Integrating Computation in Logic: Deduction Modulo

Olivier Hermant

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- It has been forgotten by the formalization of the mathematics.
- reborn with informatics: rewriting rules.
- we need a balance between deduction steps and computation steps.

Deduction systems: the logical framework

- first-order logic: function and predicate symbols, logical connectors: $\wedge, \vee, \Rightarrow, \neg$, and quantifiers $\forall, \exists$.

$$Even(0)$$
$$\forall n(Even(n) \Rightarrow Odd(n+1))$$
$$\forall n(Odd(n) \Rightarrow Even(n+1))$$

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- a sequent :

$$\overbrace{\Gamma}^{\text{hyp.}} \vdash \overbrace{A}^{\text{conc.}}$$

- rules to form them: sequent calculus (or natural deduction)
- framework: intuitionnistic logic (classical, linear, higher-order, constraints ...)

Deduction System : sequents calculus (LJ)

- A deduction rule:

$$\frac{\Gamma \vdash A \qquad \Gamma \vdash B}{\Gamma \vdash A \wedge B}$$

- right and left rules

$$\frac{}{\Gamma, A \vdash A}\text{axiom} \qquad \frac{\Gamma, A \vdash B \;\; \Gamma \vdash A}{\Gamma \vdash B}\text{cut}$$

$$\frac{\Gamma \vdash A \;\; \Gamma \vdash B}{\Gamma \vdash A \wedge B}\wedge\text{-r} \qquad \frac{\Gamma, A, B \vdash C}{\Gamma, A \wedge B \vdash C}\wedge\text{-l}$$

$$\frac{\Gamma, \forall x A[x], A[t] \vdash B}{\Gamma, \forall x A[x] \vdash B}\forall\text{-g, any } t \qquad \frac{\Gamma \vdash A[x]}{\Gamma \vdash \forall x A[x]}\forall\text{-r, } x \text{ free}$$

Example: 1

$$\forall x P(x) \vdash P(0) \wedge P(1)$$

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Example: 1

$$\dfrac{\dfrac{\dfrac{\forall x P(x), P(0) \vdash P(0)}{\forall x P(x) \vdash P(0)}\,\forall\text{-l} \qquad \dfrac{\forall x P(x), P(1) \vdash P(1)}{\forall x P(x) \vdash P(1)}\,\forall\text{-l}}{\forall x P(x) \vdash P(0) \wedge P(1)}\,\wedge\text{-r}$$

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$$\dfrac{\dfrac{\forall x P(x), P(1), P(0) \vdash P(0) \wedge P(1)}{\forall x P(x), P(0) \vdash P(0) \wedge P(1)}\ \forall\text{-I}}{\forall x P(x) \vdash P(0) \wedge P(1)}\ \forall\text{-I}$$

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- the first rule is not always “don’t care”: free variable condition.

Axioms vs. rewriting

Axioms	Rewriting
$x + S(y) = S(x + y)$ $x + 0 = x$ $x * 0 = 0$ $x * S(y) = x + x * y$ $(x * y = 0) \Leftrightarrow (x = 0 \vee y = 0)$	$x + S(y) \rightarrow S(x + y)$ $x + 0 \rightarrow x$ $x * 0 \rightarrow 0$ $x * S(y) \rightarrow x + x * y$ $(x * y = 0) \rightarrow (x = 0 \vee y = 0)$
$\vdots$ $\dfrac{\dfrac{}{\mathcal{T} \vdash 2 * 2 = 4}}{\mathcal{T} \vdash \exists x(2 * x = 4)}$	$\dfrac{\dfrac{}{\vdash 4 = 4}}{\vdash \exists x(2 * x = 4)}$

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- General form (free variables are possible):

$$l \to r$$

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- deduction rules transform as such:

$$\text{axiom}\ \frac{}{\Gamma, A \vdash A} \qquad \text{becomes} \qquad \frac{}{\Gamma, A \vdash B}\ \text{axiom},\ A \equiv B$$

Deduction modulo : sequent calculus modulo

$$\frac{}{\Gamma, A \vdash B}\text{axiom } A \equiv B \qquad \frac{\Gamma, A \vdash C \quad \Gamma \vdash B}{\Gamma \vdash C}\text{cut } A \equiv B$$

$$\frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash C} \wedge\text{-r } A \wedge B \equiv C \qquad \frac{\Gamma, A, B \vdash C}{\Gamma, D \vdash C} \wedge\text{-l } A \wedge B \equiv D$$

$$\frac{\Gamma, B, A[t] \vdash C}{\Gamma, B \vdash C}\forall\text{-l } \forall x A[x] \equiv B \qquad \frac{\Gamma \vdash A[x]}{\Gamma \vdash B}\forall\text{-r}^{*} \ \forall x A[x] \equiv B$$

Example: 3

- consider the rewriting system $\mathcal{R}$:

$$\begin{aligned} P(0) &\rightarrow A \\ P(1) &\rightarrow B \end{aligned}$$

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Cut rule: a detour

$$\frac{\Gamma, A \vdash B \quad \Gamma \vdash C}{\Gamma \vdash B}\ \text{cut},\ A \equiv C$$

- show $\Gamma \vdash A$
- show $\Gamma, A \vdash B$
- then, you have showed $\Gamma \vdash B$
- it is the application of a lemma.

