"The Wager," Overview of the Book, and Gödel's Completeness Theorem

Selmer Bringsjord

Rensselaer AI & Reasoning (RAIR) Lab
Department of Cognitive Science
Department of Computer Science
Lally School of Management & Technology
Rensselaer Polytechnic Institute (RPI)
Troy, New York 12180 USA

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Note: This is a version of coverage of Gödel's Completeness Theorem designed for those who've had at least one standard/ standard-paced university-level course in formal logic.

Background Context …

Gödel's Great Theorems (OUP)

by Selmer Bringsjord

- Introduction ("The Wager")
- Brief Preliminaries (elementary discrete math, incl. ZOL, FOL)
- The Completeness Theorem
- The First Incompleteness Theorem
- The Second Incompleteness Theorem
- The Speedup Theorem
- The Continuum-Hypothesis Theorem
- The Time-Travel Theorem
- Gödel's "God Theorem"
- Could a Machine Match Gödel's Genius?

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Some Timeline Points

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1906 Brünn, Austria-Hungary

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Undergrad in seminar by Schlick

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1929 Doctoral Dissertation: Proof of Completeness Theorem
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"I have proved that syntax and semantics are fundamentally the same."

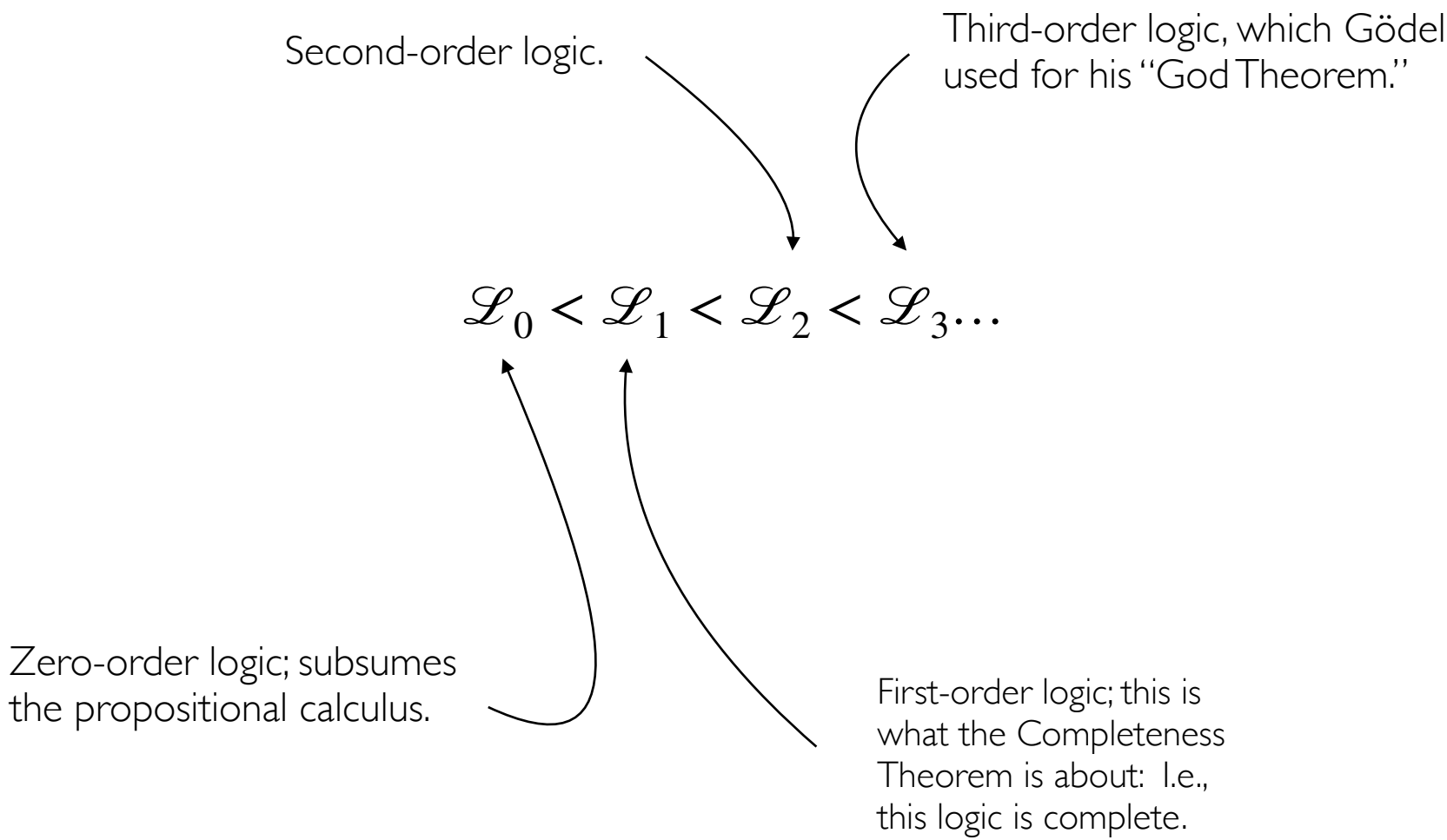
Preliminaries: Propositional Calculus & First-Order Logic

. . .

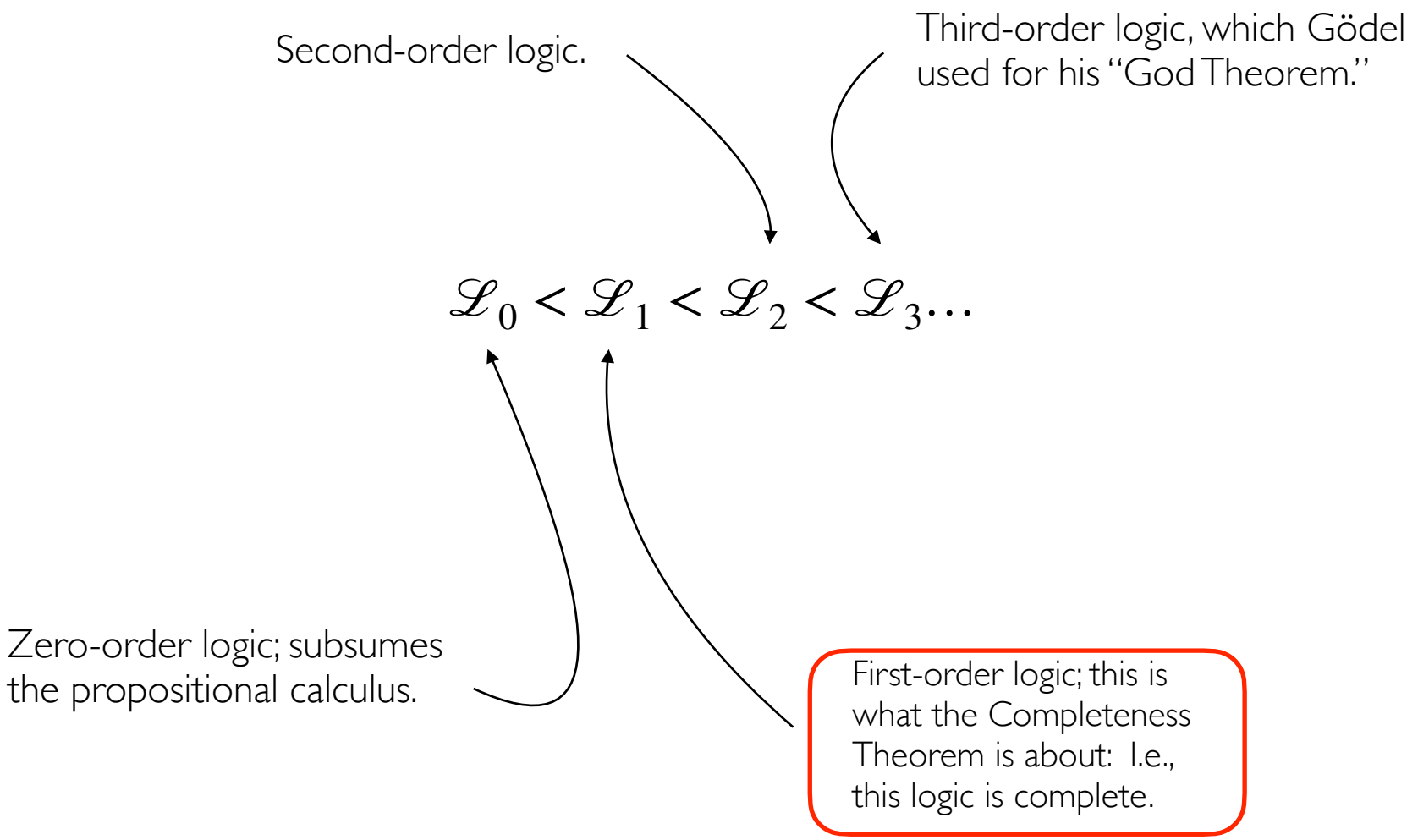
Actually …

$$\mathscr{L}_0 < \mathscr{L}_1 < \mathscr{L}_2 < \mathscr{L}_3 \cdots$$

Actually …


Second-order logic.
Third-order logic, which Gödel used for his "God Theorem."
$\mathscr{L}_0 < \mathscr{L}_1 < \mathscr{L}_2 < \mathscr{L}_3 \cdots$
Zero-order logic; subsumes the propositional calculus.
First-order logic; this is what the Completeness Theorem is about: I.e., this logic is complete.

Actually . . .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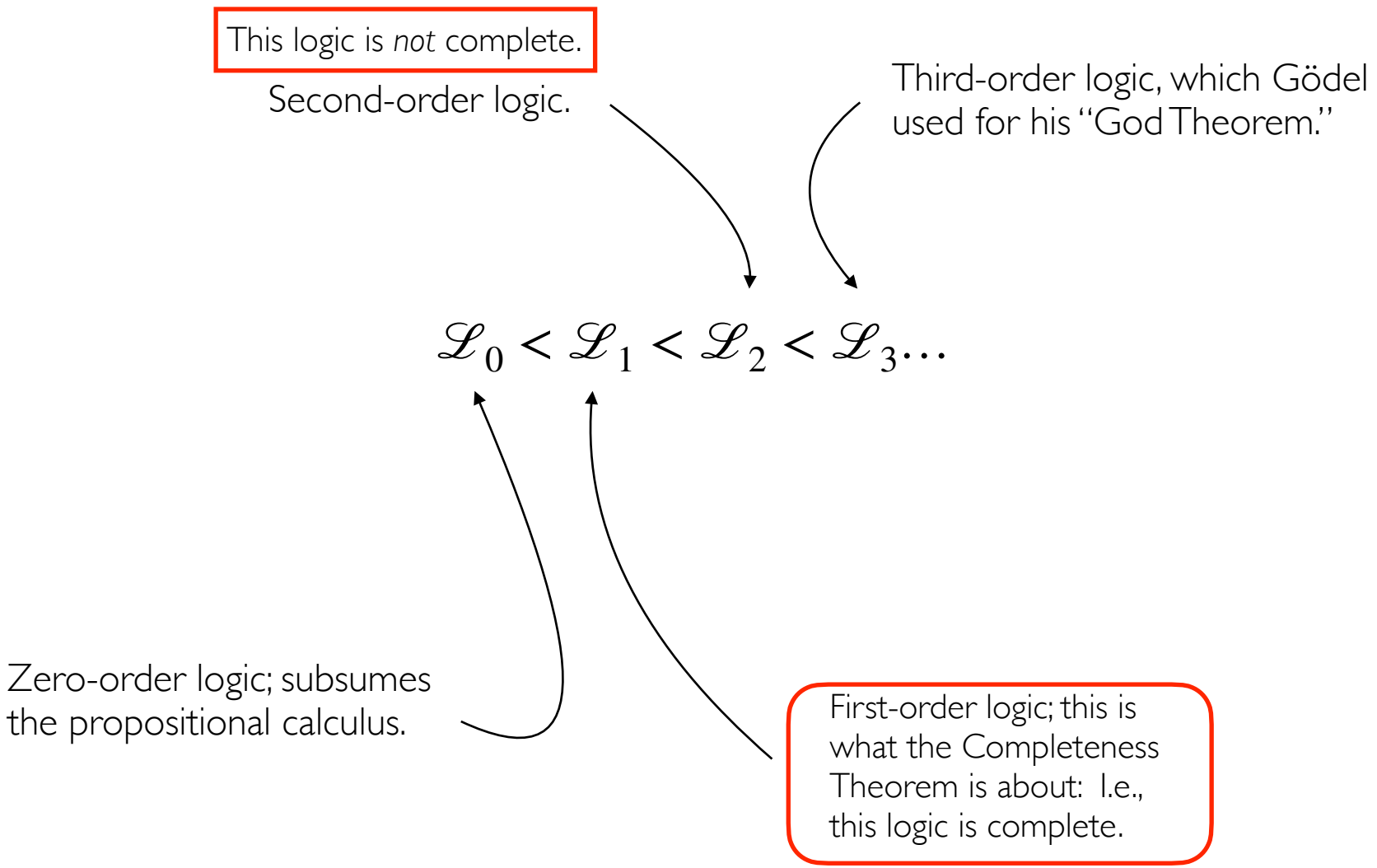
This logic is *not* complete.
Second-order logic.
Third-order logic, which Gödel used for his "God Theorem."
$\mathscr{L}_0 < \mathscr{L}_1 < \mathscr{L}_2 < \mathscr{L}_3 \cdots$
Zero-order logic; subsumes the propositional calculus.
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R&W's Axiomatization of the Propositional Calculus

