xi_0 \boxed{\phi}; \Delta$ holds by the same argument in the other direction.

□

Proving the soundness of rules involving binders (ipis, ipet, apis, apet) is also quite tedious, which can be understood as stemming from the fact that substitutions simulate the complex dynamics of the lines of identity of EG in a *global* rather than local way. In particular, one needs to be careful about the scope of bound variables, which in EG would be handled locally with (de)iteration rules.

Lemma 9.5.6 (Universal instantiation) *If $\sigma : y \rightarrow \mathbb{T}$ is capture-avoiding in $\Phi \sqsupset \Delta$, then $x, y \cdot \Phi \sqsupset \Delta \models x \cdot \sigma(\Phi) \sqsupset \sigma(\Delta)$.*

Proof. Let w a world in some Kripke structure \mathcal{K} , $w' \geq w$, e a w -evaluation and e' a w' -evaluation such that $w \Vdash x, y \cdot \Phi \sqsupset \Delta [e]$ and $w' \Vdash \sigma(\Phi) [e|_x e']$. Therefore $w' \Vdash \Phi [e|_x e' |_{y'} \llbracket \sigma \rrbracket_{e|_x e'}]$ by Lemma ??, and thus $w' \Vdash \Phi [e|_{xuy} (e' |_{y'} \llbracket \sigma \rrbracket_{e|_x e'})]$ by Fact ??. Then by hypothesis, there must be some $z \cdot \Psi \in \Delta$ and w' -evaluation e'' such that $w' \Vdash \Psi [e|_{xuy} (e' |_{y'} \llbracket \sigma \rrbracket_{e|_x e'}) |_{z'} e'']$, and thus $w' \Vdash \Psi [e|_x e' |_{y'} \llbracket \sigma \rrbracket_{e|_x e'} |_{z'} e'']$. Since σ is capture-avoiding in $\Phi \sqsupset \Delta$, we know that for any $x \in y$ we have $\text{fv}(\sigma(x)) \cap z = \emptyset$, and thus $\llbracket \sigma(x) \rrbracket_{e|_x e' |_{z'} e''} = \llbracket \sigma(x) \rrbracket_{e|_x e'}$. Hence by Fact ?? and Fact ?? we get $w' \Vdash \Psi [e|_x e' |_{z'} e'' |_{y'} \llbracket \sigma \rrbracket_{e|_x e' |_{z'} e''}]$, and by Lemma ?? we conclude that $w' \Vdash \sigma(\Psi) [e|_x e' |_{z'} e'']$. □

Lemma 9.5.7 (Existential instantiation) *If $\sigma : y \rightarrow \mathbb{T}$ is capture-avoiding in Φ , then $\gamma \sqsupset x \cdot \sigma(\Phi); \Delta \models \gamma \sqsupset x, y \cdot \Phi; \Delta$.*

Proof. Let $\gamma = z \cdot \Xi$, and w a world in some Kripke structure \mathcal{K} , $w' \geq w$, e a w -evaluation and e' a w' -evaluation such that $w \Vdash \gamma \sqsupset x \cdot \sigma(\Phi); \Delta [e]$ and $w' \Vdash \Xi [e|_z e']$. Then by hypothesis, there must be some w' -evaluation e'' such that either:

- $w' \Vdash \Xi' [e|_z e' |_{z'} e'']$ for some $z' \cdot \Xi' \in \Delta$, and we conclude immediately;
- or $w' \Vdash \sigma(\Phi) [e|_z e' |_x e'']$. Then by Lemma ?? we have $w' \Vdash \Phi [e|_z e' |_x e'' |_y \llbracket \sigma \rrbracket_{e|_z e' |_x e''}]$, and thus we can conclude with $w' \Vdash \Phi [e|_z e' |_{x \cup y} (e'' |_y \llbracket \sigma \rrbracket_{e|_z e' |_x e''})]$ by Fact ??.

□

We are now equipped with enough lemmas to prove the soundness of each rule, starting with the *local* version of natural rules. In fact we are able to prove more: that every \otimes -rule is *invertible*, i.e. its conclusion entails its premiss.

Lemma 9.5.8 (Local soundness) *If $\Phi \rightarrow_{\otimes} \Psi$, then $\Phi \models \Psi$.*

Proof. Let w a world in some Kripke structure \mathcal{K} , $w' \geq w$, e a w -evaluation and e' a w' -evaluation. We proceed by inspection of every \otimes -rule.

- (poll↓, poll↑) By Lemma ??.
- (epis)
 1. Suppose that $w \Vdash \Phi [e]$. Then by Lemma ?? we have $w' \Vdash \Phi [e]$, and thus we can conclude for instance with $w' \Vdash \Phi [e|_{\emptyset} e' |_{\emptyset} e]$.
 2. Suppose that $w \Vdash \Diamond \Phi [e]$. Then since we trivially have $w \geq w$ and $w \Vdash \emptyset [e|_{\emptyset} e]$, we get that $w \Vdash \Phi [e|_{\emptyset} e |_{\emptyset} e'']$ for some w -evaluation e'' , and thus $w \Vdash \Phi [e]$.
- (epet) Let $\gamma = x \cdot \Phi$. We trivially have that $w' \Vdash \emptyset [e|_x e' |_{\emptyset} e]$, and thus can conclude.
- (ipis) We trivially have $x, y \cdot \Phi \supset \Delta \models x, y \cdot \Phi \supset \Delta$ by Fact ??, and thus we can conclude by Lemma ??.
- (ipet) The first direction is trivial by Lemma ??.
- In the other direction, let $\gamma = z \cdot \Xi$, and suppose that $w \Vdash \gamma \supset x \cdot \sigma(\Phi); x, y \cdot \Phi; \Delta [e]$ and $w' \Vdash \Xi [e|_z e']$. Then there must be some w' -evaluation e'' such that either:
 - $w' \Vdash \Xi' [e|_z e' |_{z'} e'']$ for some $z' \cdot \Xi' \in \Delta$, and we conclude immediately;
 - $w' \Vdash \Phi [e|_z e' |_{x \cup y} e'']$, and we also conclude immediately;
 - or $w' \Vdash \sigma(\Phi) [e|_z e' |_x e'']$, and we conclude with the same argument as in the proof of Lemma ??.
- (srep) Let $\gamma_i = y_i \cdot \Psi_i$ for $1 \leq i \leq n$.
 1. Suppose that $w \Vdash x \cdot \Phi, (\Diamond \{\gamma_i\}_i^n) \supset \Delta [e]$ and $w' \Vdash \Phi [e|_x e']$. We show that $w' \Vdash \gamma_i \supset \Delta [e|_x e']$ for all $1 \leq i \leq n$, i.e. for every $w'' \geq w'$ and w'' -evaluation e'' , $w'' \Vdash \Psi_i [e|_x e' |_{y_i} e'']$ implies that there is some $z \cdot \Xi \in \Delta$ and w'' -evaluation e''' such that $w'' \Vdash \Xi [e|_x e' |_{y_i} e'' |_z e''']$. By assumption, Lemma ?? and the fact that $\text{fv}(\Phi) \cap y_i = \emptyset$, we have $w'' \Vdash \Phi [e|_x e' |_{y_i} e'']$. Also since $w'' \Vdash \Psi_i [e|_x e' |_{y_i} e'']$ we immediately get $w'' \Vdash \Diamond \{\gamma_i\}_i^n [e|_x e']$, and thus $w'' \Vdash \Diamond \{\gamma_i\}_i^n [e|_x e' |_{y_i} e'']$ since $\text{fv}(\Diamond \{\gamma_i\}_i^n) \cap y_i = \emptyset$. Thus by Fact ?? we have $w'' \Vdash \Phi, (\Diamond \{\gamma_i\}_i^n) [e|_{x \cup y_i} (e' |_{y_i} e'')]$,

- and by hypothesis (and the fact that $w'' \geq w$ by transitivity) we obtain that $w'' \Vdash \Xi [e|_{xuy_i} (e' |_{y_i} e'') |_z e''']$ for some $z \cdot \Xi \in \Delta$ and w'' -evaluation e''' . Then we conclude again by Fact ??.
2. Suppose that $w \Vdash x \cdot \Phi \supset \{\gamma_i \supset \Delta\}_i^n [e]$ and $w' \Vdash \Phi, (\supset \{\gamma_i\}_i^n) [e|_x e']$. Then there must be some $1 \leq i \leq n$ and w' -evaluation e'' such that $w' \Vdash \Psi_i [e|_x e' |_{y_i} e'']$, and for all $1 \leq j \leq n$ we know that $w' \Vdash \gamma_j \supset \Delta [e|_x e']$. Thus since $w' \leq w'$ by reflexivity, there must be some $z \cdot \Xi \in \Delta$ and w' -evaluation e''' such that $w' \Vdash \Xi [e|_x e' |_{y_i} e'' |_z e''']$, and we can conclude with $w' \Vdash \Xi [e|_x e' |_{y_i \cup z} (e'' |_z e''')] by Fact ??.$

□

Then the soundness of the contextual closure of natural rules follows immediately from functoriality:

Lemma 9.5.9 (Natural soundness) *If $\Phi \rightarrow_{\clubsuit} \Psi$ then $\Phi \models \Psi$.*

Proof. By Lemma ?? and Lemma ??.

□

The soundness of cultural rules is straightforward with the previous lemmas:

Lemma 9.5.10 (Cultural soundness) *If $\Phi \rightarrow_{\heartsuit} \Psi$ then $\Psi \models \Phi$.*

Proof. By inspection of every \heartsuit -rule.

(grow, crop) By Lemma ?? and Lemma ??.

(pull, glue) By Lemma ?? and Lemma ??.

(apis) By Lemma ?? and Lemma ??.

(apet) By Lemma ?? and Lemma ??.

□

Then it follows that every derivation in the flower calculus is sound:

Lemma 9.5.11 *If $\Phi \rightarrow^* \Psi$ then $\Psi \models \Phi$.*

Proof. By Lemma ??, Lemma ?? and Fact ??, Fact ??.

□

In particular, every provable flower is “true”:

Theorem 9.5.12 (Soundness) *If $\vdash \phi$ then $\models \phi$.*

9.6 Completeness

In this section, we give a direct completeness proof for the natural fragment \mathbb{F} of the flower calculus: every true flower ϕ is naturally provable, i.e. $\models \phi$ implies $\vdash_{\mathbb{F}} \phi$. Since this fragment is analytic, we cannot adapt directly most of the completeness proofs for standard proof systems that can be found in the literature. Indeed, most of them exploit the transitivity of syntactic entailment \vdash , and more precisely the fact that it is easily shown syntactically with the help of a non-analytic principle for composing proofs: in Hilbert systems it is the rule of *modus ponens*, in sequent calculi the *cut* rule, and in natural deduction the *substitution* theorem.

Fortunately as mentioned in Section ??, a few people have noticed that with Kripke semantics, it is not too difficult to find completeness proofs that do not rely on the assumption of transitivity for \vdash , thus allowing for a *semantic* proof of cut-elimination [92][99][93]. Here we propose an adaptation of this technique to our flower calculus, based on a completeness proof for cut-free sequent calculus given by Hermant in [93], which is itself close to the original completeness proof of Gödel with respect to classical Tarski models. Quite remarkably, the overall structure of the argument is the same, even though both the forcing relation on flowers and the rules of the flower calculus differ significantly from the forcing relation on formulas and sequent calculus rules. A novelty of our proof is that it dispenses completely with the need for *Henkin witnesses*, thus avoiding some technicalities involving among others the manipulation of an infinite hierarchy of first-order languages.

[93]: Hermant (2005), ‘Semantic Cut Elimination in the Intuitionistic Sequent Calculus’

Theories

First we need to generalize our notions of syntactic and semantic entailment to possibly *infinite* sets of flowers, so-called *theories*:

Definition 9.6.1 (Theory) *Any set $\mathcal{T} \subseteq \mathbb{F}$ of flowers is called a theory. In particular, a bouquet can be regarded as a finite theory, by forgetting the number of repetitions of its elements. We say that a bouquet Φ is provable from a theory \mathcal{T} , written $\mathcal{T} \vdash \Phi$, if there exists a bouquet $\Psi \subseteq \mathcal{T}$ such that $\Psi \vdash \Phi$. Given a Kripke structure \mathcal{K} , a world w in \mathcal{K} and a w -evaluation e , we say that \mathcal{T} is forced by w under e , written $w \Vdash \mathcal{T}[e]$, if $w \Vdash \phi[e]$ for all $\phi \in \mathcal{T}$. Then Φ is a consequence of \mathcal{T} , written $\mathcal{T} \models_{\mathcal{K}} \Phi$, if $w \Vdash \mathcal{T}[e]$ implies $w \Vdash \Phi[e]$ for every world w in \mathcal{K} and w -evaluation e .*

Lemma 9.6.1 (Weakening) *If $\mathcal{T} \subseteq \mathcal{T}'$ and $\mathcal{T} \vdash \phi$, then $\mathcal{T}' \vdash \phi$.*

Proof. This follows immediately from our definition of provability from a theory (Definition ??). \square

The following notions are crucial to define the *completion* procedure at the heart of any Gödel-style completeness proof:

Definition 9.6.2 (ψ -consistency) *A theory \mathcal{T} is ψ -consistent when $\mathcal{T} \not\vdash_{\mathbb{F}} \psi$.*

Definition 9.6.3 (ψ -completeness) *A theory \mathcal{T} is ψ -complete when for all $\phi \in \mathbb{F}$, either $\mathcal{T}, \phi \vdash_{\otimes} \psi$ or $\phi \in \mathcal{T}$.*

Intuitively, a theory \mathcal{T} is ψ -consistent when one cannot deduce ψ from it, and ψ -complete when it *decides* any formula ϕ relatively to ψ . This is better understood by considering the special case where $\psi = \bot$ is the *absurd* flower: then consistency means that one cannot derive any contradiction from \mathcal{T} ; and completeness that \mathcal{T} either *refutes* ϕ syntactically with a proof of $\Phi, \phi \vdash (\bot)$ for some $\Phi \subseteq \mathcal{T}$, or already *validates* it “semantically”, i.e. without the need for a proof since $\phi \in \mathcal{T}$.

Completion

In the following, we suppose some enumeration $(\phi_n)_{n \in \mathbb{N}}$ of \mathbb{F} , which should be definable constructively given the inductive nature of flowers (Definition ??).

Let $\psi \in \mathbb{F}$, and \mathcal{T} a ψ -consistent theory. We now define the completion procedure, which constructs an extension $\text{Com}(\mathcal{T}) \supseteq \mathcal{T}$ with the property that $\text{Com}(\mathcal{T})$ is ψ -consistent and ψ -complete.

Definition 9.6.4 (n -completion) *The n -completion $\text{Com}^n(\mathcal{T})$ of \mathcal{T} is defined recursively as follows:*

$$\begin{aligned} \text{Com}^0(\mathcal{T}) &= \mathcal{T} \\ \text{Com}^{n+1}(\mathcal{T}) &= \begin{cases} \text{Com}^n(\mathcal{T}) \cup \phi_n & \text{if } \text{Com}^n(\mathcal{T}) \cup \phi_n \text{ is } \psi\text{-consistent} \\ \text{Com}^n(\mathcal{T}) & \text{otherwise} \end{cases} \end{aligned}$$

Definition 9.6.5 (Completion) *The completion $\text{Com}(\mathcal{T})$ of \mathcal{T} is the denumerable union of all n -completions:*

$$\text{Com}(\mathcal{T}) = \bigcup_{n \in \mathbb{N}} \text{Com}^n(\mathcal{T})$$

Lemma 9.6.2 $\text{Com}(\mathcal{T})$ is ψ -consistent.

Proof. It is immediate by recurrence on n that $\text{Com}^n(\mathcal{T})$ is ψ -consistent. Then suppose that $\text{Com}(\mathcal{T}) \vdash_{\otimes} \psi$, that is there is some bouquet $\Phi \subseteq \text{Com}(\mathcal{T})$ such that $\Phi \vdash_{\otimes} \psi$. For each $\phi \in \Phi$, there is some rank n such that $\phi \in \text{Com}^n(\mathcal{T})$. Let m be the greatest such rank. Then $\Phi \subseteq \text{Com}^m(\mathcal{T})$, and thus by weakening (Lemma ??) $\Phi \vdash_{\otimes} \psi$. Contradiction. \square

Lemma 9.6.3 $\text{Com}(\mathcal{T})$ is ψ -complete.