Example: 4

- consider the rewriting system $\mathcal{R}$:

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Example: 4

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$$\begin{array}{lcl} P(0) & \to & A \\ P(1) & \to & B \end{array}$$

$$\frac{\forall x P(x), A \vdash A \wedge B \qquad \forall x P(x) \vdash A}{\forall x P(x) \vdash A \wedge B}\ \text{cut}$$

Example: 4

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- an unnecessary detour
- we could have cutted on any formula!

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- we show $\Gamma, A \vdash B$ and $\Gamma \vdash A$
- then we have showed $\Gamma \vdash B$.
- lemma: the good way for a human being.
- in practice: not adapted for automatic demonstration.
  Nb: resolution method *do not* proceed by cuts !

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- eliminating cuts: a key result.

$$\Gamma \vdash A \quad \triangleright \quad \Gamma \vdash_{cf} A$$

- two main paths towards:
  - proof normalization (syntactic).
  - semantical methods.

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- two main paths towards:
  - proof normalization (syntactic).
  - semantical methods.
- in deduction modulo: indecidable, need for general criterions on $\mathcal{R}$

The normalization method(s)

- Curry-Howard: proofs = programs
- formulas = types
- proof tree = typing tree
- at the heart of proof assistants (PVS, Coq, Isabelle, ...)
- when a program calculates, it performs a cut elimination procedure.

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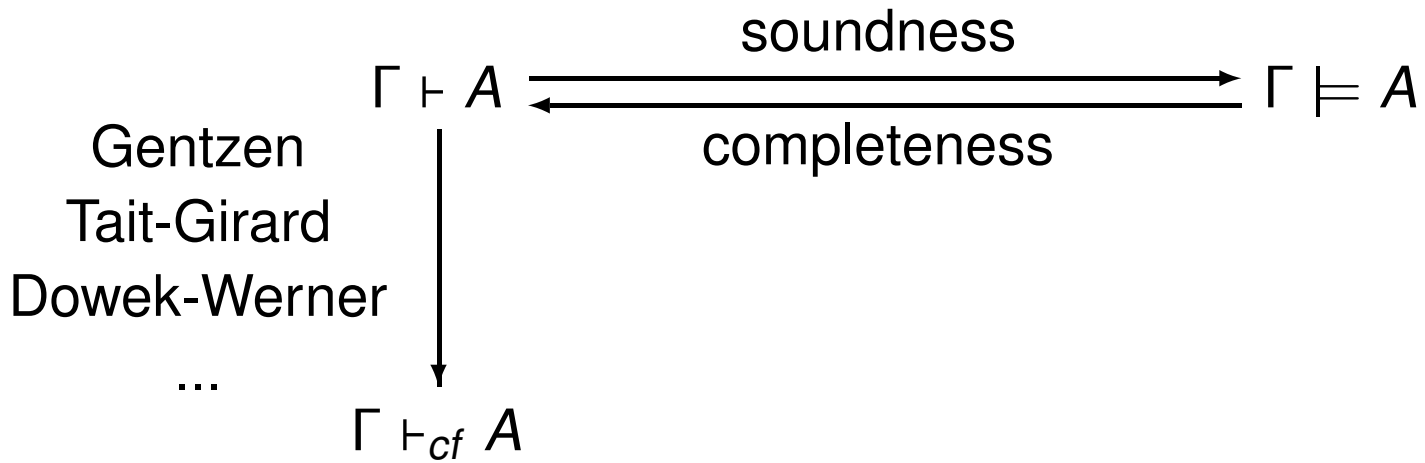
- when a program calculates, it performs a cut elimination procedure.
- show that all typables function terminates.

The semantical method(s)

- define a semantical space (truth value). Ex: Boolean algebras.
- we must have soundness/completeness wrt the semantic.

The semantical method



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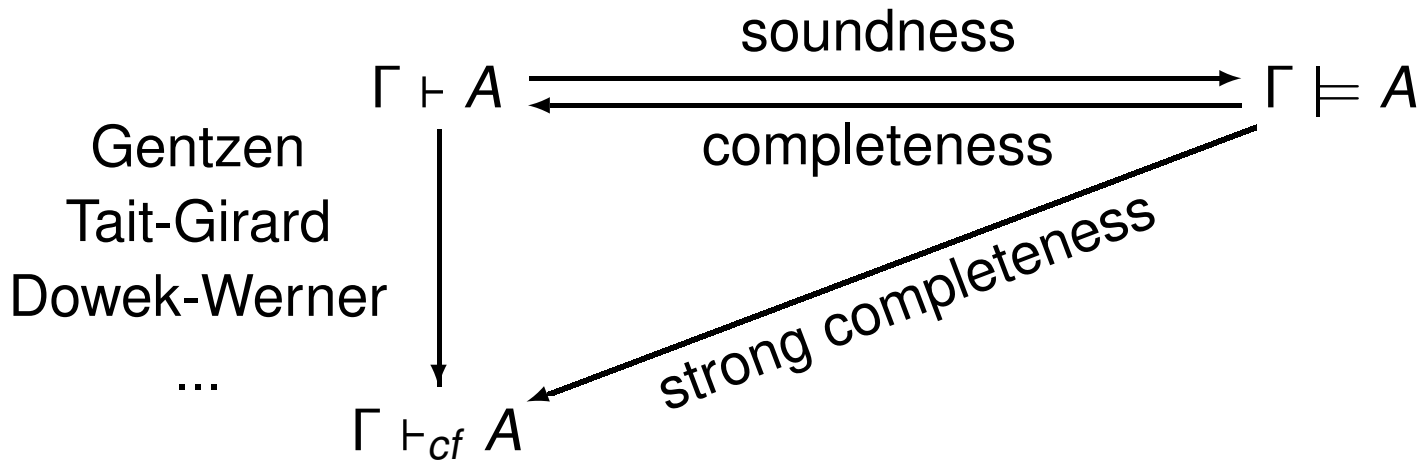