A1 $(\phi \vee \phi) \rightarrow \phi$

A2 $\phi \rightarrow (\phi \vee \psi)$

A3 $(\phi \vee \psi) \rightarrow (\psi \vee \phi)$

A4 $(\psi \rightarrow \chi) \rightarrow ((\phi \vee \psi) \rightarrow (\phi \vee \chi))$

R&W's Axiomatization of the Propositional Calculus

$$\begin{array}{ll} \text{A1} & (\phi \vee \phi) \rightarrow \phi \\ \text{A2} & \phi \rightarrow (\phi \vee \psi) \\ \text{A3} & (\phi \vee \psi) \rightarrow (\psi \vee \phi) \\ \text{A4} & (\psi \rightarrow \chi) \rightarrow ((\phi \vee \psi) \rightarrow (\phi \vee \chi)) \end{array}$$

All instances of these schemata are true no matter what the input (true or false). (Agreed?) And indeed every single formula in the propositional calculus that is true no matter what the permutation (as shown in a truth table, e.g.), can be proved (somehow) from these four axioms (using any standard collection of inference schemata). This, Gödel (& later, Newell & Simon, when modern AI was born!) knew, and could use.

R&W's Axiomatization of the Propositional Calculus

$$\text{A1} \quad (\phi \vee \phi) \rightarrow \phi$$

```
(if (or \phi \phi) \phi)
```

$$\text{A2} \quad \phi \rightarrow (\phi \vee \psi)$$

```
(if \phi (or \phi \psi))
```

$$\text{A3} \quad (\phi \vee \psi) \rightarrow (\psi \vee \phi)$$

```
(if (or \phi \psi) (or \psi phi))
```