Proof. Suppose that there is some ϕ such that $\text{Com}(\mathcal{T}), \phi \not\vdash_{\otimes} \psi$ and $\phi \notin \text{Com}(\mathcal{T})$, and let $\phi = \phi_n$. Then $\text{Com}(\mathcal{T}) \cup \phi_n$ is ψ -consistent, and thus by weakening (Lemma ??) so is $\text{Com}^n(\mathcal{T}) \cup \phi_n$. This entails that $\phi_n \in \text{Com}^{n+1}(\mathcal{T}) \subseteq \text{Com}(\mathcal{T})$. Contradiction. \square

Adequacy

The following two propositions constitute the central argument that allows the completeness proof to go through despite the analyticity of \otimes -rules. They are a direct adaptation of [93, Proposition 7], which Hermant identifies as “an important property of any A -consistent, A -complete theory, [...] that it enjoys some form of the subformula property”.

Roughly, the first proposition captures the (intuitionistic) truth-conditions that make a flower *valid* (i.e. true in every model) by modelling them on material implication, just like Peirce would do with his scroll (see Section ??): ϕ is true if the content Φ_i of one of its petals (consequents) is, or if the content Φ of its pistil (antecedant) is not.

Proposition 9.6.4 (Analytic truth) *Let $\psi \in F$, \mathcal{T} some ψ -consistent and ψ -complete theory, and $\phi = x \cdot \Phi \supset \Delta$ with $\Delta = \{\delta_i\}_{i=1}^n = \{x_i \cdot \Phi_i\}_{i=1}^n$ such that $\phi \in \mathcal{T}$. Then for every substitution $\sigma : x \rightarrow \mathbb{T}$, either $\sigma(\Phi_i) \subseteq \mathcal{T}$ for some $1 \leq i \leq n$, or $\mathcal{T} \vdash_{\otimes} \sigma(\Phi)$.*

Proof. Suppose the contrary, i.e. there is a substitution σ such that $\mathcal{T} \vdash_{\otimes} \sigma(\Phi)$ and for all $1 \leq i \leq n$, there is some $\phi_i \in \Phi_i$ ① such that $\sigma(\phi_i) \notin \mathcal{T}$. Thus by ψ -completeness of \mathcal{T} , we get $\mathcal{T}, \sigma(\phi_i) \vdash_{\otimes} \psi$. So there are $\Psi \subseteq \mathcal{T}$ and $\Psi_i \subseteq \mathcal{T} \cup \sigma(\phi_i)$ such that $\Psi \vdash_{\otimes} \sigma(\Phi)$ ② and $\Psi_i \vdash_{\otimes} \psi$ ③. Now it cannot be the case that $\Psi_i \subseteq \mathcal{T}$, otherwise by weakening and ψ -consistency of \mathcal{T} we would have $\Psi_i \vdash_{\otimes} \psi$. So there must exist $\Psi'_i \subseteq \mathcal{T}$ such that $\Psi_i = \Psi'_i \cup \sigma(\phi_i)$ ④. Again by weakening and ψ -consistency of \mathcal{T} , we get $\Psi, \bigcup_{i=1}^n \Psi'_i, \phi \vdash_{\otimes} \psi$. Now we derive a contradiction by showing $\Psi, \bigcup_{i=1}^n \Psi'_i, \phi \vdash_{\otimes} \psi$. Let Ξ be a context such that $\Psi, \bigcup_{i=1}^n \Psi'_i, \phi \succ \Xi$ ⑤. Then $\Xi \boxed{\psi} \rightarrow_{\otimes}^* \Xi \boxed{}$ with the following derivation:

$$\begin{array}{ll}
 \Xi \boxed{\psi} & \rightarrow_{\text{epis}} \Xi \cdot \mathsf{D} \cdot \psi \\
 & \rightarrow_{\text{poll}\uparrow} \Xi \cdot \phi \mathsf{D} \cdot \psi \quad (5) \\
 & \rightarrow_{\text{ipis}} \Xi \cdot (\cdot \sigma(\Phi) \mathsf{D} \sigma(\Delta)), \phi \mathsf{D} \cdot \psi \\
 & \rightarrow_{\text{poll}\downarrow} \Xi \cdot (\cdot \mathsf{D} \sigma(\Delta)), \phi \mathsf{D} \cdot \psi \quad (2, 5) \\
 & \rightarrow_{\text{srep}} \Xi \cdot \phi \mathsf{D} \cdot \{\sigma(\delta_i) \mathsf{D} \cdot \psi\}_{i=1}^n \\
 & = \Xi \cdot \phi \mathsf{D} \cdot \{x_i \cdot \sigma(\Phi_i) \mathsf{D} \cdot \psi\}_{i=1}^n \\
 & \rightarrow_{\text{poll}\downarrow}^n \Xi \cdot \phi \mathsf{D} \cdot \{x_i \cdot \sigma(\Phi_i) \mathsf{D} \cdot \psi\}_{i=1}^n \quad (1, 3, 4, 5) \\
 & \rightarrow_{\text{epet}}^n \Xi \cdot \phi \mathsf{D} \cdot \\
 & \rightarrow_{\text{epet}} \Xi \boxed{}
 \end{array}$$

□

Dually, the second proposition captures the grounds on which a flower can be deemed *invalid* (i.e. false in at least one model): ϕ is not true if assuming that its pistil Φ is true is not sufficient to conclude that one of its petals Φ_i is.

Proposition 9.6.5 (Analytic refutation) *Let $\psi \in F$, \mathcal{T} some ψ -consistent and ψ -complete theory, and $\phi = x \cdot \Phi \supset \Delta$ with $\Delta = \{\delta_i\}_{i=1}^n = \{x_i \cdot \Phi_i\}_{i=1}^n$ such*

that $\mathcal{T} \vdash_{\clubsuit} \phi$. Then for every $1 \leq i \leq n$ and substitution $\sigma : x_i \rightarrow \mathbb{T}$, there is some $\phi_i \in \Phi_i$ such that $\mathcal{T}, \Phi \vdash_{\clubsuit} \sigma(\phi_i)$.

Proof. Suppose the contrary, i.e. there are some $1 \leq i \leq n$ and $\sigma : x_i \rightarrow \mathbb{T}$ such that $\mathcal{T}, \Phi \not\vdash_{\clubsuit} \sigma(\phi_i)$. Therefore there must exist $\Psi \subseteq \mathcal{T}$ and $\Phi_0 \subseteq \Phi$ ① such that $\Psi, \Phi_0 \vdash_{\clubsuit} \sigma(\phi_i)$ ②. By hypothesis, for every $\Phi' \subseteq \mathcal{T}$ there is a context Ξ such that $\Phi' \succ \Xi$ and $\Xi[\phi] \rightarrow_{\clubsuit}^* \Xi[\]$. We now derive a contradiction by showing $\Xi[\phi] \rightarrow_{\clubsuit}^* \Xi[\]$ for all Ξ such that $\Psi \succ \Xi$ ③:

$$\begin{array}{lcl} \Xi[\phi] & \rightarrow_{\text{ipet}} & \Xi \left[\frac{x \cdot \Phi \sqsupset \cdot \sigma(\phi_i); \Delta}{x \cdot \Phi \sqsupset \cdot ; \Delta} \right] \\ & \rightarrow_{\text{poll}} & \Xi \left[\frac{x \cdot \Phi \sqsupset \cdot ; \Delta}{x \cdot \Phi \sqsupset \cdot ; \Delta} \right] \\ & \rightarrow_{\text{epet}} & \Xi[\] \end{array} \quad (①, ②, ③)$$

□

Remark 9.6.1 Note that both Proposition ?? and Proposition ?? are proved indirectly by contradiction, but that the contradiction is obtained by exhibiting a concrete derivation, exploiting respectively the universal instantiation of pistils with the ipis rule, and the existential instantiation of petals with the ipet rule. Thus there seems to be some constructive content to these proofs, despite their use of a classical reasoning principle. Also, this is the only place in the completeness proof where we build derivations, and all \clubsuit -rules (and only them) seem to be required to conclude.

Lastly, we define the so-called *universal Kripke structure* $\clubsuit(\psi)$ relative to a flower ψ :

Definition 9.6.6 (Universal Kripke structure) *Let $\psi \in \mathbb{F}$. The universal Kripke structure $\clubsuit(\psi)$ has:*

- The set of ψ -consistent and ψ -complete theories as its worlds;
- Set inclusion as its accessibility relation;
- For each world \mathcal{T} , a first-order structure whose domain is the set of terms \mathbb{T} , and whose interpretation map is given by:
 - $\llbracket f \rrbracket(\vec{t}) = f(\vec{t})$
 - $\llbracket p \rrbracket = \{\vec{t} \mid p(\vec{t}) \in \mathcal{T}\}$

One can easily check that the monotonicity conditions of Kripke structures hold for $\clubsuit(\psi)$.

We are now equipped to prove the main *adequacy* lemma, which relates forcing in $\clubsuit(\psi)$ with ψ -consistency and ψ -completeness:

Lemma 9.6.6 (Adequacy) *Let $\phi, \psi \in \mathbb{F}$, \mathcal{T} a ψ -consistent and ψ -complete theory, and σ a substitution. Then 1. $\sigma(\phi) \in \mathcal{T}$ implies $\mathcal{T} \Vdash \phi[\sigma]$, and 2. $\mathcal{T} \vdash_{\clubsuit} \sigma(\phi)$ implies $\mathcal{T} \Vdash \phi[\sigma]$.*

Proof. By recurrence on $|\phi|$.

- Suppose $\phi = p(\vec{t})$.
 1. By definition of forcing (Definition ??) and $\clubsuit(\psi)$ (Definition ??), $\mathcal{T} \Vdash p(\vec{t})[\sigma]$ precisely when $\sigma(p(\vec{t})) \in \mathcal{T}$.
 2. Suppose that $\mathcal{T} \Vdash \phi[\sigma]$, that is $\sigma(\phi) \in \mathcal{T}$. Then by weakening (Lemma ??), we get $\sigma(\phi) \Vdash_{\clubsuit} \sigma(\phi)$. But this is impossible by reflexivity of \vdash (Lemma ??).
- Suppose $\phi = x \cdot \Phi \sqsupset \{x_i \cdot \Phi_i\}_i^n$.
 1. Let $\mathcal{U} \supseteq \mathcal{T}$ be a ψ -consistent and ψ -complete theory. Obviously $\sigma(\phi) = x \cdot \sigma|_x(\Phi) \sqsupset \{x_i \cdot \sigma|_{x \cup x_i}(\Phi_i)\}_i^n \in \mathcal{U}$, and thus by Proposition ??, for every substitution τ , either $|_x \tau \circ \sigma|_{x \cup x_i}(\Phi_i) = \sigma|_x \tau|_{x_i}(\Phi_i) \subseteq \mathcal{U}$ for some $1 \leq i \leq n$, or $\mathcal{U} \Vdash_{\clubsuit} |_x \tau \circ \sigma|_x(\Phi) = \sigma|_x \tau(\Phi)$. In the first case, we get $\mathcal{U} \Vdash \Phi_i[\sigma|_x \tau|_{x_i}]$ by IH. In the second case, we get $\mathcal{U} \Vdash \Phi[\sigma|_x \tau]$ by IH. In other words, $\mathcal{U} \Vdash \Phi[\sigma|_x \tau]$ implies $\mathcal{U} \Vdash \Phi_i[\sigma|_x \tau|_{x_i}]$, that is $\mathcal{T} \Vdash \phi[\sigma]$.
 2. By Proposition ??, for every $1 \leq i \leq n$ and substitution τ , there is some $\phi_i \in \Phi_i$ such that $\mathcal{T}, \sigma|_x(\Phi) \Vdash_{\clubsuit} |_{x_i} \tau \circ \sigma|_{x \cup x_i}(\phi_i) = \sigma|_x |_{x_i} \tau(\phi_i)$. By the completion procedure, we get a theory $\mathcal{U} = \text{Com}(\mathcal{T} \cup \sigma|_x(\Phi)) \supseteq \mathcal{T} \cup \sigma|_x(\Phi)$ which is both $\sigma|_x |_{x_i} \tau(\phi_i)$ -consistent and $\sigma|_x |_{x_i} \tau(\phi_i)$ -complete. Then by IH, $\mathcal{U} \Vdash \Phi[\sigma|_x]$ since $\sigma|_x(\Phi) \subseteq \mathcal{U}$, and $\mathcal{U} \Vdash \phi_i[\sigma|_x |_{x_i} \tau]$ since \mathcal{U} is $\sigma|_x |_{x_i} \tau(\phi_i)$ -consistent, that is $\mathcal{T} \Vdash \phi[\sigma]$.

□

Lemma 9.6.7 Let $\psi \in \mathbb{F}$ and \mathcal{T} be a ψ -consistent theory. Then $\mathcal{T} \not\Vdash \psi$.

Proof. We show $\mathcal{T} \not\Vdash_{\clubsuit(\psi)} \psi$, and more specifically that $\text{Com}(\mathcal{T}) \Vdash \mathcal{T}[1]$ but $\text{Com}(\mathcal{T}) \not\Vdash \psi[1]$.

- Let $\phi \in \mathcal{T}$. Then $1(\phi) = \phi \in \text{Com}(\mathcal{T})$, thus by ψ -consistency (Lemma ??) and ψ -completeness (Lemma ??) of the completion, one can apply adequacy (Lemma ??) to get $\text{Com}(\mathcal{T}) \Vdash \phi[1]$.
- Similarly, we can apply adequacy (Lemma ??) to get $\text{Com}(\mathcal{T}) \not\Vdash \psi[1]$.

□

We get completeness as the direct (and classical) contraposition of Lemma ??, in the case where $\mathcal{T} = \emptyset$:

Theorem 9.6.8 (Completeness) $\models \phi$ implies $\vdash_{\clubsuit} \phi$.

Combined with strong deduction (Theorem ??), this also yields a strong completeness theorem for the full flower calculus (actually for the fragment $\clubsuit \cup \{\text{grow}\}$):

Theorem 9.6.9 (Strong completeness) $\Phi \models \Psi$ implies $\Psi \rightarrow^* \Phi$.

Proof. By Lemma ?? we have that $\Phi \sqsupset \Psi \rightarrow^* \emptyset$, and by Theorem ?? we can conclude. □

9.7 Automated proof search

Analyticity and invertibility The completeness of \otimes -rules (Theorem ??) suggests that some efficient proof search procedure might be devised for the flower calculus, and even a complete one for the propositional fragment where every sprinkler is empty¹². Indeed in sequent calculi, analyticity (the subformula property) greatly reduces the search space when looking for a proof of a given sequent, and one might expect the same to apply in the natural fragment \otimes of the flower calculus. Also, the invertibility of \otimes -rules implies that the procedure will not need to perform *backtracking*, a great source of non-determinism in proof search¹³, and particularly so in intuitionistic logic¹⁴.

Depth and interaction However, there is another great source of non-determinism that does not arise in Gentzen systems, but is inherent to any deep inference formalism: it is precisely the fact that rules can be applied in contexts of *arbitrary* depth, thus inducing a number of choices that is exponential in the latter. Kahramanogullari has proposed some attempts to tame this problem in [105] and [103], and our approach bears some similarities to his. In particular, we propose in the following a (sketch of a) proof search algorithm for the propositional flower calculus, whose core rests on an *interaction* relation between contexts which is a generalization of the pollination relation (Definition ??), and is close to the *structural* relation of Kahramanogullari [103, Definition 2.13].

Definition 9.7.1 (Interaction) *Let $\Phi\Box, \Psi\Box$ be two contexts. We say that $\Phi\Box$ can interact with $\Psi\Box$ when there exist contexts $\Xi\Box, \Phi_0\Box, \Psi_0\Box$ such that either:*

► **(Cross-interaction)**

$$\begin{aligned}\Phi\Box &= \Xi \boxed{\Phi_0\Box, \Psi_0\Box} \\ \text{and } \Psi\Box &= \Xi \boxed{\Phi_0\Box, \Psi_0\Box}\end{aligned}$$

and we write $\Phi\Box \bowtie \Psi\Box$;

► **(Self-interaction)** *there is some Δ such that*

$$\begin{aligned}\Phi\Box &= \Xi \boxed{\Phi_0\Box \multimap \Psi_0\Box; \Delta} \\ \text{and } \Psi\Box &= \Xi \boxed{\Phi_0\Box \multimap \Psi_0\Box; \Delta}\end{aligned}$$

and we write $\Phi\Box \bowtie \Psi\Box$.

It is clear that \bowtie is a symmetric relation, while \bowtie is not. Also, we write $\overset{+}{\bowtie}$ and $\overset{-}{\bowtie}$ (resp. $\overset{+}{\bowtie}$ and $\overset{-}{\bowtie}$) to further specify when $\Xi\Box$ is positive (resp. negative).