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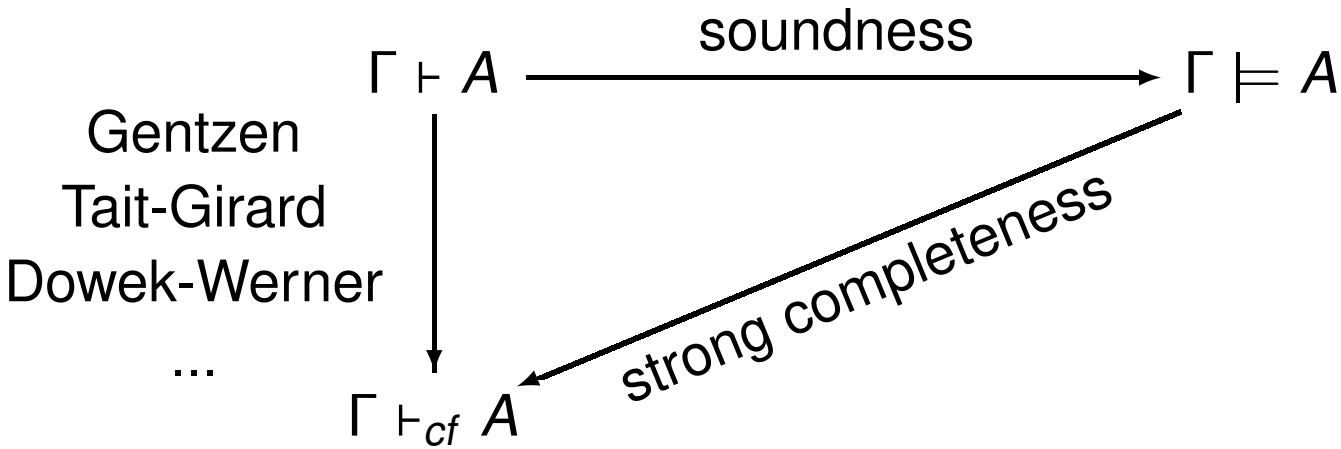

A semantic for deduction modulo

Two main semantics for intuitionistic logic:

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- Heyting algebras [Lipton,Okada]

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- $D : \alpha \rightarrow \mathcal{S}et$ a monotone function (interpretation domain for terms).

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- K the set of worlds, partially ordered with $\leq$ (a "temporal relation": past, present, possible futures: partial information)
- $D : \alpha \rightarrow \mathcal{S}et$ a monotone function (interpretation domain for terms).
- $\Vdash$ is a relation between worlds and formulas, verifiying:

A semantic for deduction modulo

- P atomic: if $\alpha \leq \beta$ and $\alpha \Vdash P$, then $\beta \Vdash P$.
- $\alpha \Vdash A \Rightarrow B$ iff for any $\beta \geq \alpha$, when $\beta \Vdash A$ then $\beta \Vdash B$.
- $\alpha \Vdash A \vee B$ iff $\alpha \Vdash A$ or $\alpha \Vdash B$.

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- $\alpha \Vdash A \vee B$ iff $\alpha \Vdash A$ or $\alpha \Vdash B$.
- Additional constraint in deduction modulo:

$$A \equiv B \quad \text{implies} \quad \alpha \Vdash A \Leftrightarrow \alpha \Vdash B$$

Kripke structures at work

- $A \vee (\neg A)$ is well-known not to be valid in intuitionistic logic.
- we build a structure that is invalidating this formula. Note: at least two worlds (single world = boolean model).
- $\neg A = A \Rightarrow \bot$

$$\begin{array}{c} \beta \Vdash A \\ | \\ \alpha \Vdash \emptyset \end{array}$$

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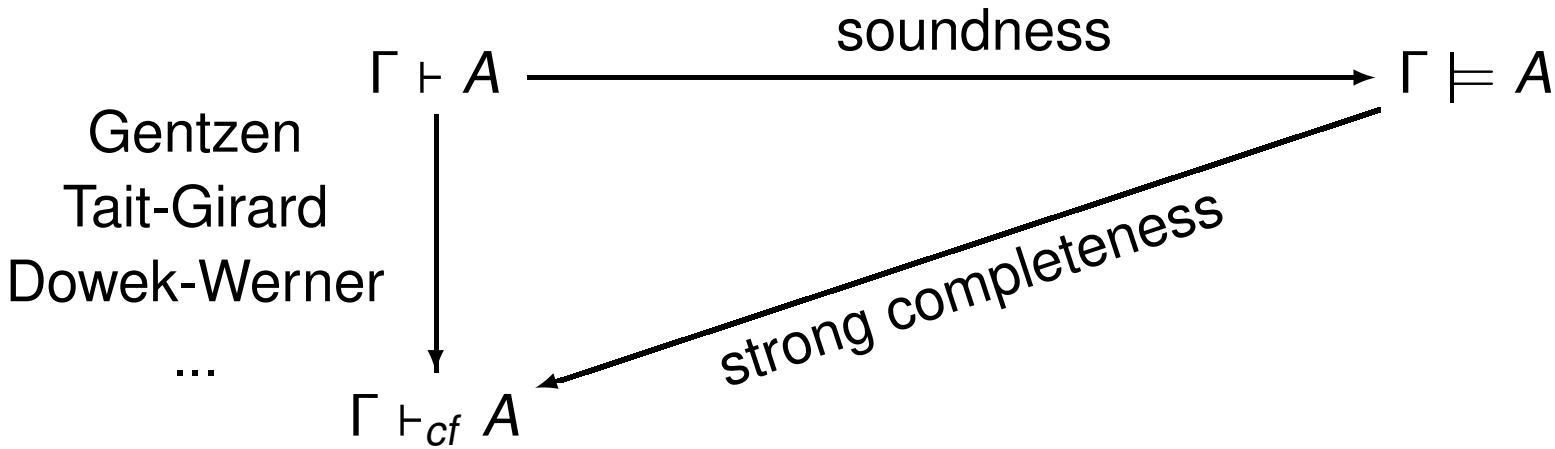
Constructive proof: the algorithm behind