$$\text{A4} \quad (\psi \rightarrow \chi) \rightarrow ((\phi \vee \psi) \rightarrow (\phi \vee \chi))$$

```
(if (if \psi \chi) (if (or \phi \psi) (or \phi \chi)))
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Exercise 1:

Verify that these are true-no-matter what in a truth tree in HyperSlate®; then prove using our rules for the prop. calc.; or perhaps better yet, have the oracle prove in HyperSlate®.

$$(\phi \wedge \psi) \rightarrow (\psi \vee \chi)$$

$$\phi \rightarrow (\psi \rightarrow \phi)$$

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Truth Tree showing this formula true no matter what the inputs.

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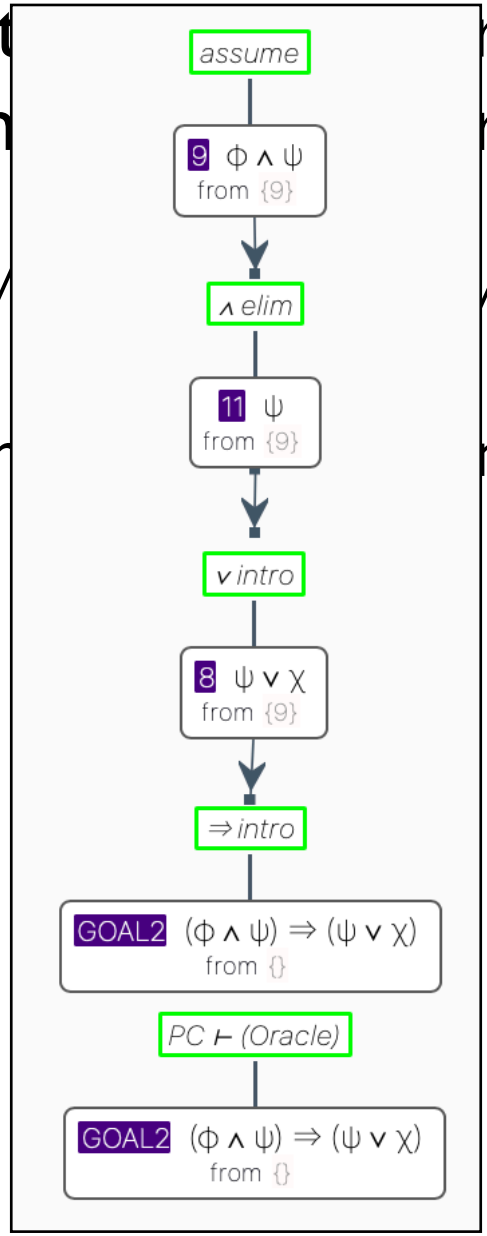

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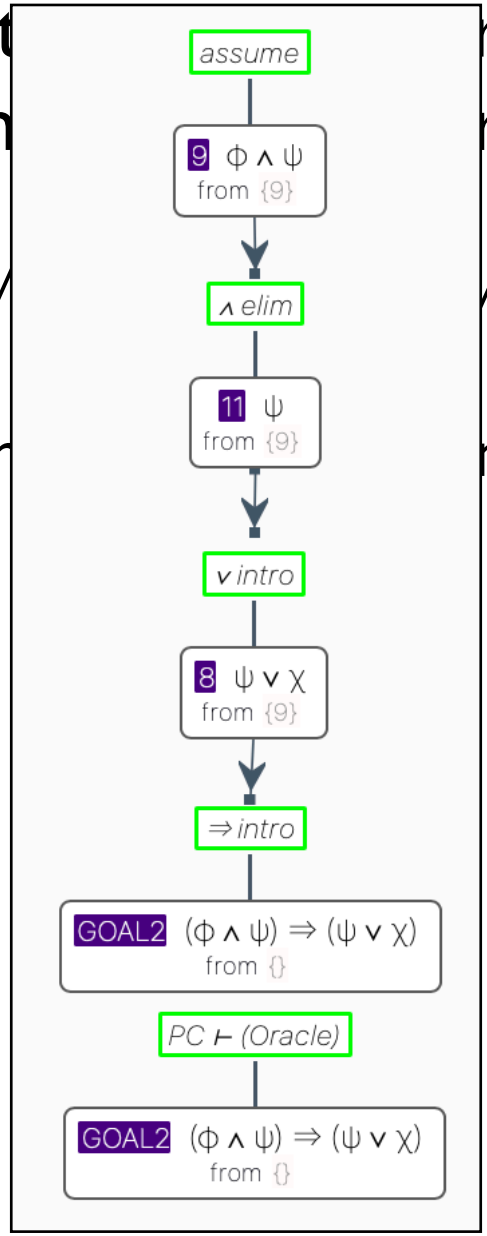

Proof:

resolution-based!

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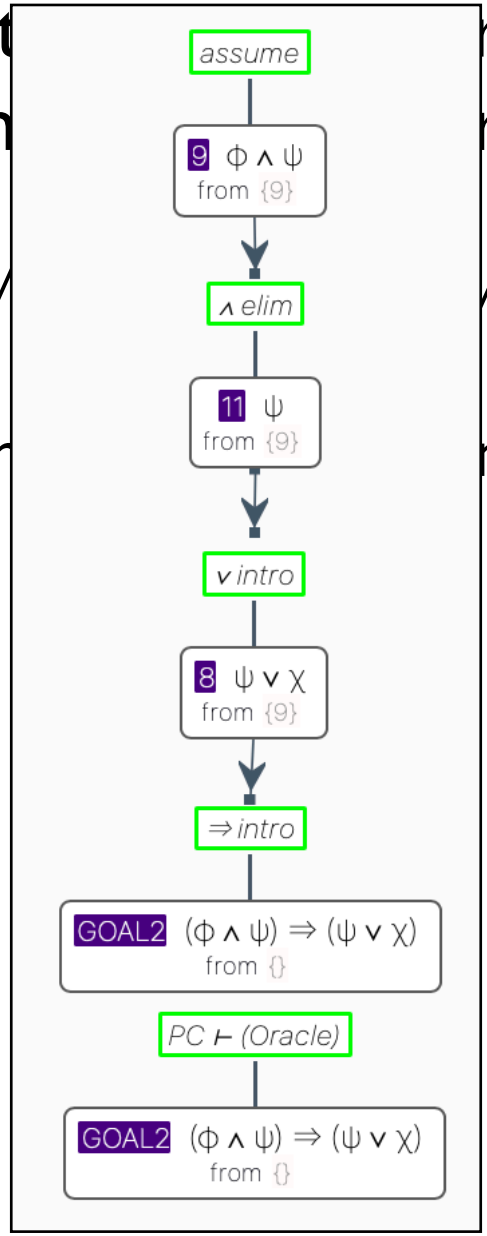

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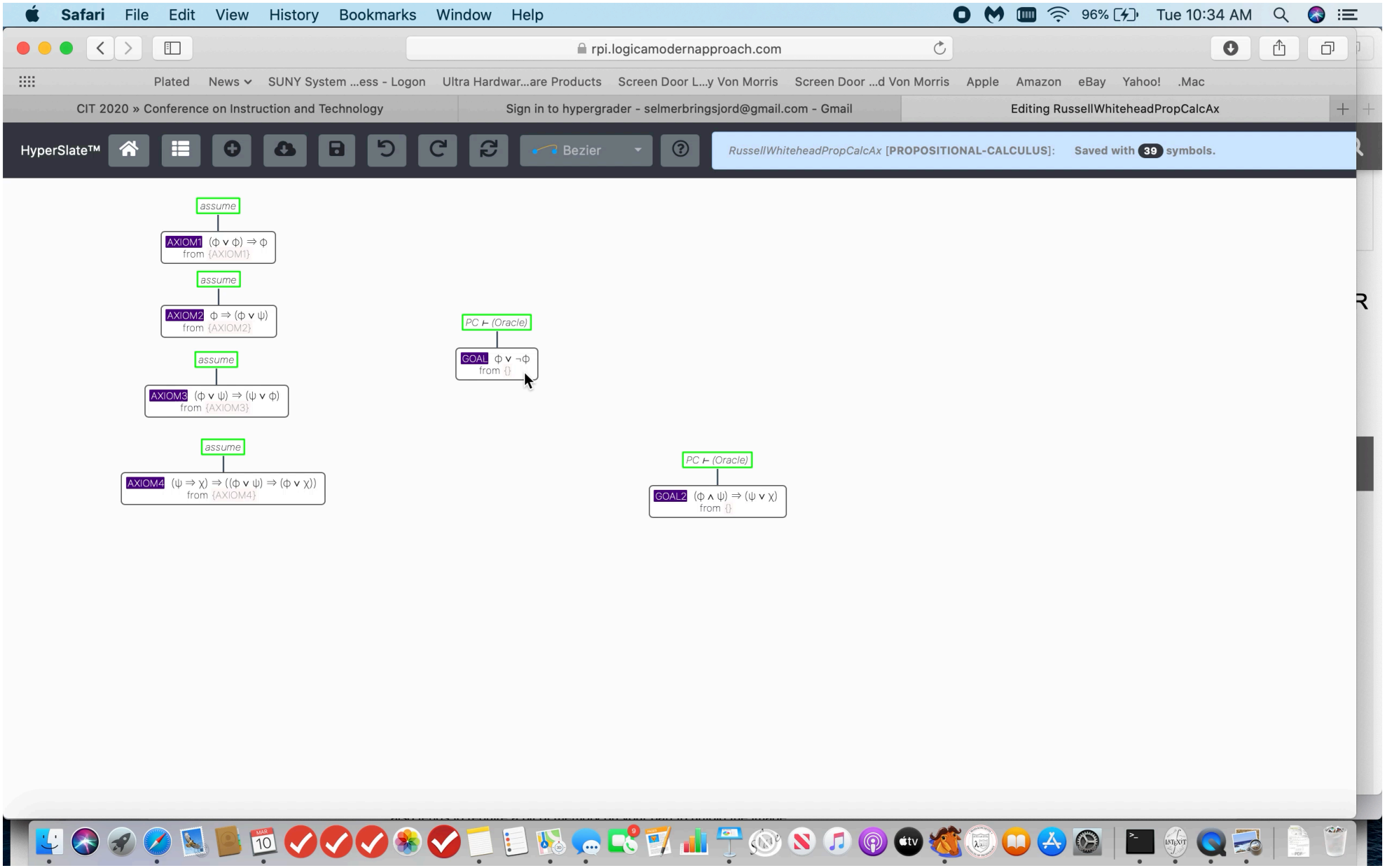
As HyperSlate® Tutorial



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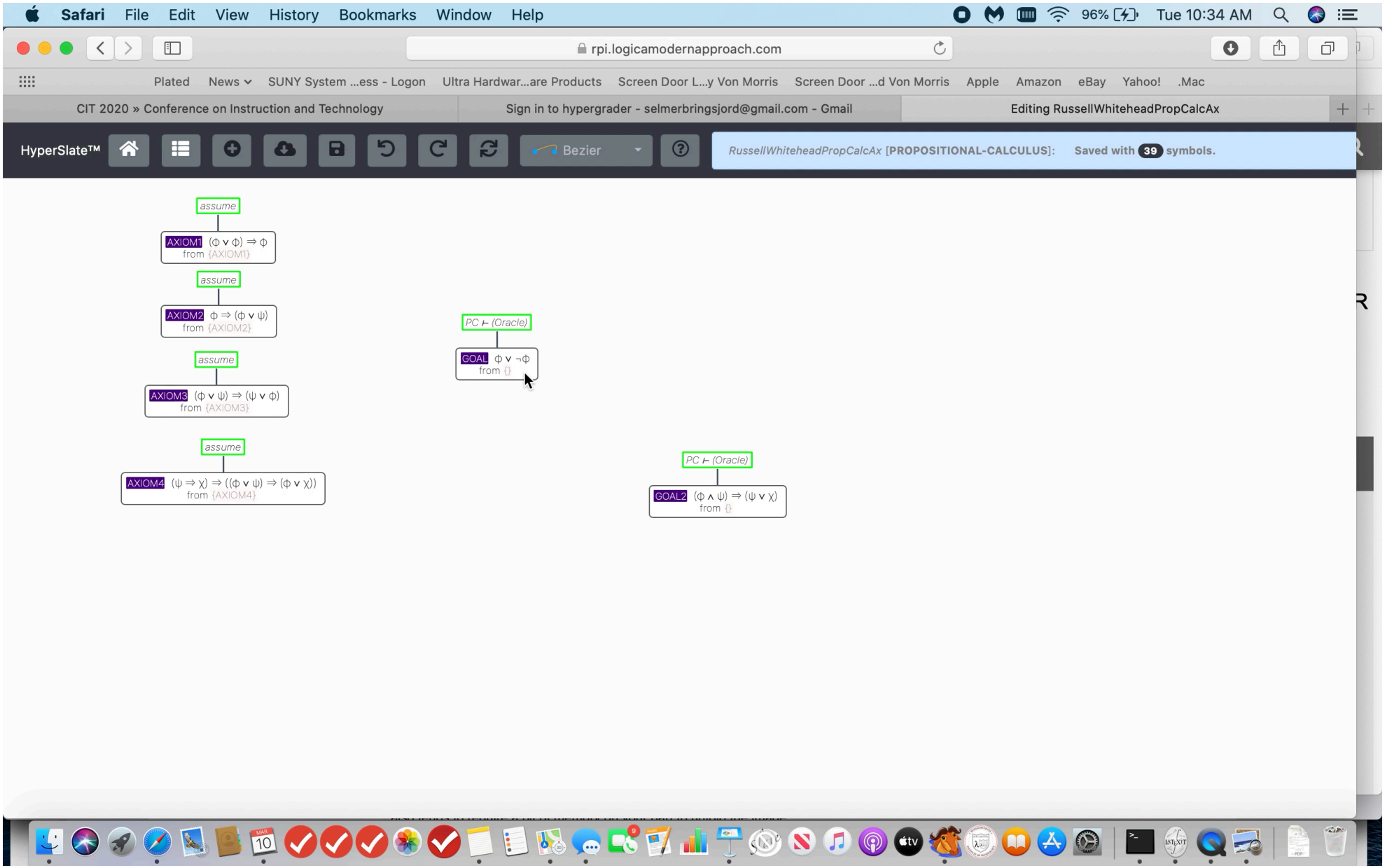

The Grammar of $\mathscr{L}_0$ = the Pure Predicate Calculus

$$
\begin{array}{lcl}
\textit{Formula} & \Rightarrow & \textit{AtomicFormula} \\
 & | & (\textit{Formula Connective Formula}) \\
 & | & \neg\ \textit{Formula}
\end{array}
$$

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\begin{array}{lcl}
\textit{AtomicFormula} & \Rightarrow & (\textit{Predicate Term}_1 \ldots \textit{Term}_k) \\
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Some Simple Examples

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Sally likes Bill.

(**Likes** sally bill)

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Lexicon

Sally likes Bill and Bill likes Sally.

Sally likes Bill's mother.

Sally likes Bill only if Bill's mother is tall.

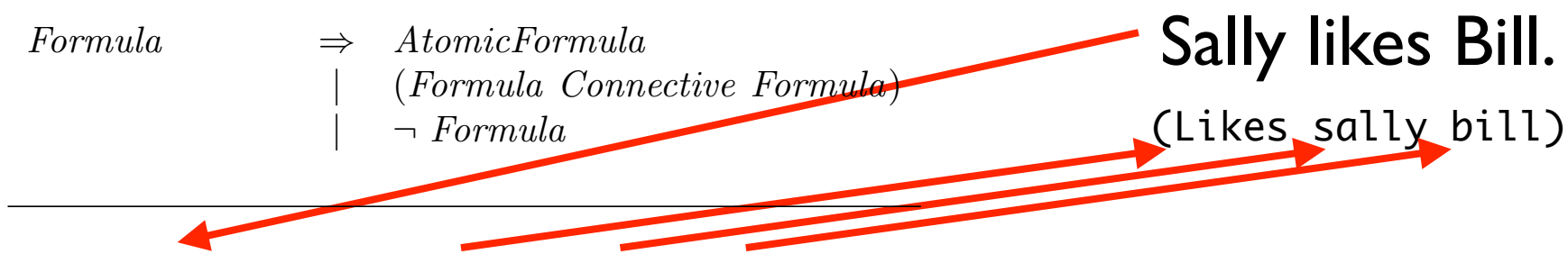
Matilda is Bill's super-smart mother.

5 plus 5 equals the number 10.

...

Can Roger be counted upon to declare: "Yes that sentence is okay!" whenever it's conforms to this grammar?

Some Simple Examples



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Sally likes Bill.

`(Likes sally bill)`

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`Likes`

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If Sally likes Bill then Sally likes Bill.

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If Sally likes Bill then Sally likes Bill.

Sally likes Bill's mother, or not.