12: It is well-known that provability in intuitionistic propositional logic is decidable, a result first demonstrated by Gentzen [63].

13: See also Section ?? for a discussion on this topic.

14: The only fully invertible proof system for intuitionistic (predicate) logic that we know of is the labelled sequent calculus G3IntQ from Lyon's thesis [117] (we thank Lutz Straßburger for pointing that to us). However, a peculiarity of labelled sequent calculi is that they need to incorporate *semantical* notions like the worlds and accessibility relation of Kripke structures into the syntax of sequents, in order to make every rule invertible [71]. We do not need such devices in the flower calculus, which will be crucial from a user interface standpoint in Section ??.

[105]: Kahramanogullari (2006), 'Reducing Nondeterminism in the Calculus of Structures'

[103]: Kahramanogullari (2014), 'Interaction and Depth against Nondeterminism in Proof Search'

Causality Our algorithm will be driven by the search for dual occurrences of atoms, a recurring idea in this thesis.

Definition 9.7.2 (Occurrence) *An occurrence is a pair $(\Phi\Box, \phi)$ of a flower ϕ and a context $\Phi\Box$. It is said to be atomic if ϕ is an atom.*

Then, two atomic occurrences can interact when their contexts can. In the (linear) classical setting of [103], there is no preferred direction in the information flow between two interacting atoms, which can be seen as the essence of the (linear) law of excluded middle $A \wp A^\perp$. However in our intuitionistic setting, implication forces a direction from premisses to conclusions, which is reflected in our distinction between the symmetric cross-interaction relation \bowtie , and the asymmetric self-interaction relation \bowtie^{15} . In turn, the asymmetry of \bowtie will impose a causality on atoms, where one atom can potentially be *justified* by the other:

Definition 9.7.3 (Justification) *A justification is an oriented pair of atomic occurrences $\mathbf{a} = (\Phi\Box, a) \hookrightarrow (\Psi\Box, b)$.*

One can then naturally aggregate justifications into *arguments*:

Definition 9.7.4 (Argument) *An argument is a finite set \mathfrak{A} of justifications. Every argument \mathfrak{A} can be seen as the set of edges of a directed graph, whose vertices are the occurrences appearing in the justifications of \mathfrak{A} . Conversely, every directed graph on a set of occurrences can be seen as an argument, whose justifications are the edges of the graph.*

We identify two essential arguments inherent to any bouquet:

Definition 9.7.5 (Vehicle and Anchor) *Let Φ a bouquet, and $\mathcal{A}(\Phi) = \{(\Psi\Box, a) \mid \Phi = \Psi[a]\}$ its set of atomic occurrences.*

The vehicle of Φ is the argument $\mathcal{V}(\Phi) \subseteq \mathcal{A}(\Phi) \times \mathcal{A}(\Phi)$ such that $(\Psi\Box, a) \hookrightarrow (\Psi'\Box, a') \in \mathcal{V}(\Phi)$ iff the following conditions hold:

(Identity) $a = a'$;

(Polarity) $\Psi\Box$ is negative and $\Psi'\Box$ is positive;

(Interaction) either $\Psi\Box \bowtie \Psi'\Box$, $\Psi\Box \bowtie^+ \Psi'\Box$ and $\Psi\Box = \Box$, or $\Psi'\Box \bowtie^+ \Psi\Box$.

Dually, the anchor of Φ is the argument $\mathcal{A}(\Phi) \subseteq \mathcal{A}(\Phi) \times \mathcal{A}(\Phi)$ such that $(\Psi\Box, a) \hookrightarrow (\Psi'\Box, a') \in \mathcal{A}(\Phi)$ iff the following conditions hold:

(Polarity) $\Psi\Box$ is positive and $\Psi'\Box$ is negative;

(Interaction) $\Psi\Box \bowtie \Psi'\Box$.

Intuitively, the vehicle of a bouquet Φ is the set of possible justifications that *can* be performed by the prover/player, whose goal is to justify every positive atom; while the anchor is the set of justifications that *must* be provided on demand by the environment/opponent, whose task is to justify every negative atom. The reason that we identify this structure, is that we want crucially to avoid *cycles* in our justification attempts during proof search. These may arise in the dialogical interaction between the prover and its environment of hypotheses, when justifications of the former are composed with those of the latter. Formally, this interaction is expressed by the *union* of arguments:

15: Arguably, the linear heart of this phenomenon can be studied in the logic BV, which adds to the commutative connective \wp a non-commutative or *sequential* operator \triangleright . Interestingly, BV is the logic that motivated the whole development of the deep inference methodology by Guglielmi [84], because it could not be accurately expressed in shallow Gentzen formalisms.

Definition 9.7.6 (Compatibility) *Given a justification α and an argument \mathfrak{A} , we say that α is compatible with \mathfrak{A} , written $\alpha \downarrow \mathfrak{A}$, when there is no cycle in $\mathfrak{A} \cup \{\alpha\}$.*

Pollination The vehicle and anchor of any bouquet Φ can easily be computed, by noticing that the context $\Xi\Box$ in Definition ?? is simply the *least common ancestor* of the atoms $\Psi\Box$ and $\Psi'\Box$ in the tree representation of Φ , which we write $\text{lca}(\Psi\Box, \Psi'\Box)$. This forms the basis for the first *phase* of our algorithm, that we call the *pollination* phase¹⁶. Roughly, the idea is that given a goal Φ , we want to perform eagerly every justification α in the vehicle $\mathcal{V}(\Phi)$, on the condition that it is compatible with the anchor $\mathcal{A}(\Phi)$ and all justifications \mathfrak{J} of the previous phases. It turns out that every such justification can be implemented by an instance of the $\text{poll}\downarrow$ rule, sometimes preceded by an instance of the $\text{poll}\uparrow$ rule. This is best described by the following *imperative* procedure, that takes as input and modifies in-place both the goal Φ , and the history \mathfrak{J} of justifications performed so far:

16: It corresponds roughly to a combination of the *application* and *linking* phases of the proof search algorithm for B_{inv} described in Subsection ??.

Procedure $\text{pollination}(\Phi, \mathfrak{J})$

```

1 foreach  $\alpha = (\Psi\Box, a) \hookrightarrow (\Psi'\Box, a') \in \mathcal{V}(\Phi) \setminus \mathfrak{J}$  do
2   if  $\alpha \downarrow \mathcal{A}(\Phi) \cup \mathfrak{J}$  then
3      $\phi\Box \leftarrow$  the direct child flower context of  $\text{lca}(\Psi\Box, \Psi'\Box)$  where
        $a$  occurs
4      $\phi'\Box \leftarrow$  the direct child flower context of  $\text{lca}(\Psi\Box, \Psi'\Box)$ 
       where  $a'$  occurs
5      $\Xi\Box \leftarrow \Psi'\Box$ 
6     if  $\phi\Box \neq \Box$  then
7       append a deep copy of  $\phi'\Box$  to the bouquet located by
          $\Psi\Box$ 
8        $\Xi\Box \leftarrow \Psi\Box$ 
9     remove  $a'$  from  $\Xi\Box$ 
10    add  $\alpha$  to  $\mathfrak{J}$ 

```

While this might not be obvious at first glance, the two steps of the ?? procedure that modify Φ are logically *sound*: indeed, the copy operation on line ?? corresponds to an instance of the $\text{poll}\uparrow$ rule, while the remove operation on line ?? corresponds to an instance of the $\text{poll}\downarrow$ rule.

Reproduction The second phase of our algorithm is the *reproduction* phase. As its name suggests, it consists in repeatedly applying the reproduction rule step on the current goal, until there is no more context in which it is applicable¹⁷. The reproduction phase can be computed by the following tail recursive procedure:

17: In the algorithm of Subsection ??, this corresponds to the part of the *decomposition* phase that treats negative \vee formulas.

Procedure reproduction(Φ)

```

1 foreach  $\phi = (\Psi \sqsupset \Delta) \in \Phi$  do
2   if there is at least one flower  $\psi = (\sqsupset \{\gamma_i\}_i^m) \in \Psi$  then
3     remove  $\psi$  from  $\Psi$ 
4     remove every petal from  $\phi$ 
5     append the petal  $\{\gamma_i \sqsupset \Delta\}_i^m$  to  $\phi$ 
6     reproduction( $\phi$ )
7   else
8     foreach  $\Xi \in \Delta$  do
9       reproduction( $\Xi$ )

```

Decomposition The third and last phase of our proof search algorithm, called *decomposition*, is also the most trivial: it simply consists in applying the *epet* rule in every applicable context in the goal, which amounts to erasing every flower with an empty petal¹⁸. Unlike the reproduction phase, it cannot be computed directly by a tail recursive procedure, because erasing flowers in the petals of a flower ϕ might make one of the petals of ϕ itself empty. One option is to iterate a tail recursive procedure until a fixpoint is reached, meaning that there are no more flowers with an empty petal. We give instead a more efficient, but non-tail recursive solution:

18: It corresponds to the *popping* phase of bubbles in Subsection ??, not the decomposition phase: here the term “decomposition” refers metaphorically to the biological process that applies to organic matter, not to the analysis of formulas into their components.

Procedure decomposition(Φ)

```

1 foreach  $\phi = (\Psi \sqsupset \Delta) \in \Phi$  do
2   if  $\emptyset \in \Delta$  then
3     remove  $\phi$  from  $\Phi$ 
4   else
5     has_empty_petal  $\leftarrow$  false
6     foreach  $\Xi \in \Delta$  do
7       decomposition( $\Xi$ )
8       if  $\Xi = \emptyset$  then
9         has_empty_petal  $\leftarrow$  true
10        break
11     if has_empty_petal then
12       remove  $\phi$  from  $\Phi$ 
13     else
14       decomposition( $\Psi$ )

```

Cycle of life We can now put together the three phases to form a so-called *lifecycle*. We decompose this in two steps:

1. first we perform one pollination phase;
2. then we cycle reproduction and decomposition phases until a fixpoint is reached.

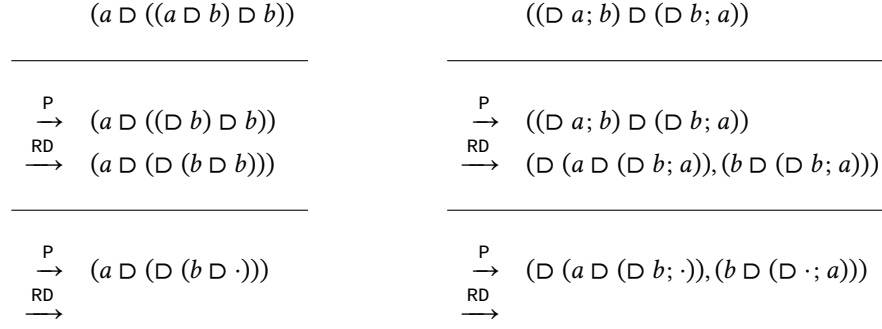


Figure 9.20: Life traces for modus ponens (left) and identity expansion of disjunction (right)

Procedure lifecycle(Φ, \mathfrak{H})

```

1 pollination( $\Phi, \mathfrak{H}$ )
2  $\Phi' \leftarrow$  deep copy of  $\Phi$ 
3 reproduction( $\Phi'$ )
4 decomposition( $\Phi'$ )
5 while  $\Phi \neq \Phi'$  do
6    $\Phi \leftarrow$  deep copy of  $\Phi'$ 
7   reproduction( $\Phi'$ )
8   decomposition( $\Phi'$ )
    
```

Note that the specific order in which phases are sequenced does not matter. The final algorithm, that we call the ?? procedure, is then the fixpoint of the ?? procedure:

Procedure life(Φ)

```

1  $\mathfrak{H} \leftarrow \emptyset$ 
2  $\Phi' \leftarrow$  deep copy of  $\Phi$ 
3 lifecycle( $\Phi', \mathfrak{H}$ )
4 while  $\Phi \neq \Phi'$  do
5    $\Phi \leftarrow$  deep copy of  $\Phi'$ 
6   lifecycle( $\Phi', \mathfrak{H}$ )
    
```

Figure ?? shows the *traces* obtained by executing the algorithm on two simple tautologies. Lifecycles are separated by horizontal lines, while an arrow with superscript P (resp. RD) indicates a pollination (resp. reproduction/decomposition) phase.

Assuming that the ?? procedure terminates on every input, the decision procedure is immediate: if $\Phi = \emptyset$ after executing $\text{life}(\Phi)$, then Φ is a tautology, otherwise it is not.

Implementation We have implemented the ?? procedure in the OCaml programming language [45]. In fact, we refined the design of the algorithm iteratively, by testing it on a set of 62 tautologies taken from Edukera's logic course [164] (the full set is available in Figure ??). Since those are expressed with symbolic formulas, we rely on a straightforward translation of formulas into (bouquets of) flowers, given in Figure ??. Out of the 62

$$\begin{aligned}
 \top^\bullet &= \emptyset \\
 \perp^\bullet &= \mathbin{\text{D}} \\
 (A \wedge B)^\bullet &= A^\bullet, B^\bullet \\
 (A \vee B)^\bullet &= \mathbin{\text{D}} A^\bullet; B^\bullet \\
 (A \supset B)^\bullet &= A^\bullet \mathbin{\text{D}} B^\bullet \\
 (\forall x. A)^\bullet &= x \cdot \mathbin{\text{D}} A^\bullet \\
 (\exists x. A)^\bullet &= \mathbin{\text{D}} x \cdot A^\bullet
 \end{aligned}$$

Figure 9.21: Translation $(-)^{\bullet}$ of formulas into bouquets

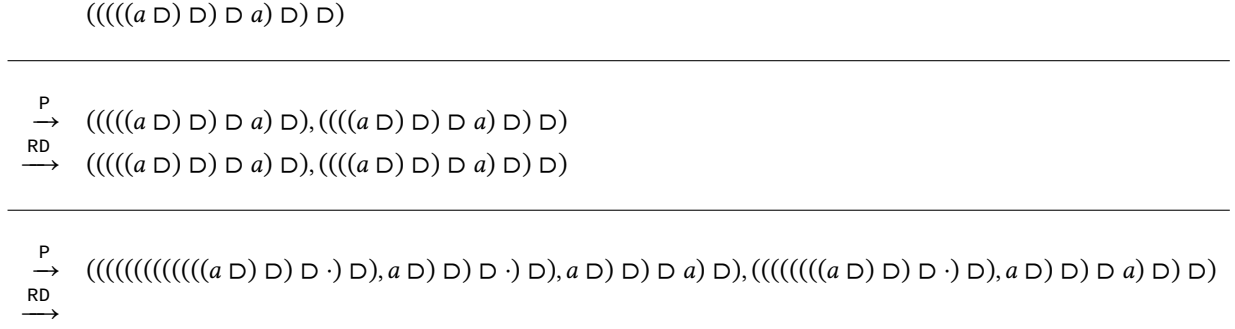


Figure 9.22: Life trace for doubly-negated double-negation elimination law

tautologies, 53 were proved by the algorithm, and among the 9 unproved tautologies, only the 2 formulas $\neg\neg(\neg\neg A \supset A)$ and $\neg\neg(((A \supset B) \supset A) \supset A)$ are intuitionistically valid, while the other 7 formulas are only classically valid.

Incompleteness Interestingly on this dataset, the algorithm only fails on formulas that correspond to the double-negation of a classical law. Of course, Theorem ?? guarantees that there must exist proofs for these formulas, using only \otimes -rules. While this may include the epis rules, we conjecture that it is not actually needed to get a complete decision algorithm. Instead, we have implemented an extension of the ?? procedure that accounts specifically for doubly-negated formulas, by first duplicating the negative negation as a special additional case of the pollination phase. In the case of the double-negation elimination law $((((a \text{ D}) \text{ D}) \text{ D } a) \text{ D}) \text{ D}$, this would give the flower

$$(((a \text{ D}) \text{ D}) \text{ D } a) \text{ D), (((a \text{ D}) \text{ D}) \text{ D } a) \text{ D}) \text{ D}$$

which is then provable by the algorithm as shown in Figure ??.

Encouraged by these positive results, we attempted to validate the algorithm on a more challenging dataset: the ILTP problem library for intuitionistic logic, version 1.1.2 [156]. Unfortunately, it turns out that neither the basic ?? procedure nor its extension are able to prove the following theorem of intuitionistic logic (problem SYJ106+1):

$$(((\neg(t \supset r) \supset p) \wedge s) \supset (\neg((p \supset q) \wedge (t \supset r)) \supset (\neg\neg p \wedge (s \wedge s))))$$

Worse, the extension seems to loop indefinitely on it.