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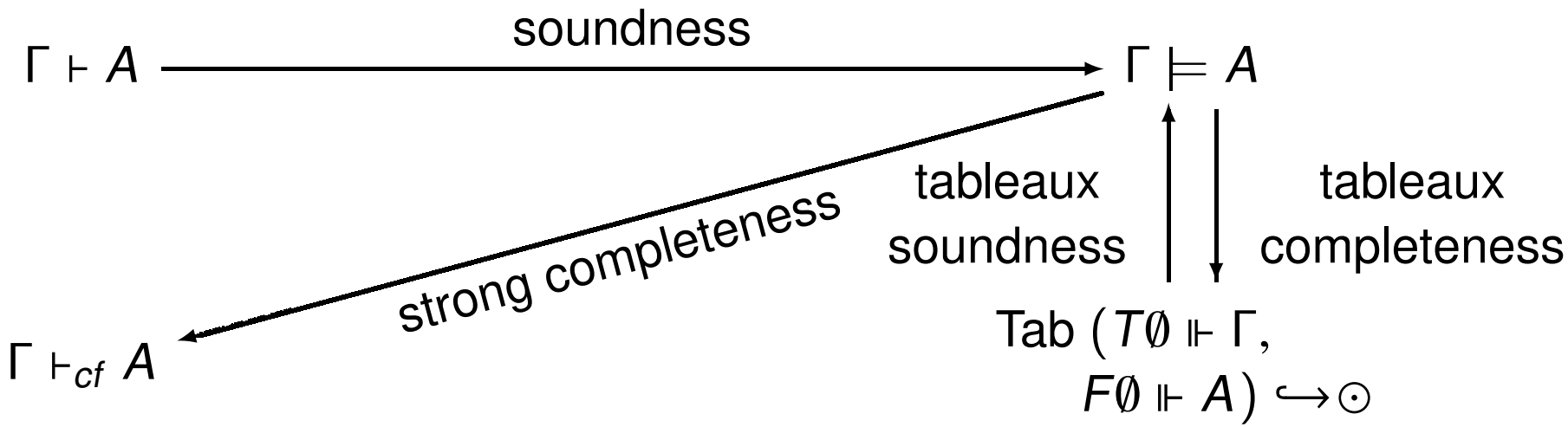

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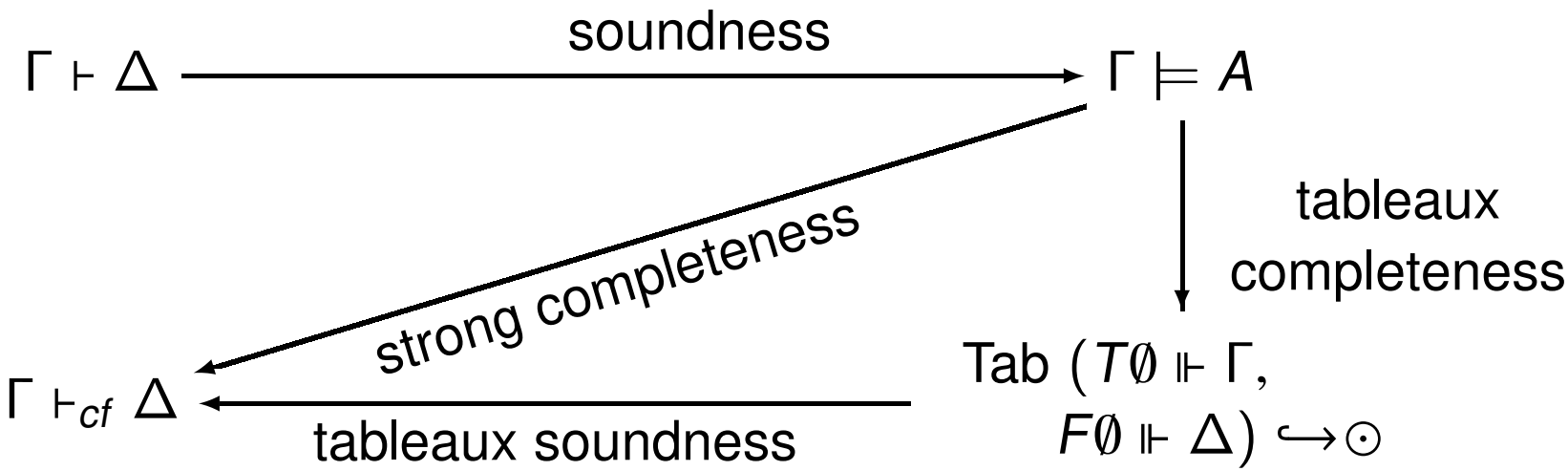

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$$\dfrac{Tp \Vdash A \vee B}{Tp \Vdash A \quad Tp \Vdash B}$$

$$\begin{array}{c} Fp \Vdash A \vee B \\ | \\ Fp \Vdash A \\ | \\ Fp \Vdash B \end{array}$$

$$\dfrac{Tp \Vdash A \Rightarrow B}{Tq \Vdash B \quad Fq \Vdash A}$$

with proviso on q

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with proviso on q

- in deduction modulo: allow rewrite rules, define a new systematic research algorithm with $\mathcal{R}$.