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Bill's smart mother is a mother.

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\begin{array}{lcl}
\textit{AtomicFormula} & \Rightarrow & (\textit{Predicate}\ \textit{Term}_1 \ldots \textit{Term}_k) \\
 & | & (\textit{Term}\ =\ \textit{Term})
\end{array}
$$

$$
\begin{array}{lcl}
\textit{Term} & \Rightarrow & (\textit{Function}\ \textit{Term}_1\ \ldots\ \textit{Term}_k) \\
 & | & \textit{Constant}
\end{array}
$$

$$
\textit{Connective} \Rightarrow \wedge \mid \vee \mid \rightarrow \mid \leftrightarrow
$$

$$
\begin{array}{ll}
\textit{Predicate} \Rightarrow & P_1 \mid P_2 \mid P_3\ \ldots \\
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If Sally likes Bill then Sally likes Bill.

Sally likes Bill's mother, or not.

Sally likes Bill and Bill likes Jane, only if Bill likes Jane.

Bill's smart mother is a mother.

...

These are all true, yes; but can they be proved?!

Slightly More Complicated Examples

$$
\begin{array}{lcl}
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 & | & (\textit{Formula}\ \textit{Connective}\ \textit{Formula}) \\
 & | & \neg\ \textit{Formula}
\end{array}
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Yes!

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Add Two Quantifiers to the Pure Predicate Calculus,
Which Yields $\mathscr{L}_1$ First-order Logic = Predicate Calculus *simpliciter*

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$$\lim_{x \to a} f(x) = L$$

iff

$$\forall \epsilon(\epsilon > 0 \rightarrow \exists \delta(\delta > 0 \wedge \forall x(d(x, a) < \delta \rightarrow d(f(x), L) < \epsilon)))$$

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(forall (\epsilon) (if (> \epsilon 0)
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$$\forall x \exists y(x \leq y) \qquad \forall x \exists y(\leq (x, y))$$

The Shoulders Available to Gödel for Standing Upon

. . .

Completeness Theorem for The Propositional Calculus

Let Γ be a set $\{\phi_1, \phi_2, \ldots\}$ of formulae in the the propositional calculus. Then either all of Γ are satisfiable, or the conjunction up to and including the point k (i.e. $\phi_1 \wedge \phi_2 \wedge \ldots \wedge \phi_k$) of failure is refutable.

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Let Γ be a set $\{\phi_1, \phi_2, \ldots\}$ of formulae in the the propositional calculus. Then either all of Γ can be simultaneously true in some scenario, or the conjunction up to and including the point k (i.e. $\phi_1 \wedge \phi_2 \wedge \ldots \wedge \phi_k$) of failure is **refutable** (i.e. $\vdash \neg(\phi_1 \wedge \phi_2 \wedge \ldots \wedge \phi_k)$).