Non-termination In fact, even the basic version of the ?? procedure does not terminate (at least in reasonable time, i.e. less than 3 minutes) on another intuitionistic theorem (problem SYJ201+1.001):

$$\begin{aligned}
& (((((p3 \Leftrightarrow p1) \\
& \supset (p1 \wedge (p2 \wedge p3))) \\
& \wedge ((p2 \Leftrightarrow p3) \supset (p1 \wedge (p2 \wedge p3)))) \\
& \wedge ((p1 \Leftrightarrow p2) \supset (p1 \wedge (p2 \wedge p3))))
\end{aligned}$$

[156]: Rathes et al. (2007), ‘The ILTP Problem Library for Intuitionistic Logic’

$$\supset (p1 \wedge (p2 \wedge p3)))$$

We did not have the opportunity yet to investigate the sources of incompleteness and non-termination of our algorithm. Indeed, the analysis of life traces on formulas of this size is quite time-consuming, if not untractable for a human. Concerning non-termination, one could hypothesize at this stage, although we find this unlikely, that the algorithm *does* terminate theoretically, but is simply extremely time-inefficient¹⁹. For instance, it takes 6 whole seconds on a laptop equipped with an i7-10610U processor (8 cores, upto 4.90 GHz per core) and 16 GB of RAM to find a proof of the following formula (problem SYJ107+1004):

$$\begin{aligned} & (((((((b \vee a) \vee b) \wedge (b \supset ((b1 \vee a1) \vee b1))) \\ & \wedge (b1 \supset ((b2 \vee a2) \vee b2))) \wedge (b2 \supset ((b3 \vee a3) \vee b3))) \wedge a4) \\ & \supset (a \vee ((b \wedge a1) \vee ((b1 \wedge a2) \vee ((b2 \wedge a3) \vee (b3 \wedge a4)))))) \end{aligned}$$

19: And also space-inefficient, since the bottleneck is the pollination phase that can duplicate flowers in an exponential fashion.

IMPLICATION	CONJUNCTION	DISJUNCTION
$(A \supset (B \supset A))$	$(A \supset (B \supset (A \wedge B)))$	$(A \supset (A \vee B))$
$(A \supset ((A \supset B) \supset B))$	$(A \supset (B \supset (C \supset (A \wedge (B \wedge C)))))$	$(B \supset (A \vee B))$
$((B \supset C) \supset ((A \supset B) \supset (A \supset C)))$	$((A \wedge B) \supset (C \supset A))$	$(B \supset (A \vee (B \vee C)))$
	$((A \wedge B) \supset (C \supset B))$	$((A \vee B) \supset ((A \supset B) \supset B))$
	$((A \wedge B) \supset (B \wedge A))$	$((A \vee B) \supset (B \vee A))$
CONSTRUCTIVE LOGIC		
	$((A \wedge B) \supset (C \supset A))$	
	$((A \wedge B) \supset (C \supset (B \wedge C)))$	
	$(A \supset (A \wedge (A \vee B)))$	
	$((A \vee (B \wedge C)) \supset (A \vee B))$	
	$((A \vee B) \supset ((A \supset B) \supset B))$	
	$((A \supset (B \supset C)) \supset ((A \supset B) \supset (A \supset C)))$	
	$((A \supset (B \supset C)) \supset ((A \wedge B) \supset C))$	
	$((A \supset B) \supset ((A \supset C) \supset (A \supset (B \wedge C))))$	
	$((A \supset B) \supset ((A \vee C) \supset (B \vee C)))$	
	$((A \wedge B) \vee (A \vee B)) \supset (A \vee B)$	
	$((A \supset C) \wedge (B \supset C)) \supset ((A \vee B) \supset C)$	
	$((\neg A \vee B) \supset (A \supset B))$	
	$((A \supset (B \supset C)) \supset ((A \wedge B) \supset C))$	
	$(A \supset ((A \supset B) \supset ((A \supset B) \supset (B \supset C)) \supset C))$	
	$((A \wedge B) \supset C) \Leftrightarrow (A \supset (B \supset C))$	
	$((A \vee B) \supset C) \Leftrightarrow ((A \supset C) \wedge (B \supset C))$	
DISTRIBUTIVITY		
	$((A \wedge (B \supset C)) \supset ((A \wedge B) \supset (A \wedge C)))$	
	$((A \wedge (B \vee C)) \Leftrightarrow ((A \wedge B) \vee (A \wedge C)))$	
	$((A \vee (B \wedge C)) \Leftrightarrow ((A \vee B) \wedge (A \vee C)))$	
	$((A \supset B) \wedge (A \supset C)) \supset (A \supset (B \wedge C))$	
	$(A \supset (B \wedge C)) \supset ((A \supset B) \wedge (A \supset C))$	
	$((A \supset B) \vee (A \supset C)) \supset (A \supset (B \vee C))$	
	$(A \supset (B \supset C)) \supset ((A \supset B) \supset (A \supset C))$	
	$((A \supset B) \supset (A \supset C)) \supset (A \supset (B \supset C))$	
	$((A \vee B) \supset C) \Leftrightarrow ((A \supset C) \wedge (B \supset C))$	
CLASSICAL LOGIC		
	$((A \wedge B) \supset (A \wedge C)) \supset (A \wedge (B \supset C))$	
	$((A \supset (B \vee C)) \supset ((A \supset B) \vee (A \supset C)))$	
	$(A \vee \neg A)$	
	$(A \vee (A \supset B))$	
	$((A \supset B) \vee (B \supset A))$	
	$(\neg \neg A \supset A)$	
	$((A \supset B) \supset A) \supset A$	
	$\neg \neg (A \vee \neg A)$	
	$\neg \neg (A \vee (A \supset B))$	
	$\neg \neg ((A \supset B) \vee (B \supset A))$	
	$\neg \neg (\neg \neg A \supset A)$	
	$\neg \neg (((A \supset B) \supset A) \supset A)$	

Figure 9.23: Testing dataset of tautologies from Edukera

9.8 The Flower Prover

Proof-by-Action While having a complete and efficient proof search procedure is a nice desideratum, our focus in this thesis is not so much on full automation — which is not possible anyway as soon as we leave the propositional fragment, but rather on automation that integrates well with, and even improves the experience of building proofs *interactively*. More specifically, the paradigm of interaction we are interested in is that of *direct manipulation* in a GUI. This was our initial motivation for studying the graphical formalism of EG, and we always kept this objective in mind when developing the flower calculus. In this section, we present ongoing work on the *Flower Prover*, a prototype of GUI in the Proof-by-Action paradigm based on the direct manipulation of flowers, that builds upon the various concepts, rules and metatheory of the previous sections.

Remark 9.8.1 Currently, the Flower Prover only handles propositional flowers with empty sprinklers.

Implementation The prototype is implemented in Elm [38], a modern functional reactive programming language that is particularly well-suited for building GUI that are based on complex compositional data-structures like flowers. It also natively compiles to HTML and JavaScript, making it easy to run and test the interface on any device equipped with a web browser. The source code is available on GitHub [46], and the interface is currently hosted online as a simple HTML page²⁰. The reader is invited to try out the Flower Prover in her own browser, although we will try to give self-contained explanations illustrated through various screenshots.

[38]: Czaplicki et al. (2013), ‘Asynchronous Functional Reactive Programming for GUIs’

20: <https://www.lix.polytechnique.fr/Labo/Pablo.DONATO/flowerprover/>

Originality We are not the first to identify the potential of EG for graphical proof building [187][115]. However, we believe that the Flower Prover is highly original in mainly two respects:

[187]: Unknown author (2001), *Visual Logic: Peirce’s Existential Graphs*

[115]: Loo (2022), *Cross-platform React app for solving existential graph-based proofs*

Intuitionistic and goal-oriented it is based on the flower calculus, which proposes a quite unusual, non-exegetic take on EG. It does so both at the level of *statements*, by building upon the intuitionistic icon of the n -ary scroll; and at the level of *proofs*, by focusing on a goal-oriented reading of rules that emphasizes the importance of *invertibility* and *analyticity* in the inference process, through the distinction between \otimes -rules and \multimap -rules.

Mobile-friendly it has been designed from the outset as a *responsive*, *touch*-based, *mobile*-friendly interface. Responsivity means that it can be run on screens of varying formats and resolutions, all with the same layout providing a uniform experience across devices. Touch-based means that every pointing interaction is optimized for touch in addition to mouse gestures, so that there is no loss in precision. The combination of these two properties makes the interface perfectly usable on mobile devices like phones and tablets²¹, which are becoming increasingly ubiquitous in personal computing. While the current generation of proof assistants targets mostly technical and expert users with text-based, keyboard-driven interactions, we believe that a broadening of audience — especially in

21: This is not the case currently for Actema (Chapter ??), which does not provide a vertical layout, and has poor support for touch interactions. While the former issue could be solved easily, the latter is somehow inherent to the symbolic nature of formulas: in scenarios where one needs to refer to a specific subterm, it is difficult to design a touch-based selection mechanism that is as precise and straightforward as a mouse-based one.

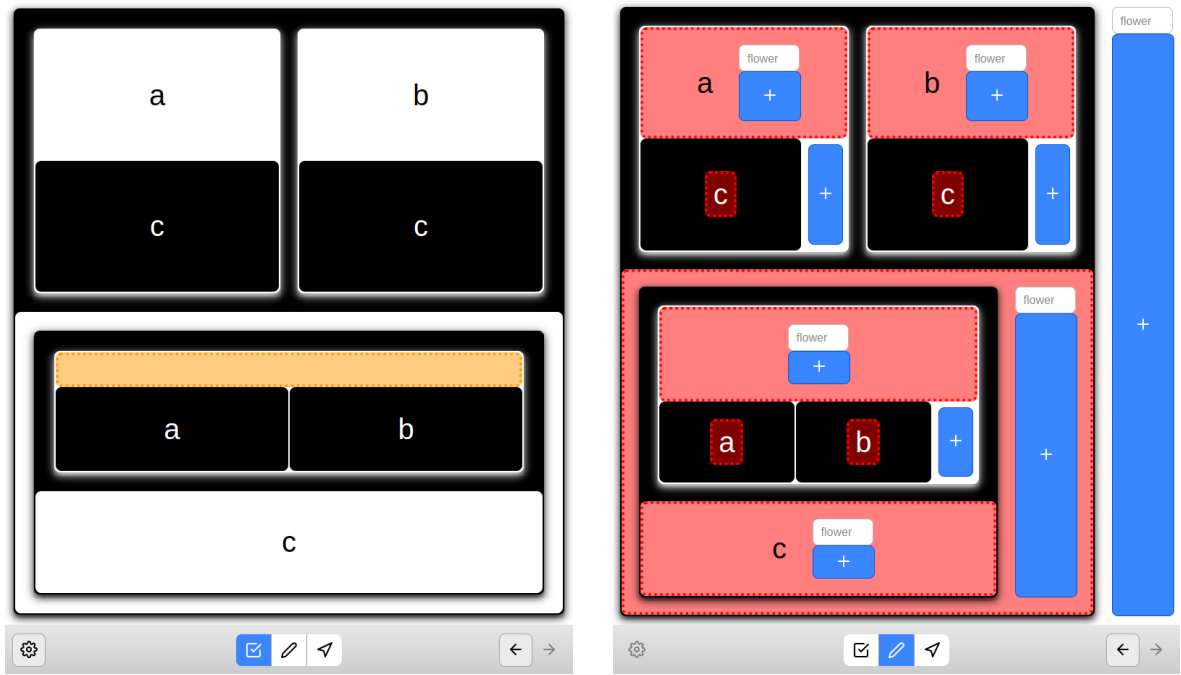


Figure 9.24: Proof mode (left) and Edit mode (right) of the Flower Prover

educational settings — if at all possible, will require a reinvention of our means of interaction with formal proofs, that is more in phase with contemporary usages of digital devices.

Modal interface The Flower Prover is organized in two main *modes* of interaction, providing different sets of available actions to the user²²:

Proof mode
Edit mode

At any point during a proof, the user can switch between the two modes by clicking on the corresponding button in the *mode selection bar*, located at the bottom of the screen (Figure ??): the proof and edit modes are mapped respectively to the left button with a checkmark icon, and the middle button with a pencil icon.

Proof mode
Edit mode

Navigation mode The reader might have noticed that there is a third, right button with a navigation icon in the mode selection bar. It can be used to enter *navigation mode*, the last mode of interaction that we intend to implement in the future. The idea is that on real-life goals, both the size and level of nesting of flowers will quickly render the interface unusable, both for reading/understanding the content and structure of goals, and manipulating them through pointing.

The purpose of the navigation mode is then to enable the user to *focus* on a specific subgoal, by simply clicking on the corresponding nested

22: Another example of modal interface is the popular text editor *vim*, with its *normal* mode for high-level manipulation of text through commands and macros, and its *edit* mode for low-level insertion and deletion of characters.

- TODO
- TODO
- Describe every action
- Example of proof trace with screenshots
- Describe every action

flower. This would make the subgoal take up the whole screen, hiding the outer context from view. Dually, it should also be possible to unfocus a previously focused subgoal – e.g. by clicking again, so that the full tree structure of the goal can be freely navigated.

This way of navigating tree structures represented as nested areas is typical of *zoomable user interfaces* or ZUI, a strand of GUI that has been developed by many pioneers in the field of human-computer interaction such as Ivan Sutherland in its Sketchpad system [178], and Alan Kay in its Smalltalk system [73].

Automation

Theories and goals In the so-called “proof view” or “goal view” of modern proof assistants like Coq and Lean, there is no distinction between local and global contexts: a subgoal will inherit automatically every hypothesis from its parent subgoals, which are flattened into a big unstructured list. To recreate this distinction and reduce the size of goals to a manageable level, the only interface mechanism offered to the user is to exit interactive proof mode, and outsource chunks of the local context as additional global lemmas and definitions in the current theory file.

Thus the user has to juggle between two different interfaces that manipulate two distinct data structures: a traditional text editor for modifying *theories*, and an IDE for writing and executing proof scripts that modify *goals*, themselves visualized in a separate proof view. This results in a duplication of means to achieve essentially the same things: for instance, reordering two lemmas will require to cut and paste one of them in the theory file, while reordering two hypotheses will require the use of a dedicated move tactic. Other examples can be found for renaming definitions, applying lemmas, constructing functions, etc.

Crucially, the two interfaces cannot communicate straightforwardly with each other. In fact, communication is completely one-way: the user can only invoke definitions and lemmas from the theory in her proof script, by referring to their names.

Statements and proofs Our above example targets imperative tactic languages, but the argument equally applies to more declarative languages like Isar in Isabelle: the point is that the *proof* language, be it imperative or declarative, is separated both conceptually and through its available means of interaction from the language of *statements* used to build theories. And this separation between proofs and statements is a natural one that is hard to question, since it is rooted in what is arguably the most important inspiration of formal logic, and also the form in which informal mathematics present themselves: *natural language*. Indeed, symbolic formulas reproduce the grammatical structure of sentences expressing logical propositions, and proofs reproduce the inferential structure of arguments built from sequences of sentences.

[178]: Sutherland (1964), ‘Sketchpad: A Man-machine Graphical Communication System’

[73]: Goldberg et al. (1976), *SMALLTALK-72 INSTRUCTION MANUAL*

Describe our current automation as a simple fixpoint applying all the applicable actions according to a set of rules. Thus the user could tune the level of automation by customizing the set of rules.

Possibility to apply automation systematically after each action, or manually by clicking on a button.

Proof trace for the same goal as before, but with default automation turned on.

Idea of reducing a proof to a set of DnD pollinations + Case reasoning with *srep*.

Diagrams However, there is an increasing number of areas in mathematics — the most prominent one being category theory — where the heart of a proof lies in the dynamical construction of a *diagram* capturing the structure of interest in given mathematical objects. The natural language proof text is often just a mean to explicit the meaning or intuition behind the diagrammatic manipulations, or simply a retranscription of the commentary that the mathematician would give when unfolding the construction on a blackboard. If one views logic as one particular type of mathematical reasoning — albeit one that is omnipresent in all branches of mathematics, then it is only natural to expect that some diagrammatic system should exist for it, that can express in the most natural way most (if not all) logical arguments. This is the *iconicity* thesis of Peirce, and what we are aiming for with the Flower Prover.