Tableau: example 1

- We want to show "$A \vee B \vdash C \Rightarrow A$"
- tranlsation in tableau language: there is NO (node of no) Kripke structure satisfying $A \vee B$ without satisfying also $C \Rightarrow A$. Let's see if the counter-model search fails or not.
- We choose as usual sequences of integers for the set of worlds (partial order: prefix).

$T\emptyset \Vdash A \vee B, F\emptyset \Vdash C \Rightarrow A$

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$$\Big|$$

$$T1 \Vdash C$$

$$\Big|$$

$$F1 \Vdash A$$

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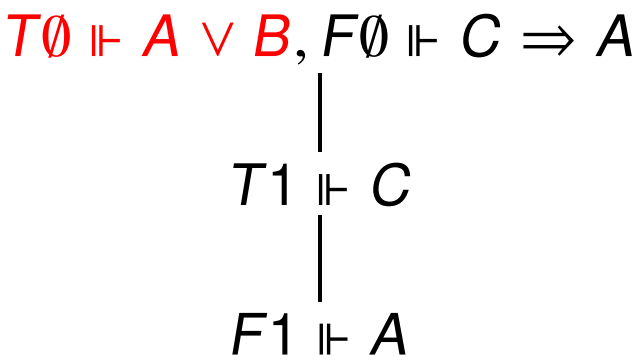

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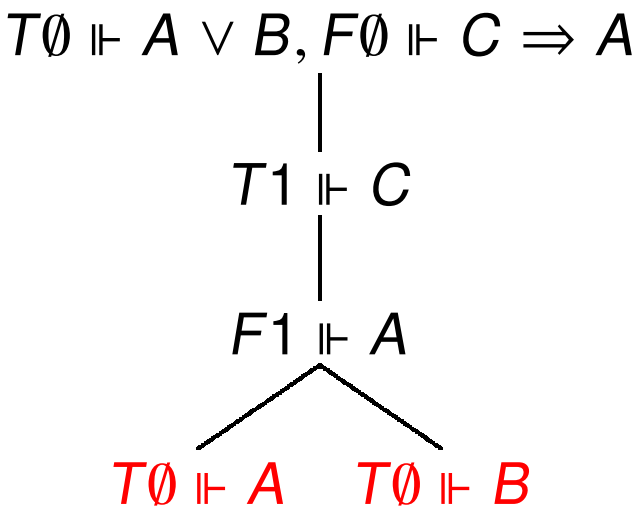

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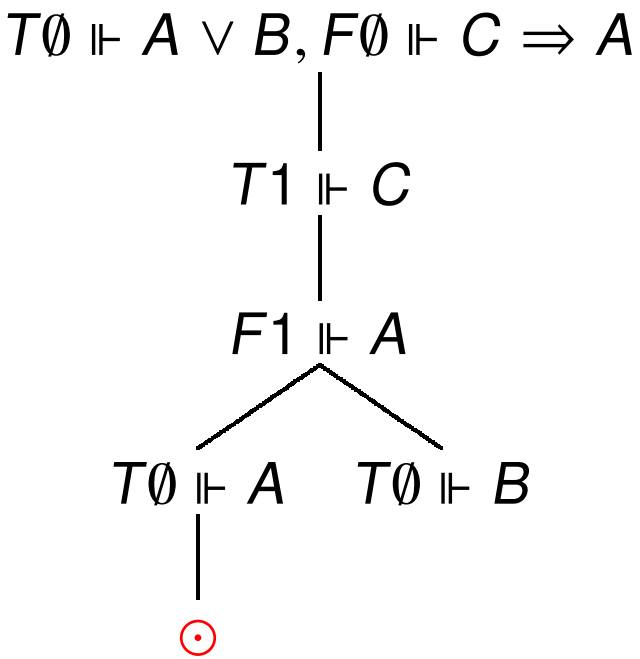

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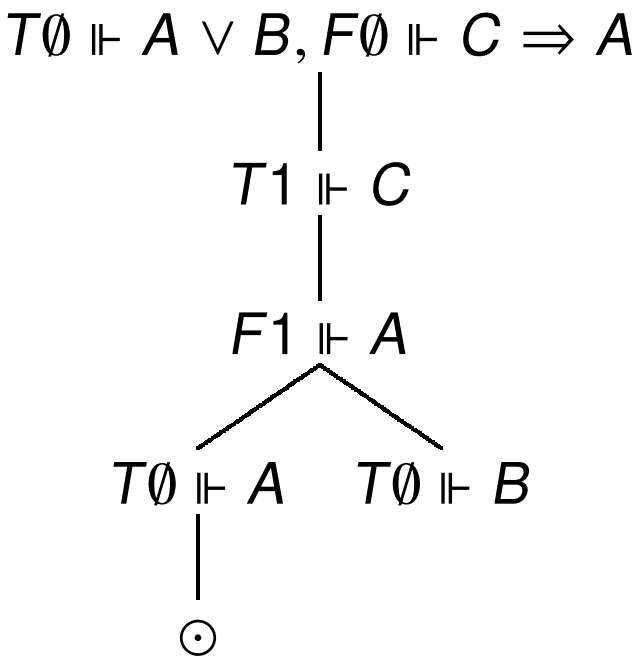