What does the Completeness Theorem say?

. . .

Completeness Theorem as an Equation

In first-order logic: NECESSARY TRUTH = PROVABILITY.

Completeness Theorem, More Precisely Put

For every first-order statement ϕ: if ϕ is a necessary or absolute truth (i.e. true in any scenario whatsoever), then ϕ is provable.

And the version Gödel targeted, and proved:

For every first-order statement ϕ: Either ϕ is true in some scenario, or ϕ is refutable (= it's negation $\neg\phi$ can be proved).

GCT

The Proof-Sketch

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To prove the theorem in the case of first-order logic ($= \mathscr{L}_1$), we need to show that given any set Γ of formulae in first-order logic, either there's a scenario on which every member of this set is true; otherwise, there is a refutation of the set, i.e. a proof from the set to an outright contradiction $\phi \wedge \neg\phi$. We can accomplish this by finding a procedure $\mathscr{P}$ that first takes the set in question and goes hunting for a scenario that does the trick. If the scenario is found, we're done. But, if such a scenario *can't* be found, then our procedure moves on to find a proof of a contradiction from Γ!

How?! The procedure $\mathscr{P}$ is the building out of a truth tree! If all the branches in the tree close, then the finding of a proof of a contradiction uses **resolution**, and the **resolution guarantee**. The guarantee is that if you have a set of formulae that can't be true in any scenario, resolution applied to the set finds a contradiction $\bot = \zeta \wedge \neg\zeta = \{\}$. **QED**

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See LAMA-BDLAHGHS.

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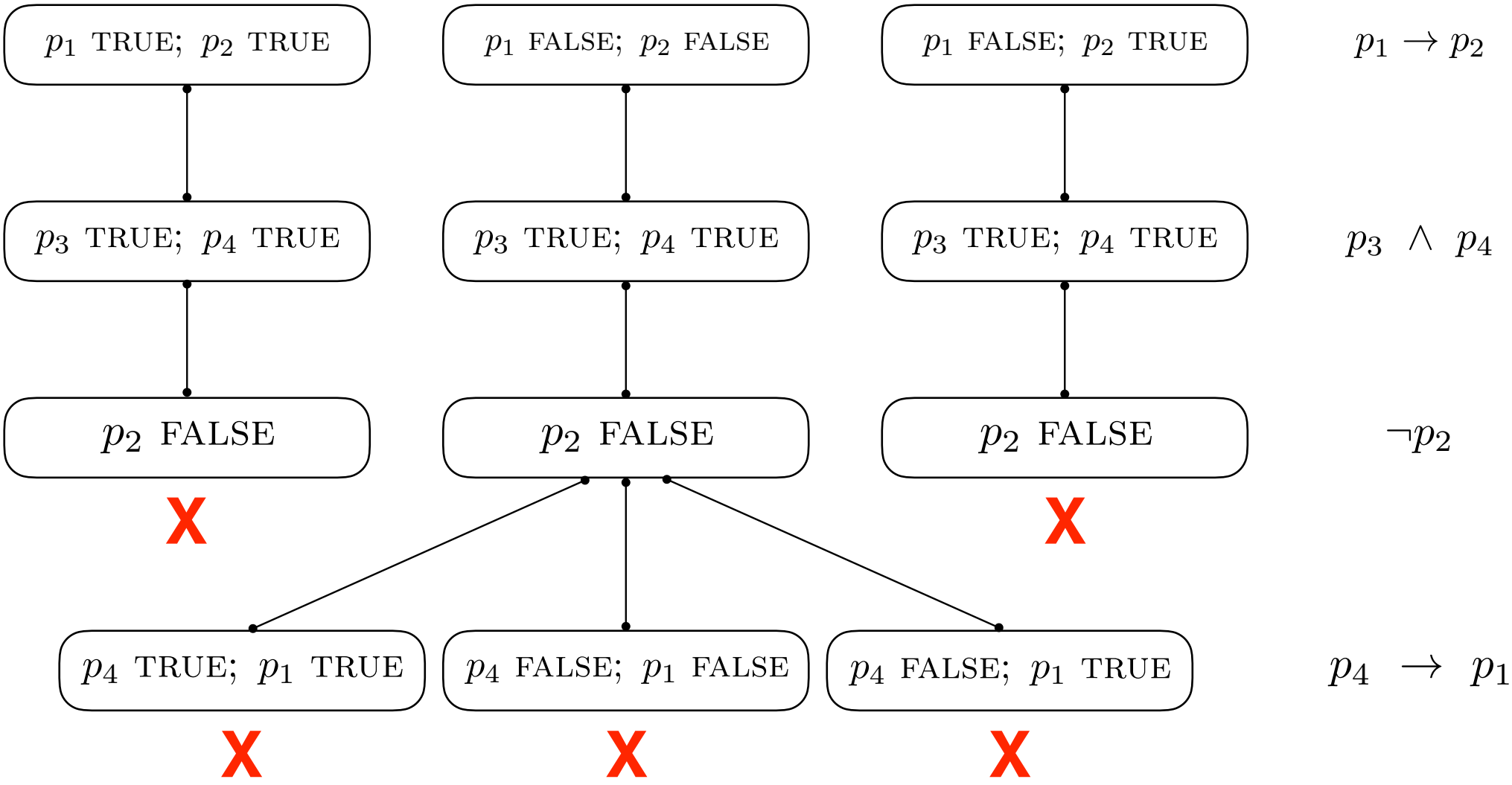
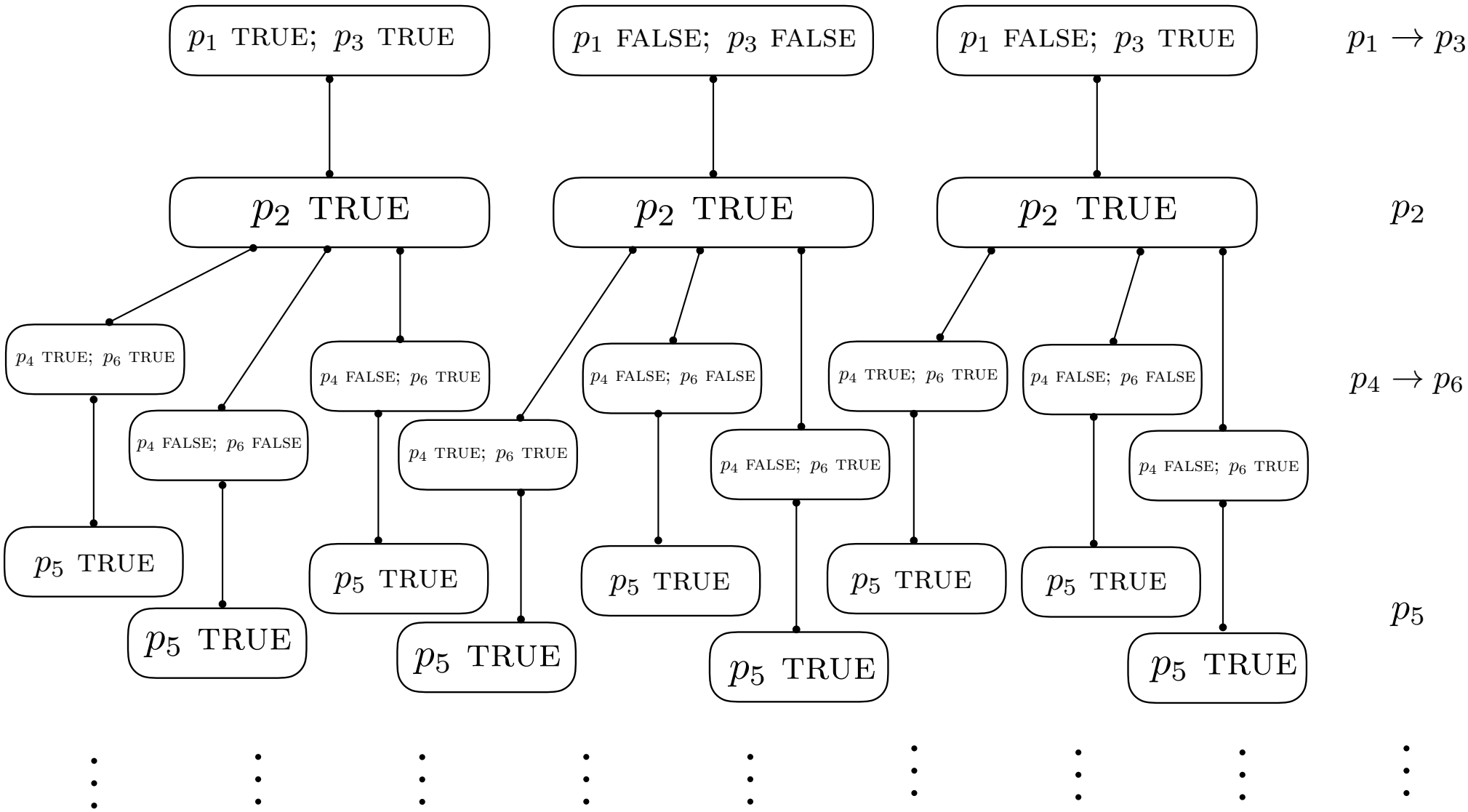
$$\Gamma := \{p_1 \to p_2,\ p_3 \wedge p_4,\ \neg p_2,\ p_4 \to p_1,\ \ldots\}$$



Therefore, there is no scenario in which all of the formulae are true!

$$\Gamma := \{p_1 \to p_3,\ p_2,\ p_4 \to p_6,\ p_5,\ p_7 \to p_9,\ p_8,\ \ldots\}$$



Therefore, since we can travel to infinity, there *is* a scenario in which all of the formulae are true: any infinite path down will do.

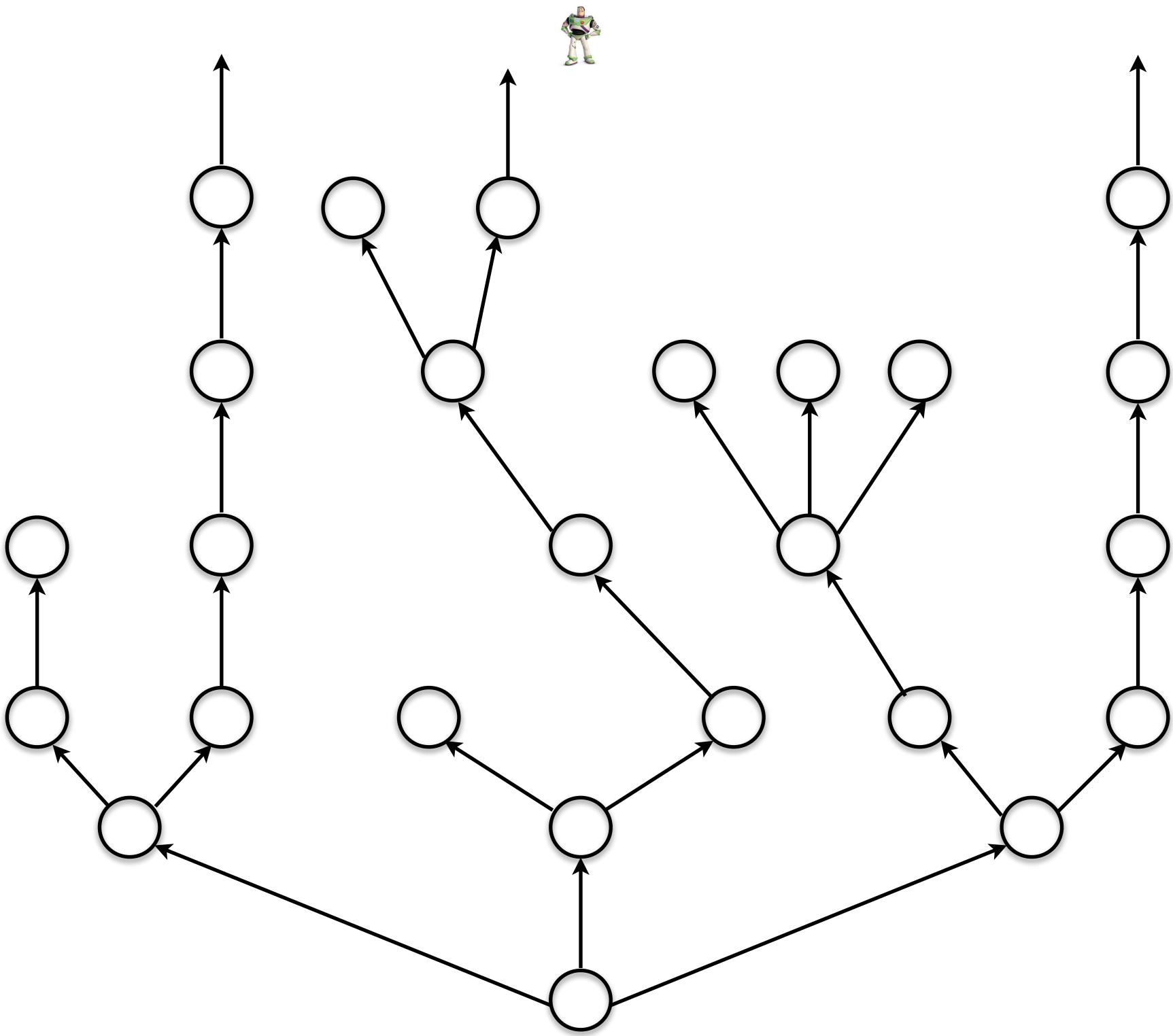
Ah, but can we travel to infinity? The assumption that there *is* an infinite branch here is based on König's Lemma …

Toward König's Lemma as Train Travel