Context navigation After this little conceptual *aparté*, let us come back to the problem of managing contexts in proofs. In the Flower Prover, the *local* context is naturally represented as *everything that is displayed on-screen*. This includes hypotheses that are available from pistils at various levels, but also potentially alternative goals (adjacent petals) and further subgoals (positively nested flowers). Then rather than being segregated in a separate interface (the text buffer of the theory), the *global* context is simply the *entire* goal. In fact, there is no reason anymore to make a terminological distinction between goals and theories: a goal is just a theory that has yet to be justified, which can itself be identified with a partial proof (or a “proof term with holes” in type theory)²³.

It would still be useful to be able to aggregate automatically the set of all lemmas and definitions (i.e. hypotheses) available in a focused subgoal $\Phi[\phi]$, so that the user does not need to navigate up and down the goal tree all the time. This can be done with the help of the pollination relation (Definition ??), by taking the union $\Psi = \{\psi \mid \psi \succ \Phi[\phi]\}$.

In terms of UI, we could then add a “shelf” displayed in all interaction modes, that exposes the global context Ψ of the current focus $\Phi[\phi]$. We anticipate only two kinds of interaction with the shelf:

Pollination

Jump to definition

Since the shelf might contain *a lot* of hypotheses, it will be important to provide efficient ways to *filter* or *search* through its content. We imagine three main ways to do so:

By name the user can type the *name* of a hypothesis in a search bar. This implies that flowers have the ability to be named by the user.

By structure the user can specify a *pattern* that must be satisfied by all hypotheses in the shelf. A pattern is just a flower that contains pattern variables, which can match any flower. Thus patterns might be built with the same tools offered in Edit mode.

By selection the user can select subterms of the goal, and then ask the system to display only hypotheses that can *interact* with these subterms. Here we imagine something along the lines of what we did for Actema (Section ??).

23: We will come back to this idea of merging proofs and statements in the same data structure in the conclusion, when discussing *development calculi*. Note however that it is already at the heart of *dependent* type theory, where terms can freely occur inside types.

TODO

TODO

Remark 9.8.2 The first two types of filtering are already available in most proof assistants, i.e. the `Search` command of Coq.

9.9 Conclusion

Related works

Intuitionistic EG In the original IEG system of Oostra, the *srep* rule is replaced by an extended (de)iteration rule, that allows to duplicate/merge not only identical flowers, but also identical *petals*, under the condition that they are attached to the same pistil²⁴ (rules *iter* and *deit* in Figure ??). Thus in a sense, (de)iteration on petals is not as *deep* as on whole flowers, where the two identical flowers can be separated by an arbitrary number of layers; which might seem like an arbitrary restriction. A posteriori, we rationalize this choice by seeing it as an attempt to stay close to the original system Alpha of Peirce. In particular, (de)iteration on petals is compatible with the quest for *illative atomicity*, where all rules should be expressed in terms of insertions and omissions (Section ??); while the *srep* rule is not. In our case, this is justified by our quest for an *invertible* calculus (natural fragment): indeed to simulate *srep* with *petal* (de)iteration, one also needs the non-invertible \Leftarrow -rule *crop* (as well as the \Leftarrow -rule *epis*_↓), as illustrated by the *srep*-free proof of Figure ??.

Focusing There is a formal connection between the poll^\dagger rule of the flower calculus, and the *absorption* rule [A] of the dyadic system Σ_2 of Andreoli, that handles the focusing behavior of exponentials in linear logic [5]. Indeed, both rules duplicate a formula available in the (non-linear) context of the sequent/location where the rule is applied, in order to enable further usage of the formula at said location. While the absorption rule removes the need for permutation-equivalences between proofs involving the *contraction* rule, the identity rule [I] of Σ_2 removes the need for the *weakening* rule by discarding the non-linear context in one go, just as the *epet* rule of the flower calculus renders the *crop* rule admissible.

Sonia Marin has noticed the connection between *bipoles* in focused proofs, and the class of geometric/coherent formulas, where the former are seen as a generalization of the latter [118]. This is to be related to our own

$$\begin{array}{c}
\overline{(a \sqsupset c), (b \sqsupset c), c \sqsupset \cdot}^{\text{epet}} \\
\overline{(a \sqsupset c), (b \sqsupset c), c \sqsupset c}^{\text{poll}\downarrow} \\
\overline{\overline{(a \sqsupset c), (b \sqsupset c), (D \sqsupset c)} \sqsupset c}^{\text{epis}\downarrow} \\
\overline{(a \sqsupset c), (b \sqsupset c), (D \sqsupset c); (D \sqsupset c) \sqsupset c}^{\text{iter}} \\
\overline{(a \sqsupset c), (b \sqsupset c), (D \sqsupset c), a; (D \sqsupset c), b) \sqsupset c}^{\text{crop}} \\
\overline{(a \sqsupset c), (b \sqsupset c), (D (a \sqsupset c), a; (b \sqsupset c), b) \sqsupset c}^{\text{poll}\downarrow} \\
\overline{\overline{(a \sqsupset c), (b \sqsupset c), (D a; b) \sqsupset c}^{\text{poll}\uparrow}}
\end{array}$$

$$\frac{\gamma \supset \delta; \Delta}{\gamma \supset \delta; \delta; \Delta} \text{ iter}$$

$$\frac{\gamma \supset \delta; \delta; \Delta}{\gamma \supset \delta; \Delta} \text{ deit}$$

Figure 9.25: (De)iteration rules for petals

24: “Cualquier lazo puede iterarse adherido *al mismo corte*” [141, p. 46].

[5]: Andreoli (1992), ‘Logic Programming with Focusing Proofs in Linear Logic’

[118]: Marin et al. (2022), ‘From axioms to synthetic inference rules via focusing’

Figure 9.26: Simulating the srep rule by iterating petals

identification of n -ary scrolls/flowers as a recursive generalization of coherent formulas at the end of Section ??.

Two years earlier, Brock-Nannestad and Ilik had already made some implicit connections between focused proofs and coherent formulas, through their *exponential normal form* for intuitionistic formulas based on Tarski's highschool identities [19]. Quite remarkably, first-order formulas in their exponential normal form have the exact same structure as flowers [19, Definition 4.2]. However, the sequent calculus HS based on them makes the tradeoff opposite to that of the natural fragment \mathfrak{F} of the flower calculus: every inference rule is *non-invertible*, but the calculus is contraction-free. One advantage of this tradeoff is that they can easily show termination of proof search, while we have not found a terminating procedure yet for the flower calculus. The authors also mention that HS could be turned into a deep inference calculus in the style of G4ip²⁵.

Development calculi In Section ??, we have seen how the rules of the flower calculus can be understood as a set of (graphical) tactics for building partial proofs interactively. In Chapter 3 of his thesis [9], Ayers calls such systems *development calculi*. In particular, he presents his own development calculus inspired by McBride's OLEG system [124] and G&G's prover [62] called the Box calculus, where both goals and partial proofs are represented by the same Box datastructure. Once again, Boxes seem to share a very similar structure with flowers, which was here motivated by the need to avoid backtracking by having the ability to maintain a disjunction of goals with so-called *disjunctive pairs*, corresponding to the petals of flowers. The main difference is that the Box calculus is based on dependent type theory instead of first-order logic: this allows to store the partial proof terms inside of the Boxes themselves, while this information is lost during the construction of flowers (but might be reconstructed from the sequence of graphical actions and the initial goal).

Ayers also mentions the category-theoretical treatment of development calculi by Sterling and Harper [175], that abstracts from any particular type of judgment. Thus it might be possible to fit the flower calculus into this framework, by identifying the set of flowers F as a category of *nested judgments*²⁶.

Subformula linking Our notion of *vehicle* (Definition ??) takes its terminology from Girard, who started giving this name to the set of axiom links of a proof structure in his transcendental syntax²⁷ [69]. But the idea of connecting dual occurrences of atoms, and thus forming a graph with an associated adjacency matrix whose structure can be exploited in proof search, really dates back to the *connection method* developed independently by Bibel and Andrews in the 1970s [15]. Otten and Kreitz have adapted the connection method to intuitionistic logic [146], stating that it is especially well-suited in an interactive theorem proving environment. Thus it might be instructive to learn from their proof search algorithm to fix ours.

In fact all proof search procedures designed in this thesis, whether for bubble calculi (Subsection ??) or the flower calculus (Section ??), rest on the fundamental observation coming from the subformula linking methodology of Chaudhuri [26], that the construction of proofs in deep inference

[19]: Brock-Nannestad et al. (2019), 'An Intuitionistic Formula Hierarchy Based on High-School Identities'

25: This is just another name for the system LJ_T of Dyckhoff already mentioned in Chapter ??.

[9]: Ayers (2021), 'A Tool for Producing Verified, Explainable Proofs.'

[124]: McBride (2000), 'Dependently Typed Functional Programs and their Proofs'

[62]: Ganesalingam et al. (2017), 'A Fully Automatic Theorem Prover with Human-Style Output'

[175]: Sterling et al. (2017), *Algebraic Foundations of Proof Refinement*

26: Nested judgments are already considered in some recent categorical semantics of type theory, and in particular those in Sterling's thesis [174]. See also [95] for a (technical) introduction to the subject.

27: Also, it conveys nicely the idea that the vehicle is the fundamental structure that *drives* the proof search algorithm.

[69]: Girard (2017), 'Transcendental syntax I: deterministic case'

[15]: Bibel et al. (2009), 'Connection method'

[146]: Otten et al. (1995), 'A connection based proof method for intuitionistic logic'

[26]: Chaudhuri (2013), 'Subformula Linking as an Interaction Method'

systems can be driven efficiently and incrementally by the connection of dual atoms. With its pollination rules, the flower calculus allows for a particularly elegant implementation of subformula linking that abstracts away from the syntactic bureaucracy of symbolic connectives, as witnessed by the pollination phase of our search procedure. In Subsection ??, we sketched some ideas that blur the frontier between automated and interactive proof search, notably with the so-called *rule of thumb* which is another manifestation of subformula linking. This integration of automated and interactive aspects is also at work in the Flower Prover, and it would be interesting to investigate further how to incorporate our drag-and-drop proof tactic (Chapter ??), but also other symbolic manipulation techniques introduced in the first part of this thesis, into the iconic framework of the Flower Prover.

Analyticity We have not discussed the rationale behind our notion of analyticity, be it historical or formal arguments explaining its origins, motivations and consequences. In a recent article [22], Bruscoli and Guglielmi propose such a detailed discussion around a precise and generic definition of analyticity for deep inference proof systems (especially the calculus of structures), which at a glance seems to encompass our own definition. It would be interesting to study more deeply their work, and related parts of the deep inference literature concerned with analyticity and its applications to efficient proof search procedures [105][103][81][30][32].

Future works

Metatheory In Section ??, we already mentioned the variant $\mathfrak{S} \setminus \{\text{epis}\} \cup \{\text{crep}\}$ of the natural fragment, that we conjecture to enjoy both soundness, completeness and a deduction theorem. But these last two results shall prove particularly harder to prove, and we currently have very few insights into how to extend the proofs of this chapter to this setting. Also, this is not withstanding the fact that we do not really see any practical applications for such results as of yet. Our initial motivation was to show the admissibility of the epis rule, because it never appears in concrete proofs. But if this requires adding the crep rule instead, then it greatly reduces the practical interest of the whole endeavor, since the crep rule does not look particularly well-suited to either automated or interactive theorem proving.

Automated proof search We shall investigate the current sources of non-termination and incompleteness for our ?? proof search procedure, through further testing on the ILTP dataset. If we succeed in passing all tests, the natural continuation will be to provide formal proofs of termination and completeness. A follow-up direction would be to extend our algorithm to the first-order setting by adding heuristics for handling sprinklers, thus losing completeness.

Another direction of research would consist in comparing our algorithm to existing search procedures for EG, in particular one that was originally developed by Peirce, and described by Oostra in [142].

[22]: Bruscoli et al. (2019), ‘On Analyticity in Deep Inference’

[105]: Kahramanoğulları (2006), ‘Reducing Nondeterminism in the Calculus of Structures’

[103]: Kahramanogullari (2014), ‘Interaction and Depth against Nondeterminism in Proof Search’

[81]: Guenot (2011), ‘Nested Proof Search as Reduction in the Lambda-Calculus’

[30]: Chaudhuri et al. (2011), ‘The Focused Calculus of Structures’

[32]: Chaudhuri et al. (2016), ‘Focused and Synthetic Nested Sequents’

[142]: Oostra (2022), ‘Advances in Peircean Mathematics: The Colombian School’

Flower Prover Implement the navigation mode in the Flower Prover, and design GUI mechanisms that support relational reasoning with sprinklers, based on the rules *ipis*, *ipet* and *apis*, *apet*.

Curry Howard We have begun to sketch some ideas for a Curry-Howard correspondence, where flowers and actions (rules) for justifying them are identified respectively with *normal* and *neutral* terms of the simply-typed λ -calculus. For instance, the computational counterpart of the rule $\text{poll}\downarrow$ in pistils would be a kind of *function application* expressed by the following app rule, which is highly reminiscent of the instantiation rule *ipis*:

$$\frac{\Xi t u : (\Phi\{u/x\} \supset \Delta\{u/x\})}{\Xi t : (\Phi, x : \phi \supset \Delta)} \text{app}$$

Given a flower ϕ and a neutral term t , i.e. an n -ary function application of the form $x t_1 \dots t_n$, the expression $t : \phi$ is a *term annotation*, that should be read in context as “this occurrence of ϕ is justified by t ”. Interestingly, ϕ itself may contain term annotations, mimicking the fact that normal and neutral terms can be defined by mutual recursion. Then in the app rule, we do not just erase the formula ϕ as in the $\text{poll}\downarrow$ rule, but also keep track of the flow of information by appending the argument u to the justification t (where $(u : \phi) \succ \Xi\Box$), and substituting u to every occurrence of the hypothetical justification x of ϕ in Φ and Δ .

As of now the syntax of annotated flowers is not yet stable, and it is unclear what would be the computational interpretation of flowers with $n \neq 1$ petals. In particular for disjunctive flowers ($n > 1$), it seems that we are closer to a notion of non-deterministic or parallel computation, than to the usual branching computation of sum or inductive types.

If our intuition is right, then the fact that flowers correspond to (normal) λ -terms would embody syntactically a recent motto from Miquel stemming from his study of the foundations of forcing and realizability in implicative algebras, where “elements can be seen both as truth values and as (generalized) realizers, thus **blurring the frontier between proofs and types**”²⁸ [131]. Or as he put it in a recent talk [132], we get the ultimate Curry-Howard identification:

$$\text{Realizer} = \text{Program} = \text{Formula} = \text{Type}$$

This could also form the basis for further studies on the connections between EG and (dependent) type theory, and ultimately lead to a tight integration of the Flower Prover with proof assistants based on the latter such as Coq, Lean and Agda. Existing explorations of the links between type theory and deep inference include, in historical order:

- a first attempt by Brännler and McKinnley to devise a Curry-Howard correspondence for a simple intuitionistic deep inference calculus with conjunction and implication [20];
- the thesis of Nicolas Guenot, and more precisely the part on “Nested Proofs as Programs” where he gives a correspondence between simply-typed λ -calculi with explicit substitutions at one end, and calculi of structures (Chapter 6) and nested sequent calculi (Chapter

28: Another recent, related incarnation of this phenomenon is the correspondence uncovered by Haydon between a linear version of EG already appearing in Peirce’s writings, and the proof nets of Girard for linear logic [87].

[131]: Miquel (2020), ‘Implicative algebras’

[20]: Brännler et al. (2008), ‘An Algorithmic Interpretation of a Deep Inference System’

- 5) for the implicational fragment of intuitionistic logic at the other end [82];
- ▶ the atomic λ -calculus, a simply-typed λ -calculus with explicit sharing that has a Curry-Howard correspondence with proofs in the formalism of *open deduction* [86];
- ▶ a type system for interaction nets based on a calculus of structures for Multiplicative Exponential Linear Logic [65];
- ▶ the thesis of Fanny He, that explores a classical variant of the atomic λ -calculus based on Saurin's $\Lambda\mu$ -calculus [89];
- ▶ the *spinal* atomic λ -calculus, an extension and improvement on the atomic λ -calculus based on a computational interpretation of the *switch* rule [165];
- ▶ the *collection calculus* that subsumes resource, intersection-typed and simply-typed λ -calculi, with a type system again in open deduction [83];
- ▶ Ongoing research by Kaustuv Chaudhuri to extend subformula linking to dependent type theory²⁹.

[86]: Gundersen et al. (2013), 'Atomic Lambda Calculus'

[65]: Gimenez et al. (2013), 'The Structure of Interaction'

[89]: He (2018), 'The Atomic Lambda-Mu Calculus'

[165]: Sherratt et al. (2020), 'Spinal Atomic Lambda-Calculus'

[83]: Guerrieri et al. (2021), 'A Deep Quantitative Type System'

29: Private communication.