Tableau: example 2

- We want to show "$\vdash (A \Rightarrow B) \Rightarrow (A \Rightarrow B)$"

$F_{\varnothing} \Vdash (A \Rightarrow B) \Rightarrow A \Rightarrow B$

Tableau: example 2

$$F_\varnothing \Vdash (A \Rightarrow B) \Rightarrow A \Rightarrow B$$

$$\Big|$$

$$T_1 \Vdash (A \Rightarrow B)$$

$$\Big|$$

$$F_1 \Vdash A \Rightarrow B$$

Tableau: example 2

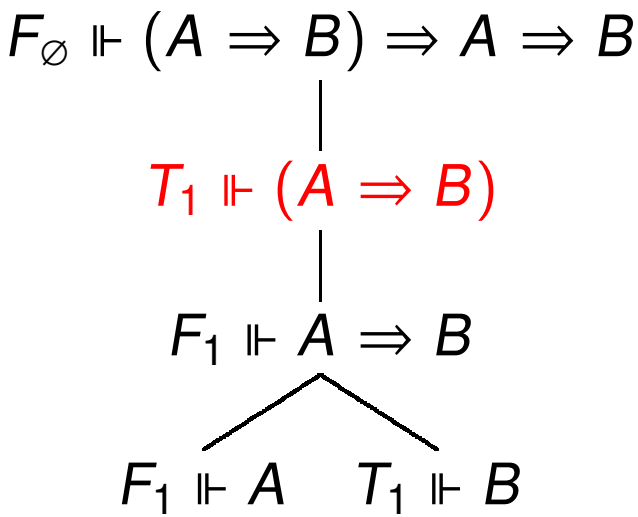
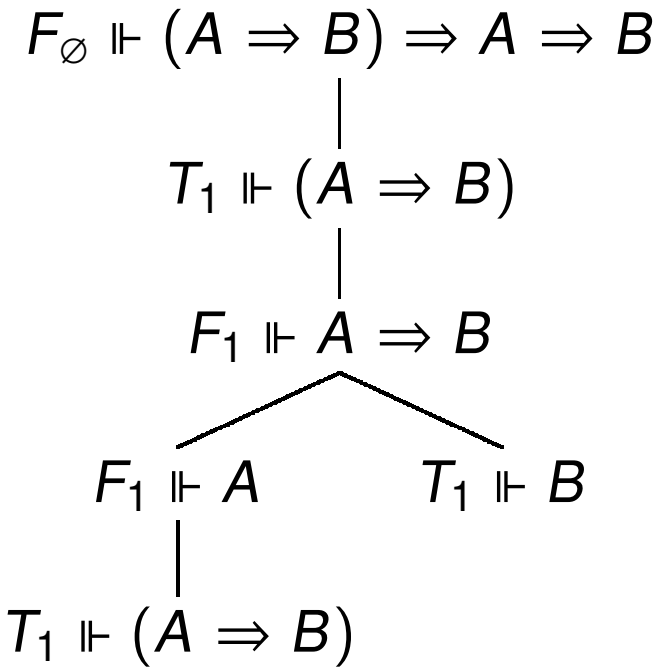


Tableau: example 2



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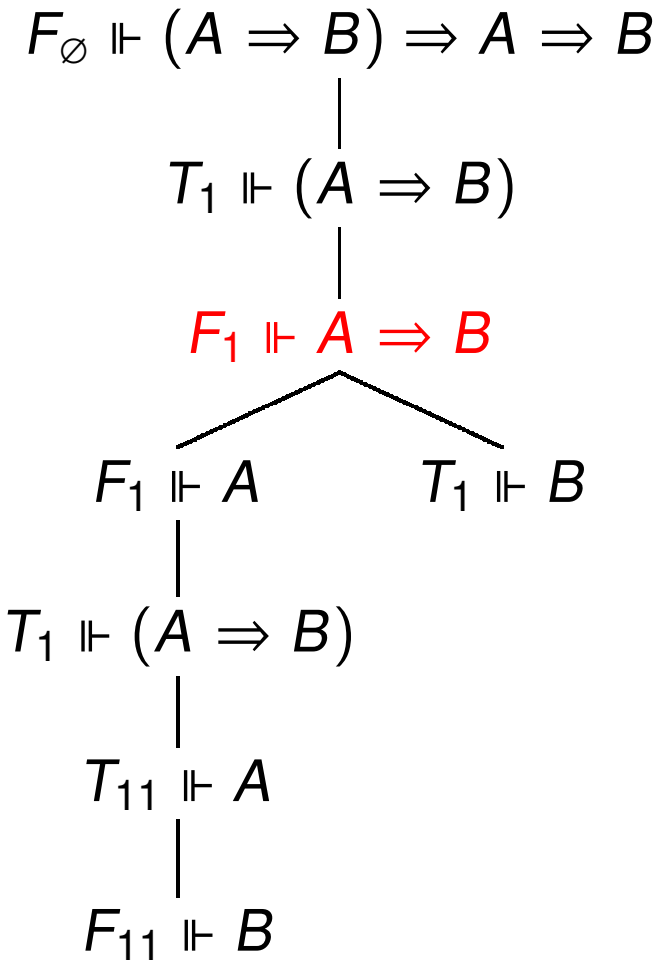