“To infinity and beyond!”

König's Lemma (train-travel version)

In a one-way train-travel map with finitely many options leading from each station, if there are partial paths forward of every finite length, there is an *infinite* path (= a path "to infinity").




Óðinn
Hrafnar


Óðinn
Hleginn
Konungr
Drunninn
Þrafnar


Óðinn
Huginn
Þrafnar


Óðinn
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(Does it not then follow, assuming that humans can find and "use" a provably correct strategy for this travel, that humans can't be fundamentally computing machines?)

NY-Centric Proof of the Lemma

(that there is an infinite branch)

Proof: We are seeking to prove that there is an infinite path (= that you can keep going forward forever = that the number of your stops forward are the size of $\mathbf{Z}^+$).

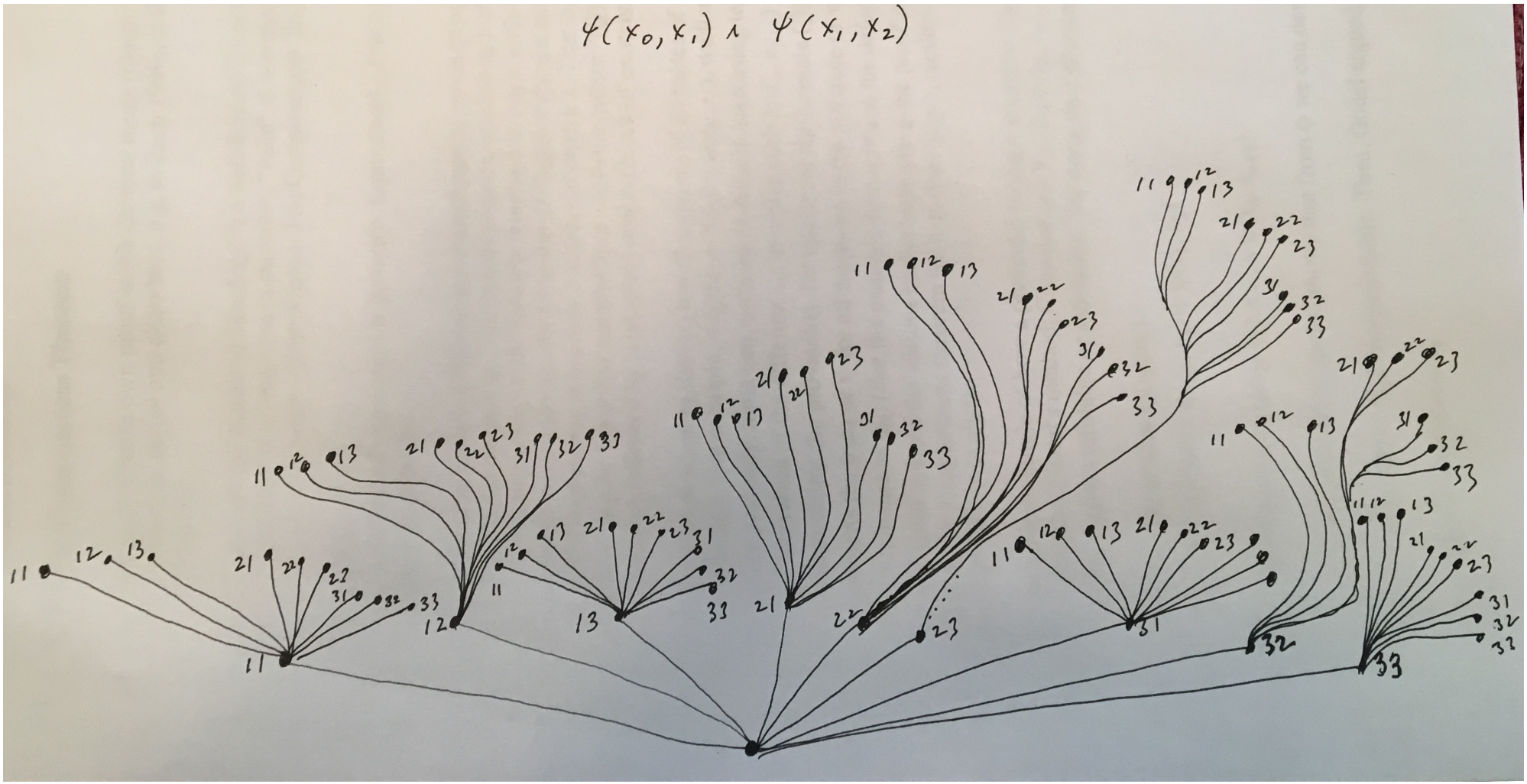
To begin, assume the antecedent of the theorem (i.e. that, (1), there are finitely many options leading from each station, and that, (2), in the map there are partial paths forward of every finite size).

Now, you are standing at Penn Station (S_1), facing k options. At least one of these options must lead to partial paths of arbitrary size (the size of any m in $\mathbf{Z}^+$). (**Sub-Proof**: Suppose otherwise for indirect proof. Then there is some positive integer n that places a ceiling on the size of partial paths that can be reached. But this violates (2) — contradiction.) Proceed to choose one of these options that lead to partial paths of arbitrary size. You are now standing at a new station (S_2), one stop after Penn Station. At least one of these options must lead to partial parts of arbitrary size (the size of any m in $\mathbf{Z}^+$). (**Sub-Proof**: Suppose otherwise for indirect proof …)

Since you can iterate this forever, you'll be on an infinite trip to infinity! Buzz will be happy.

QED

Simple Buzz-Lightyear-Like Branch



Gödel as Giant: Some Evidence

THE DISCOVERY OF MY COMPLETENESS PROOFS

LEON HENKIN

Dedicated to my teacher, Alonzo Church, in his 91st year.

§1. Introduction. This paper deals with aspects of my doctoral dissertation[1] which contributed to the early development of model theory. What was of use to later workers was less the results of my thesis, than the method by which I proved the completeness of first-order logic—a result established by Kurt Gödel in *his* doctoral thesis 18 years before.[2]