The work of Guenot on computational interpretations of nested sequent calculi seems closest to the syntax of flowers. Indeed, nested sequents are variadic by nature, and his version of nested sequents in particular exploits the possibility to have *negative* occurrences of sequents. Combined with the dependently-typed Boxes of Ayers mentioned earlier (which cannot be nested negatively), this should provide great insights for the powerful, dependently-typed version of the flower calculus that we seek for.

Theory vs. Practice

Finally, it should be noted that Peirce did not think of EG as a calculus that could aid in performing reasoning *per se*, but rather as a tool for analysing the finer structure of logical endeavor [161, pp. 110-111]:

[...] the purpose which the system was designed to fulfill was "to enable us to separate reasoning into its smallest steps so that each one may be examined by itself" (Ms 455, p.2). The aim was not to facilitate reasoning, but to facilitate the study of reasoning.

The various achievements presented in this chapter incite us to depart from this conception. Indeed, our particular viewpoint on the illative transformations, that emphasizes goal-reduction through invertible and analytic rules, enabled us to design a novel and promising type of graphical interface for interactive proof building, which integrates easily and elegantly some (limited) forms of automation. This was also made possible by the use of variables instead of lines of identity, trading a heavy graphical apparatus with local inference rules for a simple, well-known textual syntax with complex (but automated) global dynamics in the form of substitutions. Hence we believe the *opposite*, that EG *can* form the basis for an ergonomic calculus of logical deduction, in addition to being a powerful tool for meta-logical analysis.

APPENDIX

Symmetric Bubble Calculi

A

A.1 Soundness

Lemma A.1.1 (Generalized weakening) $\llbracket S \rrbracket^+ \leq \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+$.

Proof. Let $S = \Gamma' \triangleright \Delta'$. We proceed by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned} \llbracket \Gamma' \Rightarrow \Delta' \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\ &\leq \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \vee \llbracket \Delta' \rrbracket^+ \\ &\leq \llbracket \Gamma' \rrbracket^- \wedge \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \vee \llbracket \Delta' \rrbracket^+ \\ &= \llbracket \Gamma', \Gamma \Rightarrow \Delta, \Delta' \rrbracket^+ \end{aligned}$$

Recursive case

$$\begin{aligned} \llbracket \Gamma' \langle \mathcal{S} \rangle \Delta' \rrbracket^+ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma' \Rightarrow \Delta') \rrbracket^+ \\ &\leq \bigwedge_{T \in \mathcal{S}} \llbracket (T \uplus (\Gamma' \Rightarrow \Delta')) \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \quad (\text{IH}) \\ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus ((\Gamma' \Rightarrow \Delta') \uplus (\Gamma \Rightarrow \Delta)) \rrbracket^+ \\ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma', \Gamma \Rightarrow \Delta, \Delta') \rrbracket^+ \\ &= \llbracket \Gamma', \Gamma \langle \mathcal{S} \rangle \Delta, \Delta' \rrbracket^+ \end{aligned}$$

□

Lemma A.1.2 (Generalized contraction) $\llbracket S \uplus (\Rightarrow I, I) \rrbracket^+ \simeq \llbracket S \uplus (\Rightarrow I) \rrbracket^+$ and $\llbracket S \uplus (I, I \Rightarrow) \rrbracket^+ \simeq \llbracket S \uplus (I \Rightarrow) \rrbracket^+$.

Proof. Let $S = \Gamma \triangleright \Delta$. We proceed by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned} \llbracket \Gamma \Rightarrow I, I, \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \supset (\llbracket I \rrbracket^+ \wedge \llbracket I \rrbracket^+) \vee \llbracket \Delta \rrbracket^+ \\ &\simeq \llbracket \Gamma \rrbracket^- \supset \llbracket I \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket \Gamma \Rightarrow I, \Delta \rrbracket^+ \\ \\ \llbracket \Gamma, I, I \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \wedge (\llbracket I \rrbracket^- \wedge \llbracket I \rrbracket^-) \supset \llbracket \Delta \rrbracket^+ \\ &\simeq \llbracket \Gamma \rrbracket^- \wedge \llbracket I \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket \Gamma, I \Rightarrow \Delta \rrbracket^+ \end{aligned}$$

Recursive case

$$\begin{aligned} \llbracket \Gamma \langle \mathcal{S} \rangle I, I, \Delta \rrbracket^+ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma \Rightarrow I, I, \Delta) \rrbracket^+ \\ &= \bigwedge_{T \in \mathcal{S}} \llbracket (T \uplus (\Gamma \Rightarrow \Delta)) \uplus (\Rightarrow I, I) \rrbracket^+ \\ &= \bigwedge_{T \in \mathcal{S}} \llbracket (T \uplus (\Gamma \Rightarrow \Delta)) \uplus (\Rightarrow I) \rrbracket^+ \quad (\text{IH}) \\ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma \Rightarrow I, \Delta) \rrbracket^+ \\ &= \llbracket \Gamma \langle \mathcal{S} \rangle I, \Delta \rrbracket^+ \end{aligned}$$

$$\begin{aligned}
 \llbracket \Gamma, I, I \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma, I, I \Rightarrow \Delta) \rrbracket^+ \\
 &= \bigwedge_{T \in \mathcal{S}} \llbracket (T \uplus (\Gamma \Rightarrow \Delta)) \uplus (I, I \Rightarrow) \rrbracket^+ \\
 &= \bigwedge_{T \in \mathcal{S}} \llbracket (T \uplus (\Gamma \Rightarrow \Delta)) \uplus (I \Rightarrow) \rrbracket^+ \quad (\text{IH}) \\
 &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma, I \Rightarrow \Delta) \rrbracket^+ \\
 &= \llbracket \Gamma, I \langle \mathcal{S} \rangle \Delta \rrbracket^+
 \end{aligned}$$

□

Lemma A.1.3 (Generalized weak distributivity)

$$\llbracket \Gamma \triangleright \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ \leq \llbracket \Gamma \triangleright I, \Delta \rrbracket^+ \quad (\text{A.1})$$

$$\llbracket \Gamma \triangleright I, \Delta \rrbracket^+ \leq_{\mathcal{C}} \llbracket \Gamma \triangleright \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ \quad (\text{A.2})$$

$$\llbracket \Gamma, I \triangleright \Delta \rrbracket^- \leq_{\mathcal{B}} \llbracket I \rrbracket^- \wedge \llbracket \Gamma \triangleright \Delta \rrbracket^- \quad (\text{A.3})$$

$$\llbracket I \rrbracket^- \wedge \llbracket \Gamma \triangleright \Delta \rrbracket^- \leq_{\mathcal{C}} \llbracket \Gamma, I \triangleright \Delta \rrbracket^- \quad (\text{A.4})$$

Proof. We only prove (??): the proof of (??) is the same, except that we use the converse inequality of Fact ?? that holds in Boolean algebras. (??) and (??) hold by duality from (??) and (??), i.e. for (??) we have

$$\begin{aligned}
 &\llbracket \bar{\Delta} \triangleright \bar{\Gamma} \rrbracket^+ \vee \llbracket \bar{I} \rrbracket^+ \leq \llbracket \bar{\Delta} \triangleright \bar{I}, \bar{\Gamma} \rrbracket^+ \quad (??) \\
 \text{iff} \quad &\overline{\llbracket \bar{\Delta} \triangleright \bar{I}, \bar{\Gamma} \rrbracket^+} \leq_{\mathcal{B}} \overline{\llbracket \bar{\Delta} \triangleright \bar{\Gamma} \rrbracket^+ \vee \llbracket \bar{I} \rrbracket^+} \quad (\text{Fact } ??) \\
 \text{iff} \quad &\llbracket \bar{\bar{\Gamma}}, \bar{\bar{I}} \triangleright \bar{\bar{\Delta}} \rrbracket^- \leq_{\mathcal{B}} \llbracket \bar{\bar{\Gamma}} \triangleright \bar{\bar{\Delta}} \rrbracket^- \wedge \llbracket \bar{\bar{I}} \rrbracket^- \quad (\text{Lemma } ??) \\
 \text{iff} \quad &\llbracket \Gamma, I \triangleright \Delta \rrbracket^- \leq_{\mathcal{B}} \llbracket \Gamma \triangleright \Delta \rrbracket^- \wedge \llbracket I \rrbracket^- \quad (\text{Lemma } ??)
 \end{aligned}$$

We prove (??) by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned}
 \llbracket \Gamma \Rightarrow \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ &= (\llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+) \vee \llbracket I \rrbracket^+ \\
 &\leq \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ \quad (\text{Fact } ??) \\
 &= \llbracket \Gamma \Rightarrow I, \Delta \rrbracket^+
 \end{aligned}$$

Recursive case

$$\begin{aligned}
 \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ &= \bigwedge_{(\Gamma' \blacktriangleright \Delta') \in \mathcal{S}} \llbracket (\Gamma' \blacktriangleright \Delta') \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \vee \llbracket I \rrbracket^+ \\
 &= \bigwedge_{(\Gamma' \blacktriangleright \Delta') \in \mathcal{S}} \llbracket \Gamma, \Gamma' \blacktriangleright \Delta', \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+ \\
 &\approx_{\mathcal{L}} \bigwedge_{(\Gamma' \blacktriangleright \Delta') \in \mathcal{S}} \llbracket \Gamma, \Gamma' \blacktriangleright \Delta', \Delta \rrbracket^+ \vee \bigwedge_{(\Gamma' \blacktriangleright \Delta') \in \mathcal{S}} \llbracket I \rrbracket^+ \quad (\text{Fact } ??) \\
 &\approx_{\mathcal{L}} \bigwedge_{(\Gamma' \blacktriangleright \Delta') \in \mathcal{S}} (\llbracket \Gamma, \Gamma' \blacktriangleright \Delta', \Delta \rrbracket^+ \vee \llbracket I \rrbracket^+) \quad (\text{Fact } ??) \\
 &\leq \bigwedge_{(\Gamma' \blacktriangleright \Delta') \in \mathcal{S}} \llbracket \Gamma, \Gamma' \blacktriangleright I, \Delta', \Delta \rrbracket^+ \quad (\text{IH}) \\
 &= \bigwedge_{(\Gamma' \blacktriangleright \Delta') \in \mathcal{S}} \llbracket (\Gamma' \blacktriangleright \Delta') \uplus (\Gamma \Rightarrow I, \Delta) \rrbracket^+ \\
 &= \llbracket \Gamma \langle \mathcal{S} \rangle I, \Delta \rrbracket^+
 \end{aligned}$$

□

Lemma A.1.4 (Generalized currying)

$$\llbracket \Gamma, I \triangleright \Delta \rrbracket^+ \simeq \llbracket I \rrbracket^- \supset \llbracket \Gamma \triangleright \Delta \rrbracket^+ \quad (\text{A.5})$$

$$\llbracket \Gamma \triangleright I, \Delta \rrbracket^- \simeq_{\mathcal{B}} \llbracket \Gamma \triangleright \Delta \rrbracket^- \subset \llbracket I \rrbracket^+ \quad (\text{A.6})$$

Proof. We only prove (??), as (??) holds by duality as in Lemma ???. We proceed by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned} \llbracket \Gamma, I \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \wedge \llbracket I \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\ &\simeq \llbracket I \rrbracket^- \wedge \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &\simeq \llbracket I \rrbracket^- \supset \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket I \rrbracket^- \supset \llbracket \Gamma \Rightarrow \Delta \rrbracket^+ \end{aligned}$$

Recursive case

$$\begin{aligned} \llbracket \Gamma, I \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{(\Gamma' \triangleright \Delta') \in \mathcal{S}} \llbracket (\Gamma' \triangleright \Delta') \cup (\Gamma, I \Rightarrow \Delta) \rrbracket^+ \\ &= \bigwedge_{(\Gamma' \triangleright \Delta') \in \mathcal{S}} \llbracket \Gamma', \Gamma, I \triangleright \Delta, \Delta' \rrbracket^+ \\ &\simeq \bigwedge_{(\Gamma' \triangleright \Delta') \in \mathcal{S}} (\llbracket I \rrbracket^- \supset \llbracket \Gamma', \Gamma \triangleright \Delta, \Delta' \rrbracket^+) \quad (\text{IH}) \\ &\simeq \llbracket I \rrbracket^- \supset \bigwedge_{(\Gamma' \triangleright \Delta') \in \mathcal{S}} \llbracket \Gamma', \Gamma \triangleright \Delta, \Delta' \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket I \rrbracket^- \supset \bigwedge_{(\Gamma' \triangleright \Delta') \in \mathcal{S}} \llbracket (\Gamma' \triangleright \Delta') \cup (\Gamma \Rightarrow \Delta) \rrbracket^+ \\ &= \llbracket I \rrbracket^- \supset \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^+ \end{aligned}$$

□

Lemma A.1.5 (Local soundness) *If $S \rightarrow T$ then $\llbracket T \cup (\Gamma \Rightarrow \Delta) \rrbracket^+ \leq_{\mathcal{C}} \llbracket S \cup (\Gamma \Rightarrow \Delta) \rrbracket^+$.*

Proof. We show that $S \rightarrow T$ implies $\llbracket T \rrbracket^+ \leq_{\mathcal{C}} \llbracket S \rrbracket^+$ by inspection of each rule of system B. That we can mix an arbitrary top-level context $\Gamma \Rightarrow \Delta$ into S and T follows from Fact ??.

i↓

$$\begin{aligned} \llbracket \Gamma \langle \rangle \Delta \rrbracket^+ &= \bigwedge_{U \in \emptyset} \llbracket U \cup (\Gamma \Rightarrow \Delta) \rrbracket^+ \\ &= \top \\ &\simeq \llbracket \Gamma \rrbracket^- \wedge A \supset A \vee \llbracket \Delta \rrbracket^+ \\ &= \llbracket \Gamma, A \Rightarrow A, \Delta \rrbracket^+ \end{aligned}$$

i↑

$$\begin{aligned} \llbracket \Gamma \langle \Rightarrow A; A \Rightarrow \rangle \Delta \rrbracket^+ &= \llbracket \Gamma \Rightarrow A, \Delta \rrbracket^+ \wedge \llbracket \Gamma, A \Rightarrow \Delta \rrbracket^+ \\ &= (\llbracket \Gamma \rrbracket^- \supset A \vee \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \wedge A \supset \llbracket \Delta \rrbracket^+) \\ &\simeq (\llbracket \Gamma \rrbracket^- \supset A \vee \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \supset A \supset \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\ &\simeq \llbracket \Gamma \rrbracket^- \supset (A \vee \llbracket \Delta \rrbracket^+) \wedge (A \supset \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\ &\simeq \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket \Gamma \Rightarrow \Delta \rrbracket^+ \end{aligned}$$

$w-, w+$ By Lemma ??.

$c-, c+$ By Lemma ??.