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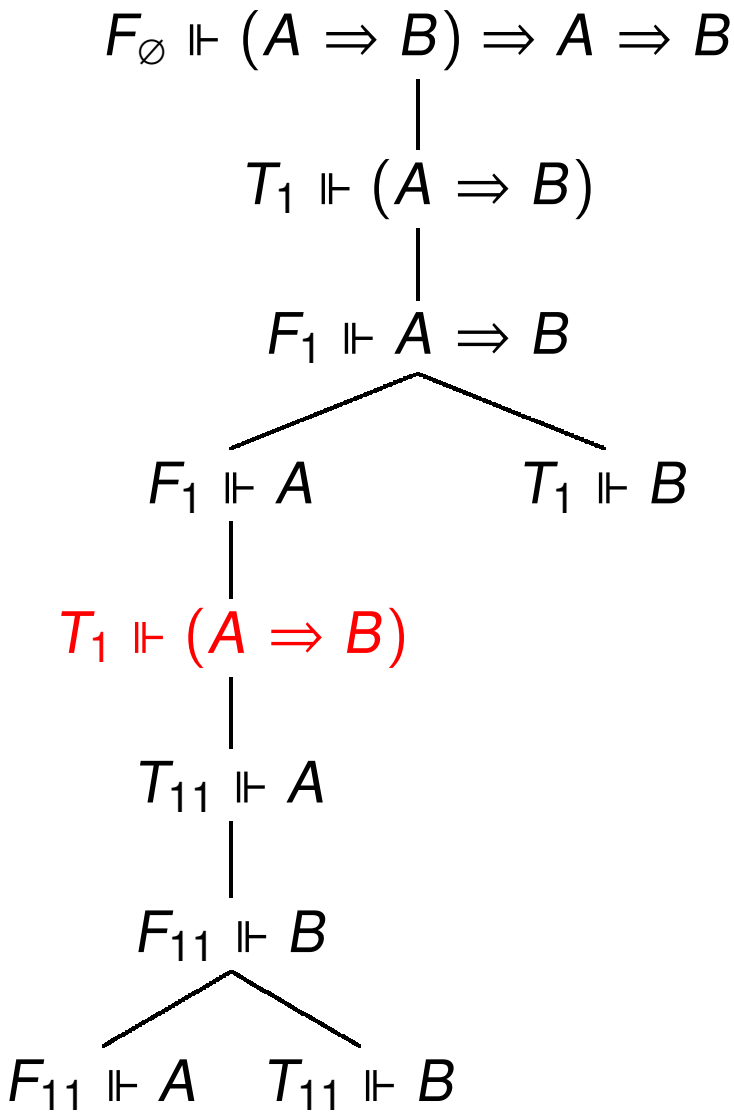

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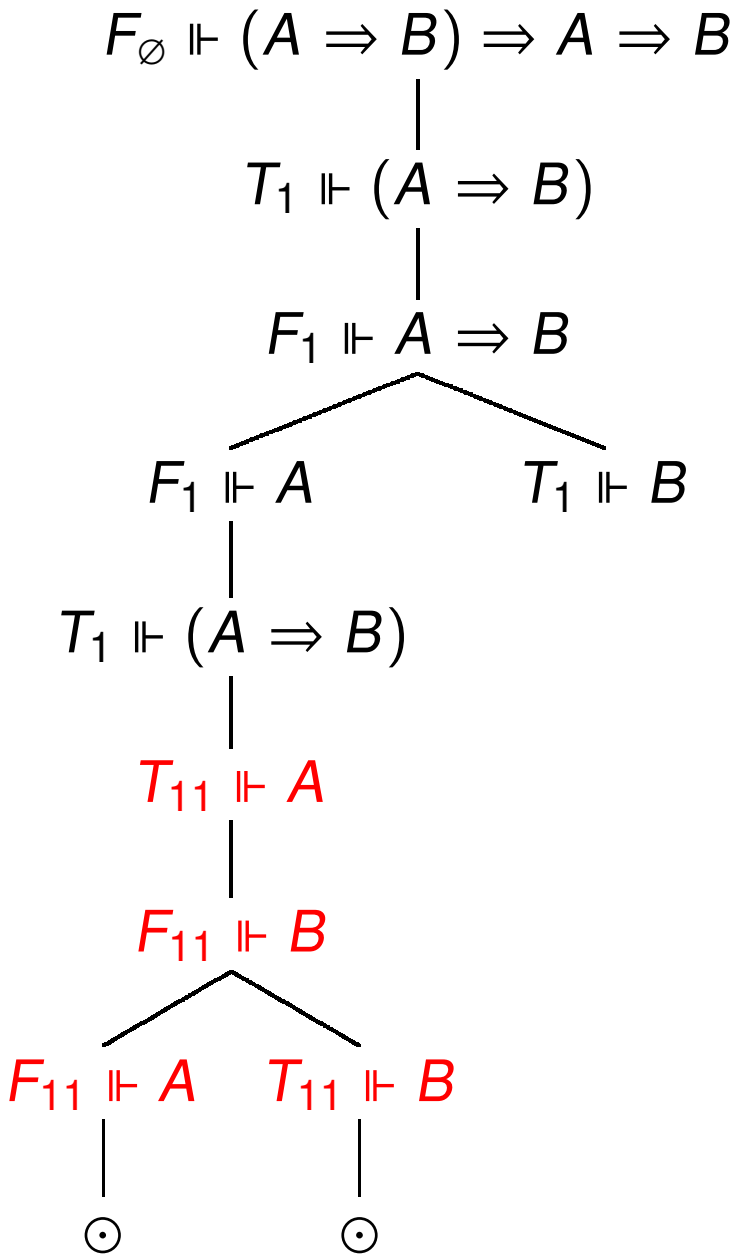