The ideas that fed my discovery of this proof were mostly those I found in the teachings and writings of Alonzo Church. This may seem curious, as his work in logic, and his teaching, gave great emphasis to the constructive character of mathematical logic, while the model theory to which I contributed is filled with theorems about very large classes of mathematical structures, whose proofs often by-pass constructive methods.

Another curious thing about my discovery of a new proof of Gödel's completeness theorem, is that it arrived in the midst of my efforts to prove an entirely different result. Such "accidental" discoveries arise in many parts of scientific work. Perhaps there are regularities in the conditions under which such "accidents" occur which would interest some historians, so I shall try to describe in some detail the accident which befell me.

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How? By ingenious tree-building, which starts by creating an enumeration of new constants $\mathfrak{c} = c_1, c_2, \ldots$that becomes our "universe of discourse"/"domain of quantification." Note that from $\mathfrak{c}$ we can algorithmically generate an enumeration of tuples $\mathfrak{c}^t = \langle c \rangle_1, \langle c \rangle_2, \ldots$ of any finite size. (Those of size *k* will work for the *x*-variables, and those of size *n* will work for the *y*-variables.) And now we can build a BIG tree at the level of the pure predicate calculus, looking for either a scenario that makes our formula true by traveling with Buzz to infinity, or getting all branches closed, in which case we turn back to the resolution guarantee! Let's make sense of this by hand on paper …

Gödel's Completeness Theorem, Degree-1 Formulae

3/8/20

L.R.

$\psi := \forall x_1, x_2, \ldots, x_k \exists y_1, y_2, \ldots, y_m \phi(x_1, x_2, \ldots, x_k; y_1, y_2, \ldots, y_m)$

$G := c_1, c_2, c_3, \ldots \quad \omega$

Then tuples of the size of the x_i variables (i.e. size k) in this progression

$G^{t\text{-}k} := \langle c \rangle_1^k, \langle c \rangle_2^k, \langle c \rangle_3^k, \ldots \quad \omega$

And, tuples of the size of the y_i variables (i.e. size m) in this progression

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And here's my enumeration

$\langle c \rangle_1^k; \langle c \rangle_1^m, \langle c \rangle_1^k; \langle c \rangle_2^m, \langle c \rangle_1^k; \langle c \rangle_3^k \ldots \omega$
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$\vdots$

In streamlined form:

11	12	13	14	15	...	ω
21	22	23	24	25	...	ω
31	32	33	34	35	...	
41	42	43	44	45	...	ω
⋮	⋮	⋮	⋮	⋮		
ω	ω	ω	ω	ω		