$f\uparrow$

$$\begin{aligned} \llbracket \Gamma \langle \mathcal{S}; \Gamma' \langle \mathcal{S}' \rangle \Delta'; S \rangle \Delta \rrbracket^+ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \wedge \llbracket \Gamma, \Gamma' \langle \mathcal{S}' \rangle \Delta', \Delta \rrbracket^+ \wedge \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \\ &\leq \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \wedge \llbracket \Gamma, \Gamma' \langle \mathcal{S}' \rangle \Delta', \Delta \rrbracket^+ \wedge \llbracket S \uplus (\Gamma, \Gamma' \Rightarrow \Delta', \Delta) \rrbracket^+ \quad (\text{Lemma ??}) \\ &= \llbracket \Gamma \langle \mathcal{S}; \Gamma' \langle \mathcal{S}' \rangle S \rangle \Delta' \rangle \Delta \rrbracket^+ \end{aligned}$$

$f-\downarrow$

$$\begin{aligned} \llbracket \Gamma \langle \Gamma', I \blacktriangleright \Delta'; \mathcal{S} \rangle \Delta \rrbracket^+ &= \llbracket \Gamma, \Gamma', I \blacktriangleright \Delta', \Delta \rrbracket^+ \wedge \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \\ &= \llbracket \Gamma, I \langle \Gamma' \blacktriangleright \Delta'; \mathcal{S} \rangle \Delta \rrbracket^+ \end{aligned}$$

$f+\downarrow$

$$\begin{aligned} \llbracket \Gamma \langle \mathcal{S}; \Gamma' \blacktriangleright I, \Delta' \rangle \Delta \rrbracket^+ &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \wedge \llbracket \Gamma, \Gamma' \blacktriangleright I, \Delta', \Delta \rrbracket^+ \\ &= \llbracket \Gamma \langle \mathcal{S}; \Gamma' \blacktriangleright \Delta' \rangle I, \Delta \rrbracket^+ \end{aligned}$$

$f+-\downarrow$ We show that $\llbracket \Gamma \triangleright (\Gamma', I \blacktriangleright \Delta'), \Delta \rrbracket^+ \leq \llbracket \Gamma, I \triangleright (\Gamma' \blacktriangleright \Delta'), \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned} \llbracket \Gamma \Rightarrow (\Gamma', I \blacktriangleright \Delta'), \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \supset \llbracket \Gamma', I \blacktriangleright \Delta' \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \\ &\simeq \llbracket \Gamma \rrbracket^- \supset (\llbracket I \rrbracket^- \supset \llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^+) \vee \llbracket \Delta \rrbracket^+ \quad (\text{Lemma ??}) \\ &\leq \llbracket \Gamma \rrbracket^- \supset (\llbracket I \rrbracket^- \supset \llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^+ \vee \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\ &\simeq \llbracket \Gamma \rrbracket^- \wedge \llbracket I \rrbracket^- \supset \llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket \Gamma, I \Rightarrow (\Gamma' \blacktriangleright \Delta'), \Delta \rrbracket^+ \end{aligned}$$

Recursive case

$$\begin{aligned} \llbracket \Gamma \langle \mathcal{S} \rangle (\Gamma', I \blacktriangleright \Delta'), \Delta \rrbracket^+ &= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma \Rightarrow (\Gamma', I \blacktriangleright \Delta'), \Delta) \rrbracket^+ \\ &= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma \triangleright (\Gamma', I \blacktriangleright \Delta'), \Delta, \Delta'' \rrbracket^+ \\ &\leq \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma, I \triangleright (\Gamma' \blacktriangleright \Delta'), \Delta, \Delta'' \rrbracket^+ \quad (\text{IH}) \\ &= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma, I \Rightarrow (\Gamma' \blacktriangleright \Delta'), \Delta) \rrbracket^+ \\ &= \llbracket \Gamma, I \langle \mathcal{S} \rangle (\Gamma' \blacktriangleright \Delta'), \Delta \rrbracket^+ \end{aligned}$$

$f+-\downarrow$ We show that $\llbracket \Gamma, (\Gamma' \blacktriangleright I, \Delta') \triangleright \Delta \rrbracket^+ \leq_{\mathcal{HB}} \llbracket \Gamma, (\Gamma' \blacktriangleright \Delta') \triangleright I, \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned} \llbracket \Gamma, (\Gamma' \blacktriangleright I, \Delta') \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \wedge \llbracket \Gamma' \blacktriangleright I, \Delta' \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\ &\simeq_{\mathcal{HB}} \llbracket \Gamma \rrbracket^- \wedge (\llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^- \supset \llbracket I \rrbracket^+) \supset \llbracket \Delta \rrbracket^+ \quad (\text{Lemma ??}) \\ &\leq_{\mathcal{HB}} (\llbracket \Gamma \rrbracket^- \wedge \llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^- \supset \llbracket I \rrbracket^+) \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &\leq_{\mathcal{HB}} \llbracket \Gamma \rrbracket^- \wedge \llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^- \supset \llbracket I \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket \Gamma, (\Gamma' \blacktriangleright \Delta') \Rightarrow I, \Delta \rrbracket^+ \end{aligned}$$

Recursive case

$$\begin{aligned}
\llbracket \Gamma, (\Gamma' \blacktriangleright I, \Delta') \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma, (\Gamma' \blacktriangleright I, \Delta') \Rightarrow \Delta) \rrbracket^+ \\
&= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma, (\Gamma' \blacktriangleright I, \Delta') \triangleright \Delta, \Delta'' \rrbracket^+ \\
&\leq_{\mathcal{HB}} \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma, (\Gamma' \blacktriangleright \Delta') \triangleright I, \Delta, \Delta'' \rrbracket^+ \quad (\text{IH}) \\
&= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma, (\Gamma' \blacktriangleright \Delta') \Rightarrow I, \Delta) \rrbracket^+ \\
&= \llbracket \Gamma, (\Gamma' \blacktriangleright \Delta') \langle \mathcal{S} \rangle I, \Delta \rrbracket^+
\end{aligned}$$

$f++\uparrow$ We show that $\llbracket \Gamma \triangleright (\Gamma' \blacktriangleright \Delta'), I, \Delta \rrbracket^+ \leq \llbracket \Gamma \triangleright (\Gamma' \blacktriangleright I, \Delta'), \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned}
\llbracket \Gamma \Rightarrow (\Gamma' \blacktriangleright \Delta'), I, \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \supset \llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^+ \vee \llbracket I \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \\
&\leq \llbracket \Gamma \rrbracket^- \supset \llbracket \Gamma' \blacktriangleright I, \Delta' \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \quad (\text{Lemma ??}) \\
&= \llbracket \Gamma \Rightarrow (\Gamma' \blacktriangleright I, \Delta'), \Delta \rrbracket^+
\end{aligned}$$

Recursive case

$$\begin{aligned}
\llbracket \Gamma \langle \mathcal{S} \rangle (\Gamma' \blacktriangleright \Delta'), I, \Delta \rrbracket^+ &= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma \Rightarrow (\Gamma' \blacktriangleright \Delta'), I, \Delta) \rrbracket^+ \\
&= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma \triangleright (\Gamma' \blacktriangleright \Delta'), I, \Delta, \Delta'' \rrbracket^+ \\
&\leq \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma \triangleright (\Gamma' \blacktriangleright I, \Delta'), \Delta, \Delta'' \rrbracket^+ \quad (\text{IH}) \\
&= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma \Rightarrow (\Gamma' \blacktriangleright I, \Delta'), \Delta) \rrbracket^+ \\
&= \llbracket \Gamma \langle \mathcal{S} \rangle (\Gamma' \blacktriangleright I, \Delta'), \Delta \rrbracket^+
\end{aligned}$$

$f--\uparrow$ We show that $\llbracket \Gamma, I, (\Gamma' \blacktriangleright \Delta') \triangleright \Delta \rrbracket^+ \leq_{\mathcal{HB}} \llbracket \Gamma, (\Gamma', I \blacktriangleright \Delta') \triangleright \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned}
\llbracket \Gamma, I, (\Gamma' \blacktriangleright \Delta') \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \wedge \llbracket I \rrbracket^- \wedge \llbracket \Gamma' \blacktriangleright \Delta' \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\
&\leq_{\mathcal{HB}} \llbracket \Gamma \rrbracket^- \wedge \llbracket \Gamma', I \blacktriangleright \Delta' \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \quad (\text{Lemma ??}) \\
&= \llbracket \Gamma, (\Gamma', I \blacktriangleright \Delta') \Rightarrow \Delta \rrbracket^+
\end{aligned}$$

Recursive case

$$\begin{aligned}
\llbracket \Gamma, I, (\Gamma' \blacktriangleright \Delta') \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma, I, (\Gamma' \blacktriangleright \Delta') \Rightarrow \Delta) \rrbracket^+ \\
&= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma, I, (\Gamma' \blacktriangleright \Delta') \triangleright \Delta, \Delta'' \rrbracket^+ \\
&\leq_{\mathcal{HB}} \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket \Gamma'', \Gamma, (\Gamma', I \blacktriangleright \Delta') \triangleright \Delta, \Delta'' \rrbracket^+ \quad (\text{IH}) \\
&= \bigwedge_{(\Gamma'' \triangleright \Delta'') \in \mathcal{S}} \llbracket (\Gamma'' \triangleright \Delta'') \uplus (\Gamma, (\Gamma', I \blacktriangleright \Delta') \Rightarrow \Delta) \rrbracket^+ \\
&= \llbracket \Gamma, (\Gamma', I \blacktriangleright \Delta') \langle \mathcal{S} \rangle \Delta \rrbracket^+
\end{aligned}$$

$f--\uparrow, f+-\uparrow$ Converse of $f--\downarrow$ (resp. $f+-\downarrow$), using the converse inequality of Fact ?? which only holds in Boolean algebras.

$f++\downarrow, f--\downarrow$ Converse of $f++\uparrow$ (resp. $f--\uparrow$), using the converse inequality of Lemma ?? which only holds in Boolean algebras.

p

$$\begin{aligned}
 \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \\
 &\simeq_{\mathcal{L}} \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \wedge \top \\
 &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \wedge \llbracket \Gamma \langle \rangle \Delta \rrbracket^+ \\
 &= \llbracket \Gamma \langle \mathcal{S}; \langle \rangle \rangle \Delta \rrbracket^+
 \end{aligned}$$

p⁻

$$\begin{aligned}
 \llbracket \Gamma \langle \rangle \Delta \rrbracket^+ &= \top \\
 &\simeq \llbracket \Gamma \rrbracket^- \wedge \perp \supset \llbracket \Delta \rrbracket^+ \\
 &= \llbracket \Gamma, \langle \rangle \Rightarrow \Delta \rrbracket^+
 \end{aligned}$$

p⁺

$$\begin{aligned}
 \llbracket \Gamma \langle \rangle \Delta \rrbracket^+ &= \top \\
 &\simeq \llbracket \Gamma \rrbracket^- \supset \top \vee \llbracket \Delta \rrbracket^+ \\
 &= \llbracket \Gamma \Rightarrow \langle \rangle, \Delta \rrbracket^+
 \end{aligned}$$

a

$$\begin{aligned}
 \llbracket \Gamma \langle S \rangle \Delta \rrbracket^+ &= \llbracket \langle S \rangle \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \\
 &= \llbracket \Gamma \langle \langle S \rangle \rangle \Delta \rrbracket^+
 \end{aligned}$$

a⁻, a⁺ We only do the proof for a⁻, the proof for a⁺ is symmetric.

We show that $\llbracket \Gamma, S \triangleright \Delta \rrbracket^+ = \llbracket \Gamma, \langle \langle S \rangle \rangle \triangleright \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned}
 \llbracket \Gamma, S \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \wedge \llbracket S \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\
 &= \llbracket \Gamma \rrbracket^- \wedge \llbracket \langle S \rangle \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\
 &= \llbracket \Gamma, \langle \langle S \rangle \rangle \Rightarrow \Delta \rrbracket^+
 \end{aligned}$$

Recursive case

$$\begin{aligned}
 \llbracket \Gamma, S \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma, S \Rightarrow \Delta) \rrbracket^+ \\
 &= \bigwedge_{T \in \mathcal{S}} \llbracket T \uplus (\Gamma, \langle \langle S \rangle \rangle \Rightarrow \Delta) \rrbracket^+ \quad (\text{IH}) \\
 &= \llbracket \Gamma, \langle \langle S \rangle \rangle \langle \mathcal{S} \rangle \Delta \rrbracket^+
 \end{aligned}$$

τ⁻, ⊥⁺ We only do the proof for τ⁻, the proof for ⊥⁺ is symmetric.

We show that $\llbracket \Gamma \triangleright \Delta \rrbracket^+ \simeq \llbracket \Gamma, \top \triangleright \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned}
 \llbracket \Gamma \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \\
 &\simeq \llbracket \Gamma \rrbracket^- \wedge \top \supset \llbracket \Delta \rrbracket^+ \\
 &= \llbracket \Gamma, \top \Rightarrow \Delta \rrbracket^+
 \end{aligned}$$

Recursive case

$$\begin{aligned}
 \llbracket \Gamma \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow \Delta) \rrbracket^+ \\
 &\simeq \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma, \top \Rightarrow \Delta) \rrbracket^+ \quad (\text{IH}) \\
 &= \llbracket \Gamma, \top \langle \mathcal{S} \rangle \Delta \rrbracket^+
 \end{aligned}$$

$\top+$

$$\begin{aligned} \llbracket \Gamma \langle \rangle \Delta \rrbracket^+ &= \top \\ &\simeq \llbracket \Gamma \rrbracket^- \supset \top \vee \llbracket \Delta \rrbracket^+ \\ &= \llbracket \Gamma \Rightarrow \top, \Delta \rrbracket^+ \end{aligned}$$

 $\perp-$

$$\begin{aligned} \llbracket \Gamma \langle \rangle \Delta \rrbracket^+ &= \top \\ &\simeq \llbracket \Gamma \rrbracket^- \wedge \perp \supset \llbracket \Delta \rrbracket^+ \\ &= \llbracket \Gamma, \perp \Rightarrow \Delta \rrbracket^+ \end{aligned}$$

$\wedge-, \vee+$ We only do the proof for $\wedge-$, the proof for $\vee+$ is symmetric.

We show that $\llbracket \Gamma, A, B \triangleright \Delta \rrbracket^+ = \llbracket \Gamma, A \wedge B \triangleright \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned} \llbracket \Gamma, A, B \Rightarrow \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \wedge A \wedge B \supset \llbracket \Delta \rrbracket^+ \\ &= \llbracket \Gamma, A \wedge B \Rightarrow \Delta \rrbracket^+ \end{aligned}$$

Recursive case

$$\begin{aligned} \llbracket \Gamma, A, B \langle \mathcal{S} \rangle \Delta \rrbracket^+ &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma, A, B \Rightarrow \Delta) \rrbracket^+ \\ &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma, A \wedge B \Rightarrow \Delta) \rrbracket^+ \quad (\text{IH}) \\ &= \llbracket \Gamma, A \wedge B \langle \mathcal{S} \rangle \Delta \rrbracket^+ \end{aligned}$$

 $\wedge+$

$$\begin{aligned} \llbracket \Gamma \langle \Rightarrow A; \Rightarrow B \rangle \Delta \rrbracket^+ &= \llbracket \Gamma \Rightarrow A, \Delta \rrbracket^+ \wedge \llbracket \Gamma \Rightarrow B, \Delta \rrbracket^+ \\ &= (\llbracket \Gamma \rrbracket^- \supset A \vee \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \supset B \vee \llbracket \Delta \rrbracket^+) \\ &\simeq \llbracket \Gamma \rrbracket^- \supset (A \vee \llbracket \Delta \rrbracket^+) \wedge (B \vee \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\ &\simeq \llbracket \Gamma \rrbracket^- \supset (\llbracket \Delta \rrbracket^+ \vee A) \wedge (\llbracket \Delta \rrbracket^+ \vee B) \quad (\text{Fact ??}) \\ &\simeq \llbracket \Gamma \rrbracket^- \supset \llbracket \Delta \rrbracket^+ \vee (A \wedge B) \quad (\text{Fact ??}) \\ &\simeq \llbracket \Gamma \rrbracket^- \supset (A \wedge B) \vee \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket \Gamma \Rightarrow A \wedge B, \Delta \rrbracket^+ \end{aligned}$$

 $\vee-$

$$\begin{aligned} \llbracket \Gamma \langle A \Rightarrow; B \Rightarrow \rangle \Delta \rrbracket^+ &= \llbracket \Gamma, A \Rightarrow \Delta \rrbracket^+ \wedge \llbracket \Gamma, B \Rightarrow \Delta \rrbracket^+ \\ &= (\llbracket \Gamma \rrbracket^- \wedge A \supset \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \wedge B \supset \llbracket \Delta \rrbracket^+) \\ &\simeq (\llbracket \Gamma \rrbracket^- \wedge A) \vee (\llbracket \Gamma \rrbracket^- \wedge B) \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &\simeq \llbracket \Gamma \rrbracket^- \wedge (A \vee B) \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\ &= \llbracket \Gamma, A \vee B \Rightarrow \Delta \rrbracket^+ \end{aligned}$$

$\supset+, \subset-$ We only do the proof for $\supset+$, the proof for $\subset-$ is symmetric.

We show that $\llbracket \Gamma \triangleright (A \Rightarrow B), \Delta \rrbracket^+ = \llbracket \Gamma \triangleright A \supset B, \Delta \rrbracket^+$ by recurrence on $|\triangleright|$.