Do you see a way to travel to ∞ in a tree based on some enumeration of this infinite array?

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$\rightarrow G^{t\text{-}m} := \langle c \rangle_1^m, \langle c \rangle_2^m, \langle c \rangle_3^m, \ldots \quad \omega$

And here's my enumeration

$\langle c \rangle_1^k; \langle c \rangle_1^m, \langle c \rangle_1^k; \langle c \rangle_2^m, \langle c \rangle_1^k; \langle c \rangle_3^k \ldots \omega$
$\langle c \rangle_2^k; \langle c \rangle_1^m, \langle c \rangle_2^k; \langle c \rangle_2^m, \langle c \rangle_2^k; \langle c \rangle_3^k \ldots \omega$
$\vdots$

In streamlined form:

11	12	13	14	15	$\ldots \omega$
21	22	23	24	25	$\ldots \omega$
31	32	33	34	35	$\ldots$
41	42	43	44	45	$\ldots \omega$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
ω	ω	ω	ω	ω	

Do you see a way to travel to ∞ in a tree based on some enumeration of this infinite array?

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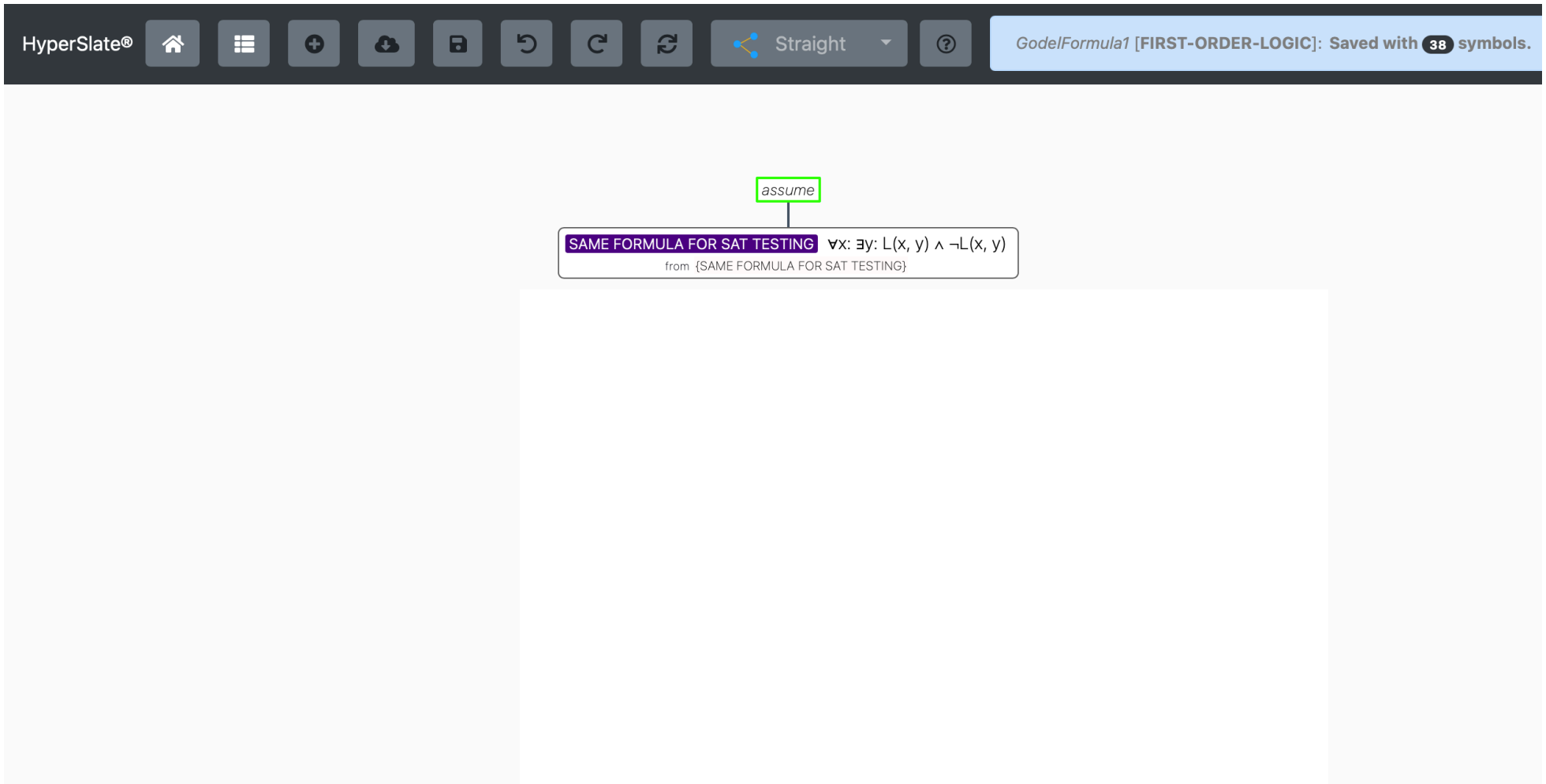

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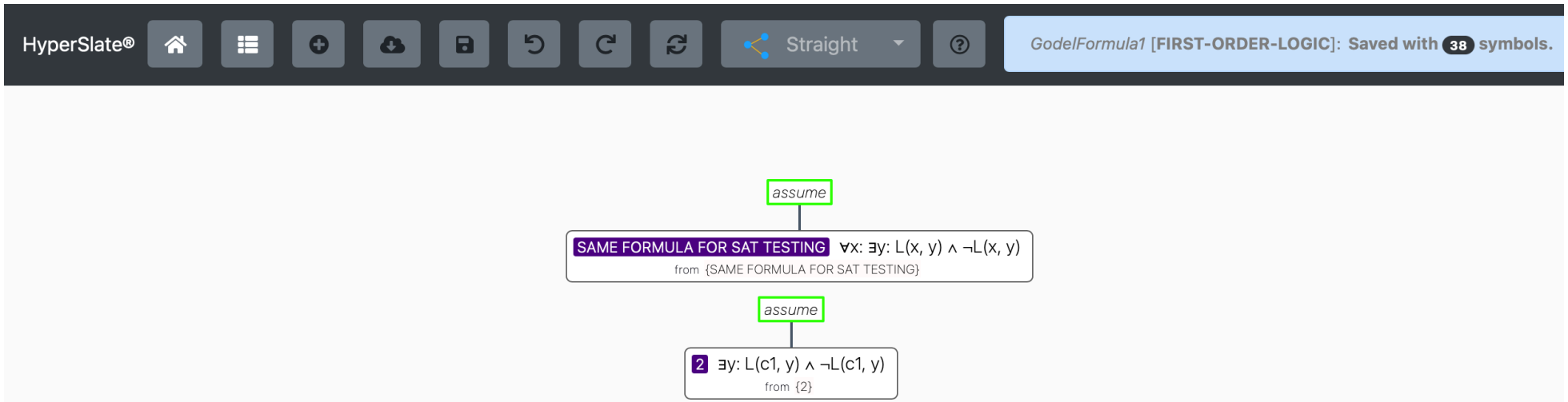

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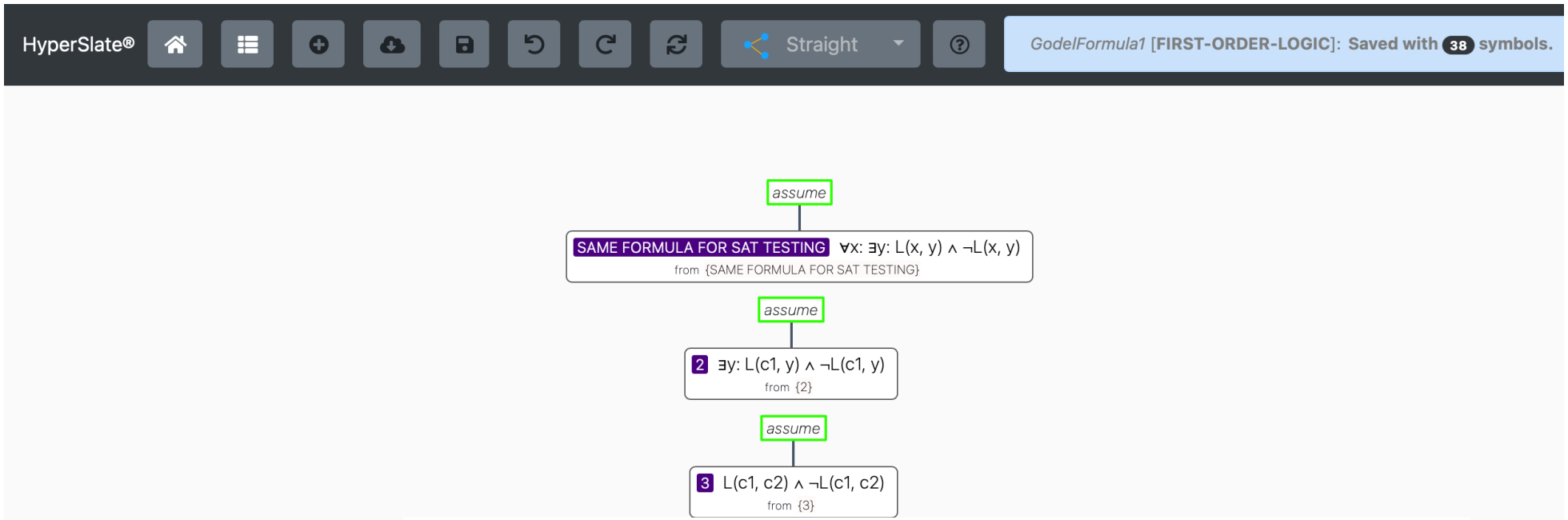

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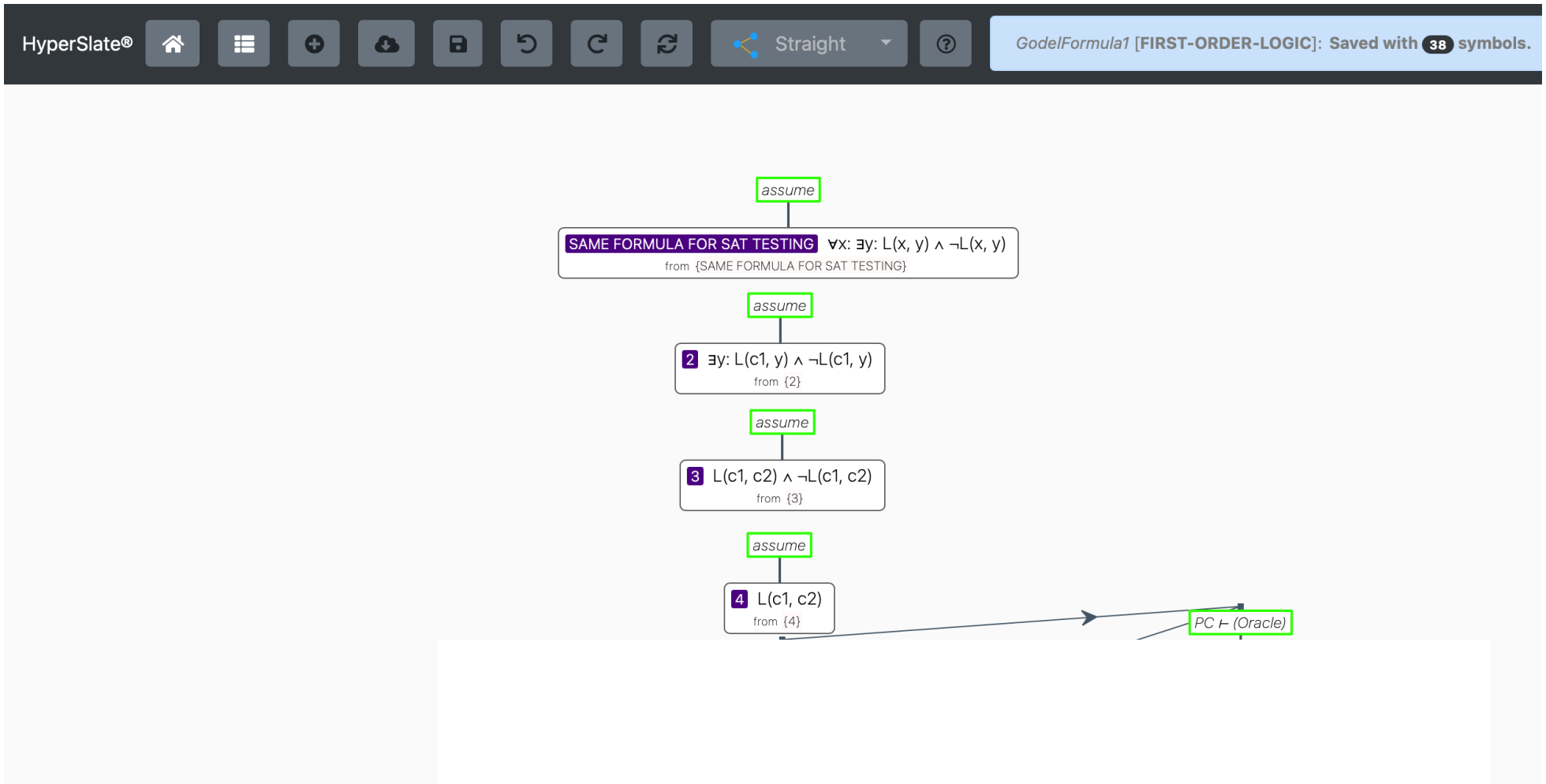

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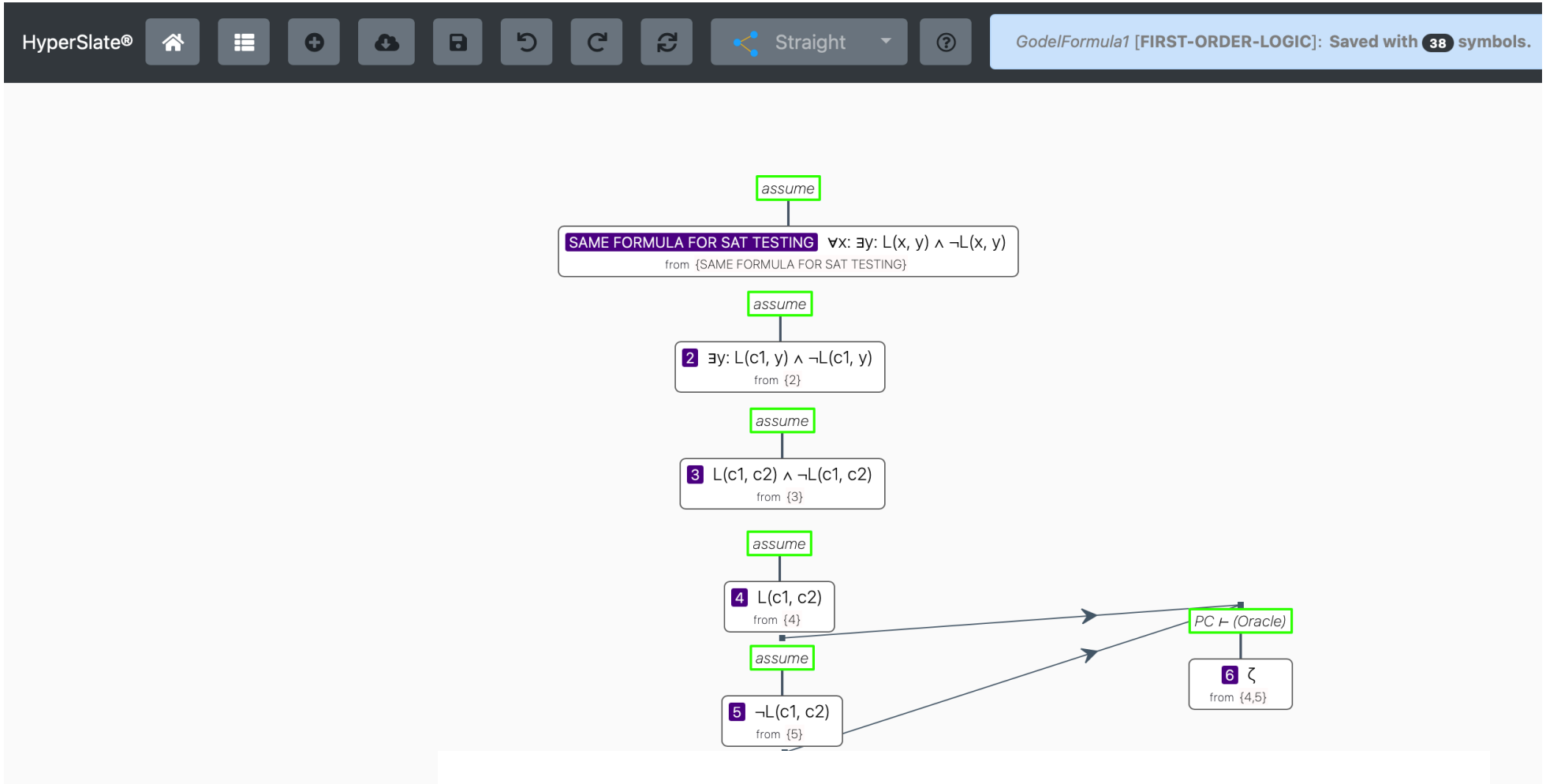

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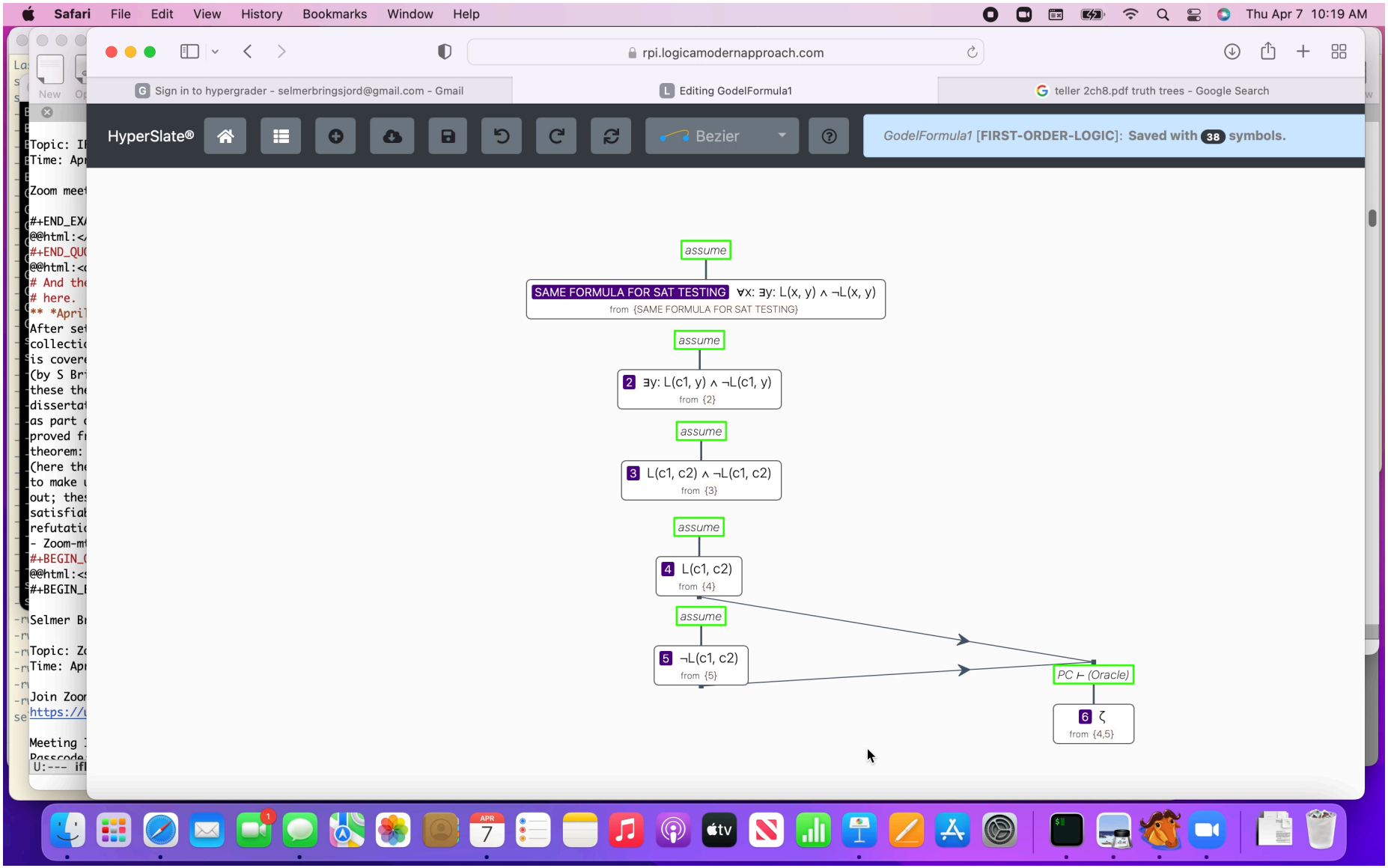

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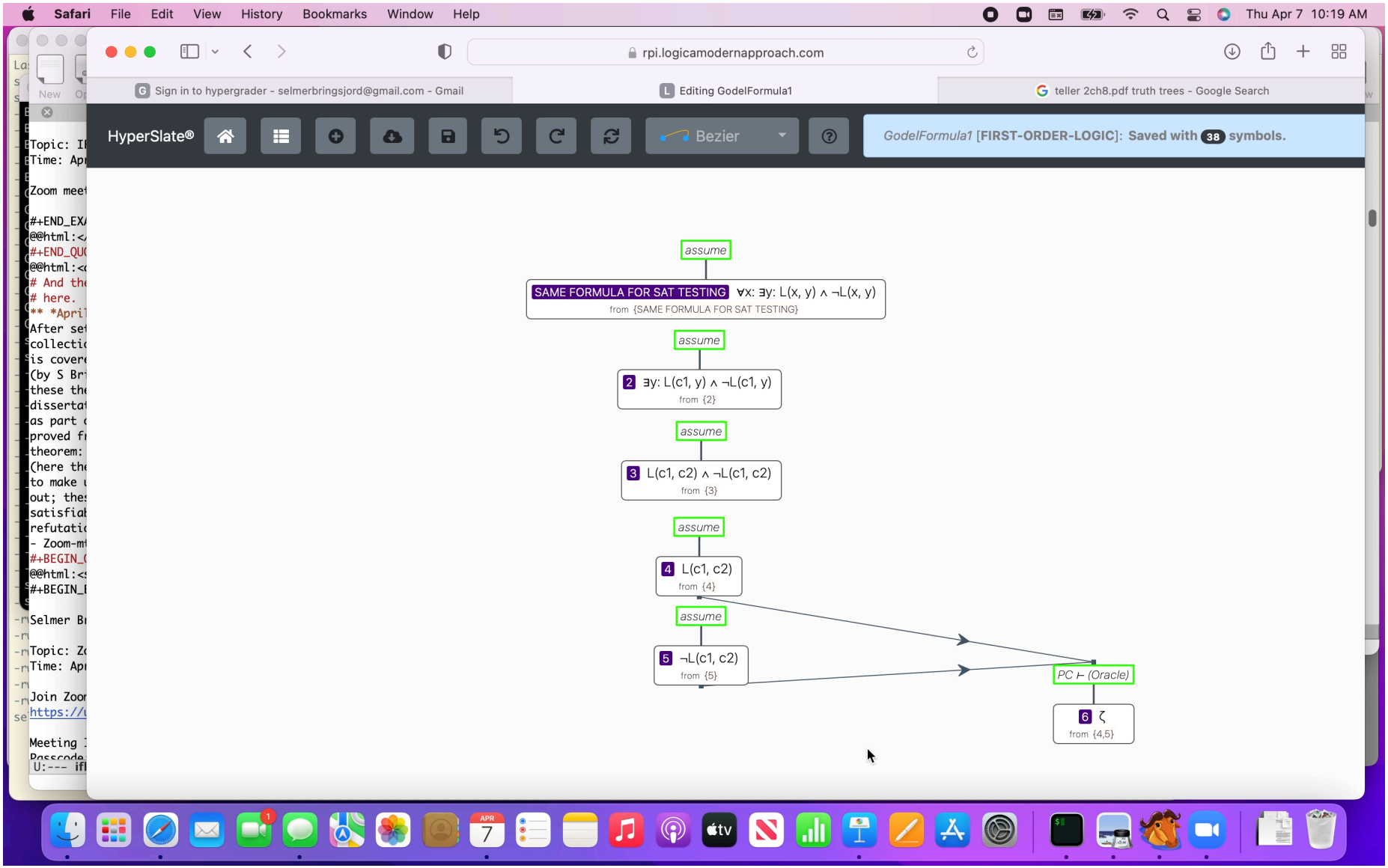

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Volunteers to do the following Buzz-Lightyear-relevant formula, from earlier in the present slide deck?

$$\forall x \exists y \; y > x$$

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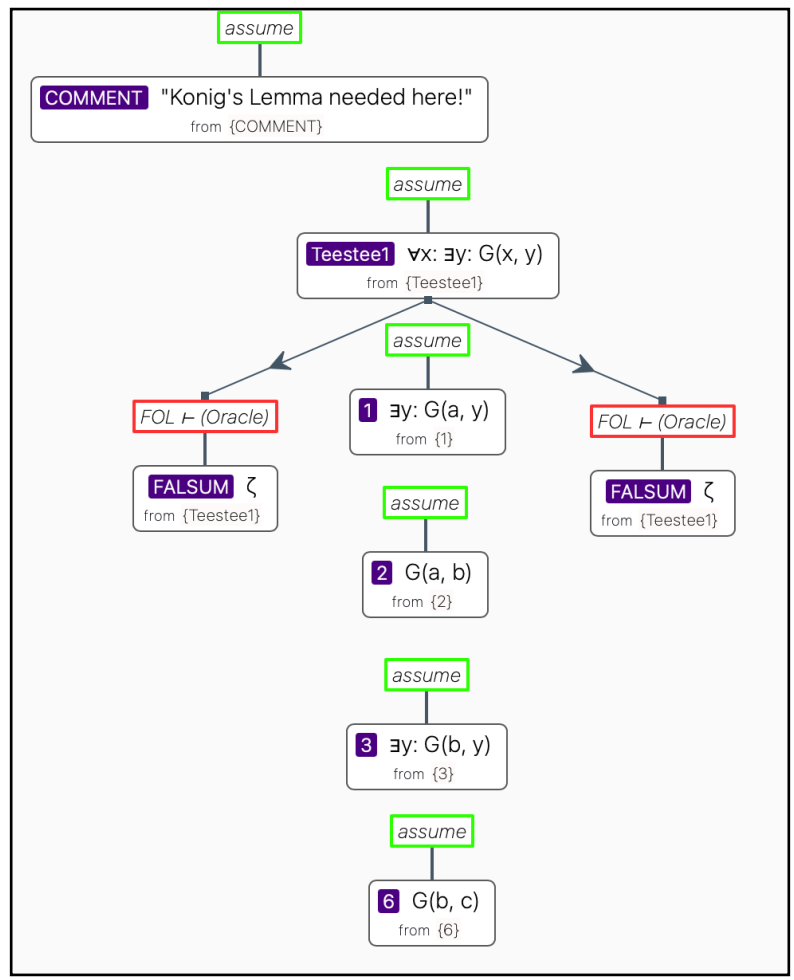
E.g.



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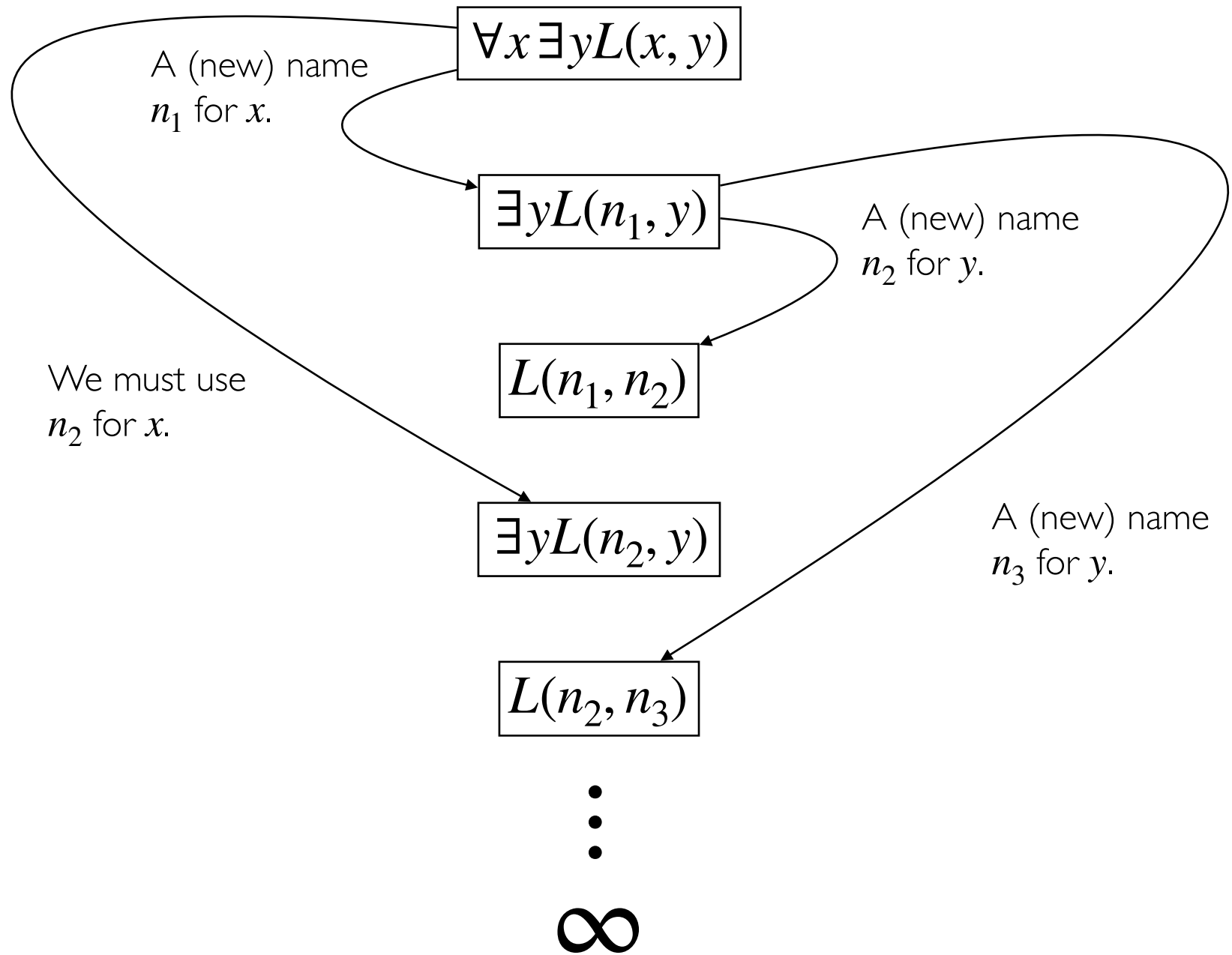
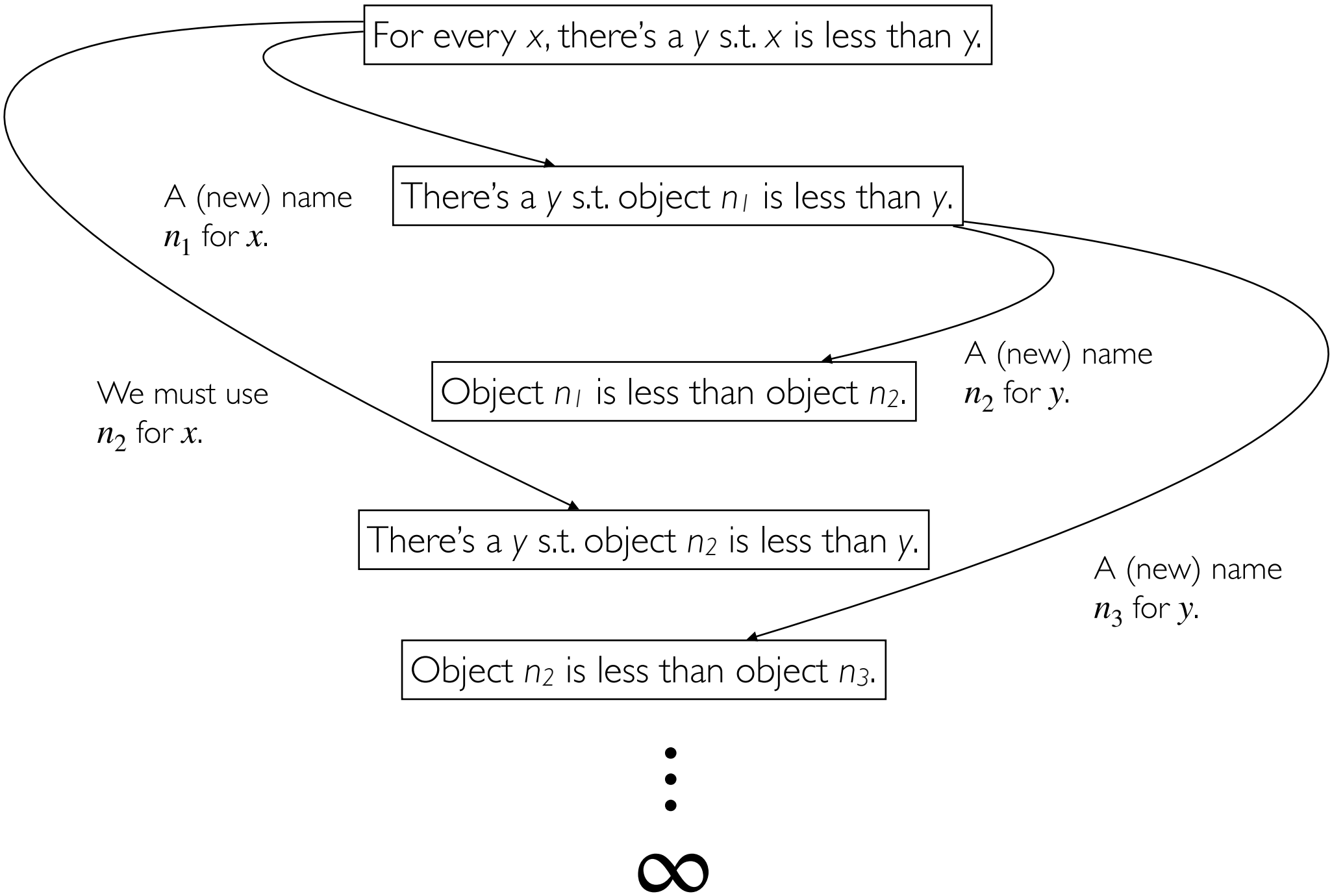

$\forall x \exists y L(x, y)$
A (new) name
n_1 for x.
$\exists y L(n_1, y)$
A (new) name
n_2 for y.
$L(n_1, n_2)$
We must use
n_2 for x.
$\exists y L(n_2, y)$
A (new) name
n_3 for y.
$L(n_2, n_3)$
∞


For every x, there's a y s.t. x is less than y.
A (new) name n_1 for x.
There's a y s.t. object n_1 is less than y.
We must use n_2 for x.
Object n_1 is less than object n_2.
A (new) name n_2 for y.
There's a y s.t. object n_2 is less than y.
A (new) name n_3 for y.
Object n_2 is less than object n_3.
∞

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