Base case

$$\begin{aligned}
\llbracket \Gamma \Rightarrow (A \Rightarrow B), \Delta \rrbracket^+ &= \llbracket \Gamma \rrbracket^- \supset \llbracket A \Rightarrow B \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \\
&= \llbracket \Gamma \rrbracket^- \supset (A \supset B) \vee \llbracket \Delta \rrbracket^+ \\
&= \llbracket \Gamma \Rightarrow A \supset B, \Delta \rrbracket^+
\end{aligned}$$

Recursive case

$$\begin{aligned}
\llbracket \Gamma \langle \mathcal{S} \rangle (A \Rightarrow B), \Delta \rrbracket^+ &= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow (A \Rightarrow B), \Delta) \rrbracket^+ \\
&= \bigwedge_{S \in \mathcal{S}} \llbracket S \uplus (\Gamma \Rightarrow A \supset B, \Delta) \rrbracket^+ \quad (\text{IH}) \\
&= \llbracket \Gamma \langle \mathcal{S} \rangle A \supset B, \Delta \rrbracket^+
\end{aligned}$$

 $\supset -$

$$\begin{aligned}
\llbracket \Gamma \langle \Rightarrow A; B \Rightarrow \rangle \Delta \rrbracket^+ &= \llbracket \Gamma \Rightarrow A, \Delta \rrbracket^+ \wedge \llbracket \Gamma, B \Rightarrow \Delta \rrbracket^+ \\
&= (\llbracket \Gamma \rrbracket^- \supset A \vee \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \wedge B \supset \llbracket \Delta \rrbracket^+) \\
&\approx (\llbracket \Gamma \rrbracket^- \supset A \vee \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \supset B \supset \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\
&\approx \llbracket \Gamma \rrbracket^- \supset (A \vee \llbracket \Delta \rrbracket^+) \wedge (B \supset \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\
&\leq \llbracket \Gamma \rrbracket^- \supset (A \supset B) \supset \llbracket \Delta \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\
&\approx \llbracket \Gamma \rrbracket^- \supset (A \supset B) \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\
&\approx \llbracket \Gamma \rrbracket^- \wedge (A \supset B) \supset \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\
&= \llbracket \Gamma, A \supset B \Rightarrow \Delta \rrbracket^+
\end{aligned}$$

 $\supset +$

$$\begin{aligned}
\llbracket \Gamma \langle \Rightarrow A; B \Rightarrow \rangle \Delta \rrbracket^+ &= \llbracket \Gamma \Rightarrow A, \Delta \rrbracket^+ \wedge \llbracket \Gamma, B \Rightarrow \Delta \rrbracket^+ \\
&= (\llbracket \Gamma \rrbracket^- \supset A \vee \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \wedge B \supset \llbracket \Delta \rrbracket^+) \\
&\approx (\llbracket \Gamma \rrbracket^- \supset A \vee \llbracket \Delta \rrbracket^+) \wedge (\llbracket \Gamma \rrbracket^- \supset B \supset \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\
&\approx \llbracket \Gamma \rrbracket^- \supset (A \vee \llbracket \Delta \rrbracket^+) \wedge (B \supset \llbracket \Delta \rrbracket^+) \quad (\text{Fact ??}) \\
&\leq \llbracket \Gamma \rrbracket^- \supset (A \supset B) \vee \llbracket \Delta \rrbracket^+ \vee \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\
&\approx \llbracket \Gamma \rrbracket^- \supset (A \supset B) \vee \llbracket \Delta \rrbracket^+ \quad (\text{Fact ??}) \\
&= \llbracket \Gamma \Rightarrow A \supset B, \Delta \rrbracket^+
\end{aligned}$$

□

A.2 Completeness

In the following proofs, we will denote a sequence of applications of a set of rules by a double inference line, and the use of a derivation obtained by induction hypothesis by a dotted line.

Lemma A.2.1 (Simulation of DBilnt) *If $X \vdash_{\text{DBilnt}} Y$ then $X \vdash_{\text{B}_{\mathcal{H}\mathcal{B}} \setminus \{\uparrow\}} Y$.*

Proof. By induction on the derivation of $X \mid_{\text{DBilnt}} Y$.

$$\begin{array}{c}
\frac{}{X, A \Rightarrow A, Y} \text{id} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X \langle \rangle Y} \text{w-}, \text{w+}}{X, A \Rightarrow A, Y} \text{i}\downarrow \\
\\
\frac{\vdots \pi_1}{X, A, (X', A \Rightarrow Y') \Rightarrow Y} \Rightarrow_{\text{L1}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X, A, (X', A \Rightarrow Y') \Rightarrow Y} \pi_1}{X, (X', A, A \Rightarrow Y') \Rightarrow Y} \text{f--}\uparrow \quad \frac{}{X, (X', A \Rightarrow Y') \Rightarrow Y} \text{c-} \\
\\
\frac{\vdots \pi_1}{X \Rightarrow (X' \Rightarrow A, Y'), A, Y} \Rightarrow_{\text{R1}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X \Rightarrow (X' \Rightarrow A, Y'), A, Y} \pi_1}{X \Rightarrow (X' \Rightarrow A, A, Y'), Y} \text{f++}\uparrow \quad \frac{}{X \Rightarrow (X' \Rightarrow A, Y'), Y} \text{c+} \\
\\
\frac{\vdots \pi_1}{X, A \Rightarrow (X', A \Rightarrow Y'), Y} \Rightarrow_{\text{L2}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X, A \Rightarrow (X', A \Rightarrow Y'), Y} \pi_1}{X, A, A \Rightarrow (X' \Rightarrow Y'), Y} \text{f-+}\downarrow \quad \frac{}{X, A \Rightarrow (X' \Rightarrow Y'), Y} \text{c-} \\
\\
\frac{X, (X' \Rightarrow A, Y') \Rightarrow A, Y}{X, (X' \Rightarrow Y') \Rightarrow A, Y} \Rightarrow_{\text{R2}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X, (X' \Rightarrow A, Y') \Rightarrow A, Y} \pi_1}{X, (X' \Rightarrow Y') \Rightarrow A, A, Y} \text{f+-}\downarrow \quad \frac{}{X, (X' \Rightarrow Y') \Rightarrow A, Y} \text{c+} \\
\\
\frac{}{X, \perp \Rightarrow Y} \perp_{\text{L}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X \langle \rangle Y} \text{w-}, \text{w+}}{X, \perp \Rightarrow Y} \perp_{\text{-}} \\
\\
\frac{}{X \Rightarrow \top, Y} \top_{\text{R}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X \langle \rangle Y} \text{w-}, \text{w+}}{X \Rightarrow \top, Y} \top_{\text{+}} \\
\\
\frac{\vdots \pi_1}{X, A \wedge B, A, B \Rightarrow Y} \wedge_{\text{L}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X, A \wedge B, A, B \Rightarrow Y} \pi_1}{X, A \wedge B, A \wedge B \Rightarrow Y} \wedge_{\text{-}} \quad \frac{}{X, A \wedge B \Rightarrow Y} \text{c-} \\
\\
\frac{\vdots \pi_1}{X \Rightarrow A, B, A \vee B, Y} \vee_{\text{R}} \quad \mapsto \quad \frac{\frac{\langle \rangle}{X \Rightarrow A, B, A \vee B \Rightarrow Y} \pi_1}{X \Rightarrow A \vee B, A \vee B, Y} \vee_{\text{+}} \quad \frac{}{X \Rightarrow A \vee B, Y} \text{c+}
\end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \quad \vdots \pi_2 \\
 \hline
 X \Rightarrow A, A \wedge B, Y \quad X \Rightarrow B, A \wedge B, Y \\
 \hline
 X \Rightarrow A \wedge B, Y \quad \wedge_R
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 \langle \rangle; \langle \rangle \\
 \hline
 \langle \rangle; X \Rightarrow B, A \wedge B, Y \quad \pi_2 \\
 \hline
 \langle X \Rightarrow A, A \wedge B, Y; X \Rightarrow B, A \wedge B, Y \rangle \quad \pi_1 \\
 \hline
 X, X \langle \Rightarrow A; \Rightarrow B \rangle A \wedge B, A \wedge B, Y, Y \quad f-, f+ \\
 \hline
 X \langle \Rightarrow A; \Rightarrow B \rangle A \wedge B, Y \quad c-, c+ \\
 \hline
 X \Rightarrow A \wedge B, A \wedge B, Y \quad \wedge+ \\
 \hline
 X \Rightarrow A \wedge B, Y \quad c+
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \quad \vdots \pi_2 \\
 \hline
 X, A \vee B, A \Rightarrow Y \quad X, A \vee B, B \Rightarrow Y \\
 \hline
 X, A \vee B \Rightarrow Y \quad \vee_L
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 \langle \rangle; \langle \rangle \\
 \hline
 \langle \rangle; X, A \vee B, B \Rightarrow Y \quad \pi_2 \\
 \hline
 \langle X, A \vee B, A \Rightarrow Y; X, A \vee B, B \Rightarrow Y \rangle \quad \pi_1 \\
 \hline
 X, X, A \vee B, A \vee B \langle A \Rightarrow; B \Rightarrow \rangle Y, Y \quad f-, f+ \\
 \hline
 X, A \vee B \langle A \Rightarrow; B \Rightarrow \rangle Y \quad c-, c+ \\
 \hline
 X, A \vee B, A \vee B \Rightarrow Y \quad \vee- \\
 \hline
 X, A \vee B \Rightarrow Y \quad c-
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \\
 \hline
 X \Rightarrow (A \Rightarrow B), A \supset B, Y \\
 \hline
 X \Rightarrow A \supset B, Y \quad \supset_R
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 X \Rightarrow (A \Rightarrow B), A \supset B, Y \quad \pi_1 \\
 \hline
 X \Rightarrow A \supset B, A \supset B, Y \quad \supset+ \\
 \hline
 X \Rightarrow A \supset B, Y \quad c+
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \\
 \hline
 X, A \subset B, (A \Rightarrow B) \Rightarrow Y \\
 \hline
 X, A \subset B \Rightarrow Y \quad \subset_L
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 X, A \subset B, (A \Rightarrow B) \Rightarrow Y \quad \pi_1 \\
 \hline
 X, A \subset B, A \subset B \Rightarrow Y \quad \subset- \\
 \hline
 X, A \subset B \Rightarrow Y \quad c-
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \quad \vdots \pi_2 \\
 \hline
 X, A \supset B \Rightarrow A, Y \quad X, A \supset B, B \Rightarrow Y \\
 \hline
 X, A \supset B \Rightarrow Y \quad \supset_L
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 \langle \rangle; \langle \rangle \\
 \hline
 \langle \rangle; X, A \supset B, B \Rightarrow Y \quad \pi_2 \\
 \hline
 \langle X, A \supset B \Rightarrow A, Y; X, A \supset B, B \Rightarrow Y \rangle \quad \pi_1 \\
 \hline
 X, X, A \supset B, A \supset B \langle \Rightarrow A; B \Rightarrow \rangle Y, Y \quad f-, f+ \\
 \hline
 X, A \supset B \langle \Rightarrow A; B \Rightarrow \rangle Y \quad c-, c+ \\
 \hline
 X, A \supset B, A \supset B \Rightarrow Y \quad \supset- \\
 \hline
 X, A \supset B \Rightarrow Y \quad c-
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \quad \vdots \pi_2 \\
 \hline
 X \Rightarrow A, A \subset B, Y \quad X, B \Rightarrow A \subset B, Y \\
 \hline
 X \Rightarrow A \subset B, Y \quad C_R
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline \hline
 \langle \rangle; \langle \rangle \\
 \hline \hline
 \langle \rangle; X, B \Rightarrow A \subset B, Y \quad \pi_2 \\
 \hline \hline
 \langle X \Rightarrow A, A \subset B, Y; X, B \Rightarrow A \subset B, Y \rangle \quad \pi_1 \\
 \hline \hline
 X, X \langle \Rightarrow A; B \Rightarrow \rangle A \subset B, A \subset B, Y, Y \quad f-, f+ \\
 \hline \hline
 X \langle \Rightarrow A; B \Rightarrow \rangle A \subset B, Y \quad c-, c+ \\
 \hline \hline
 X \Rightarrow A \subset B, A \subset B, Y \quad c+ \\
 \hline
 X \Rightarrow A \subset B, Y
 \end{array}$$

□

Lemma A.2.2 (Simulation of G3cp) *If $\Gamma \vdash_{G3cp} \Delta$, then $\Gamma \vdash_{B_H \cup \{f++\} \setminus \{i\uparrow\}} \Delta$.*

Proof. By induction on the G3cp derivation.

$$\begin{array}{c}
 \hline
 a, \Gamma \Rightarrow \Delta, a \\
 \hline
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline \hline
 \Gamma \langle \rangle \Delta \\
 \hline
 a, \Gamma \Rightarrow \Delta, a \quad i\downarrow
 \end{array}$$

$$\begin{array}{c}
 \hline
 \perp, \Gamma \Rightarrow \Delta \\
 \hline
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline \hline
 \Gamma \langle \rangle \Delta \\
 \hline
 \perp, \Gamma \Rightarrow \Delta \quad \perp-
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \\
 \hline
 A, B, \Gamma \Rightarrow \Delta \\
 \hline
 A \wedge B, \Gamma \Rightarrow \Delta \quad L\wedge
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline \hline
 A, B, \Gamma \Rightarrow \Delta \quad \pi_1 \\
 \hline
 A \wedge B, \Gamma \Rightarrow \Delta \quad \wedge-
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \\
 \hline
 \Gamma \Rightarrow \Delta, A, B \\
 \hline
 \Gamma \Rightarrow \Delta, A \vee B \quad R\vee
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline \hline
 \Gamma \Rightarrow \Delta, A, B \quad \pi_1 \\
 \hline
 \Gamma \Rightarrow \Delta, A \vee B \quad \vee+
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \quad \vdots \pi_2 \\
 \hline
 \Gamma \Rightarrow \Delta, A \quad \Gamma \Rightarrow \Delta, B \\
 \hline
 \Gamma \Rightarrow \Delta, A \wedge B \quad R\wedge
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline \hline
 \langle \rangle; \langle \rangle \\
 \hline \hline
 \langle \Gamma \Rightarrow \Delta, A; \Gamma \Rightarrow \Delta, B \rangle \quad \pi_1, \pi_2 \\
 \hline \hline
 \Gamma, \Gamma \langle \Rightarrow A; \Rightarrow B \rangle \Delta, \Delta \quad f-, f+ \\
 \hline \hline
 \Gamma \langle \Rightarrow A; \Rightarrow B \rangle \Delta \quad c-, c+ \\
 \hline \hline
 \Gamma \Rightarrow \Delta, A \wedge B \quad \wedge+
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \quad \vdots \pi_2 \\
 \hline
 A, \Gamma \Rightarrow \Delta \quad B, \Gamma \Rightarrow \Delta \\
 \hline
 A \vee B, \Gamma \Rightarrow \Delta \quad L\vee
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 \langle \langle \rangle; \langle \rangle \rangle \text{p} \\
 \hline
 \dots\dots\dots \pi_1, \pi_2 \\
 \langle A, \Gamma \Rightarrow \Delta; B, \Gamma \Rightarrow \Delta \rangle \\
 \hline
 \Gamma, \Gamma \langle A \Rightarrow; B \Rightarrow \rangle \Delta, \Delta \\
 \hline
 \Gamma \langle A \Rightarrow; B \Rightarrow \rangle \Delta \\
 \hline
 A \vee B, \Gamma \Rightarrow \Delta \quad \vee-
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \quad \vdots \pi_2 \\
 \hline
 \Gamma \Rightarrow \Delta, A \quad B, \Gamma \Rightarrow \Delta \\
 \hline
 A \supset B, \Gamma \Rightarrow \Delta \quad L\supset
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 \langle \langle \rangle; \langle \rangle \rangle \text{p} \\
 \hline
 \dots\dots\dots \pi_1, \pi_2 \\
 \langle \Gamma \Rightarrow \Delta, A; B, \Gamma \Rightarrow \Delta \rangle \\
 \hline
 \Gamma, \Gamma \langle \Rightarrow A; B \Rightarrow \rangle \Delta, \Delta \\
 \hline
 \Gamma \langle \Rightarrow A; B \Rightarrow \rangle \Delta \\
 \hline
 A \supset B, \Gamma \Rightarrow \Delta \quad \supset-
 \end{array}$$

$$\begin{array}{c}
 \vdots \pi_1 \\
 \hline
 A, \Gamma \Rightarrow \Delta, B \\
 \hline
 \Gamma \Rightarrow \Delta, A \supset B \quad R\supset
 \end{array}
 \mapsto
 \begin{array}{c}
 \langle \rangle \\
 \hline
 \Rightarrow \langle \langle \rangle \rangle \text{p}^+ \\
 \hline
 \dots\dots\dots \pi_1 \\
 \Rightarrow (A, \Gamma \Rightarrow \Delta, B) \\
 \hline
 \Rightarrow \Delta, (A, \Gamma \Rightarrow B) \\
 \hline
 \Gamma \Rightarrow \Delta, (A \Rightarrow B) \\
 \hline
 \Gamma \Rightarrow \Delta, A \supset B \quad \supset+
 \end{array}$$

□

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