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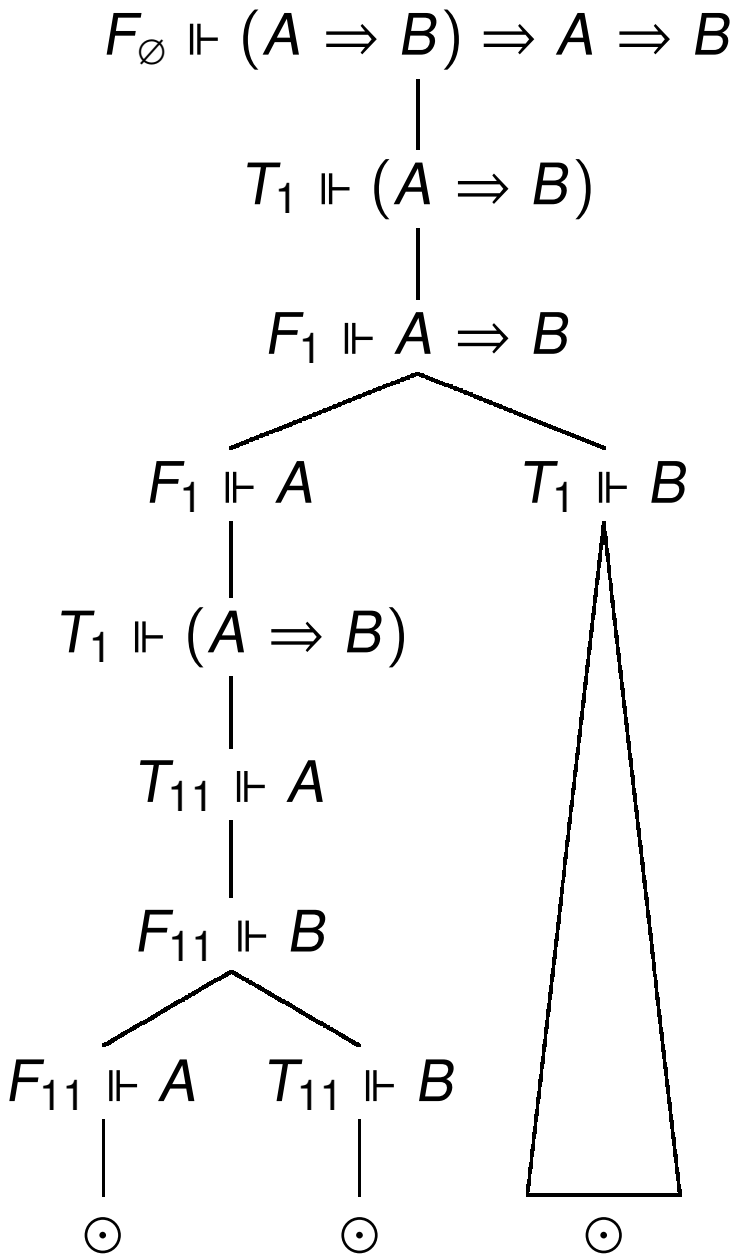

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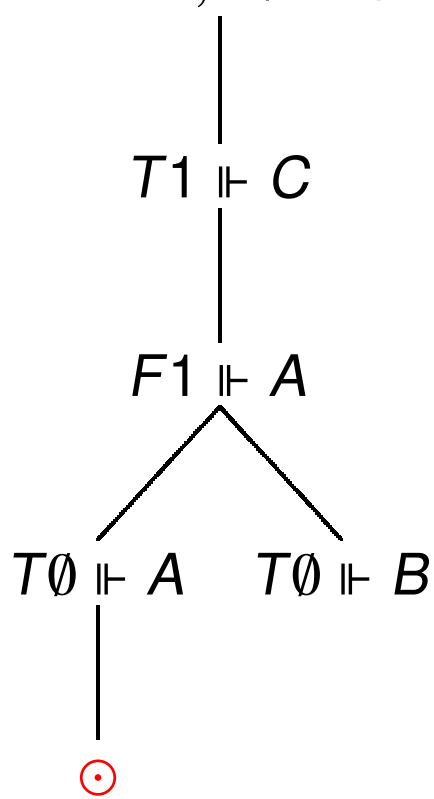
  - deduction modulo: it has also to be a model of the rewrite rules $\mathcal{R}$.
- constructive point of view: if there is no counter-model, does the method terminate? (KS definition is modified)

Remember the tableau for $A \vee B \vdash C \Rightarrow A$:



- the right path generates counter model.
- the nerve: the atomic formulas each world entails (forces), extension by induction.

Conditions on rewrite rules

Providing the confluence of the rewrite system $\mathcal{R}$, and for:

- an order condition: $\succ$, well-founded, having the subformula property, and such that $P \rightarrow^* Q$ implies $P \succ Q$.

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- the rule:

$$R \in R \to \forall y\ (\forall x(y \in x \Rightarrow R \in x) \Rightarrow (y \in R \Rightarrow (A \Rightarrow A)))$$

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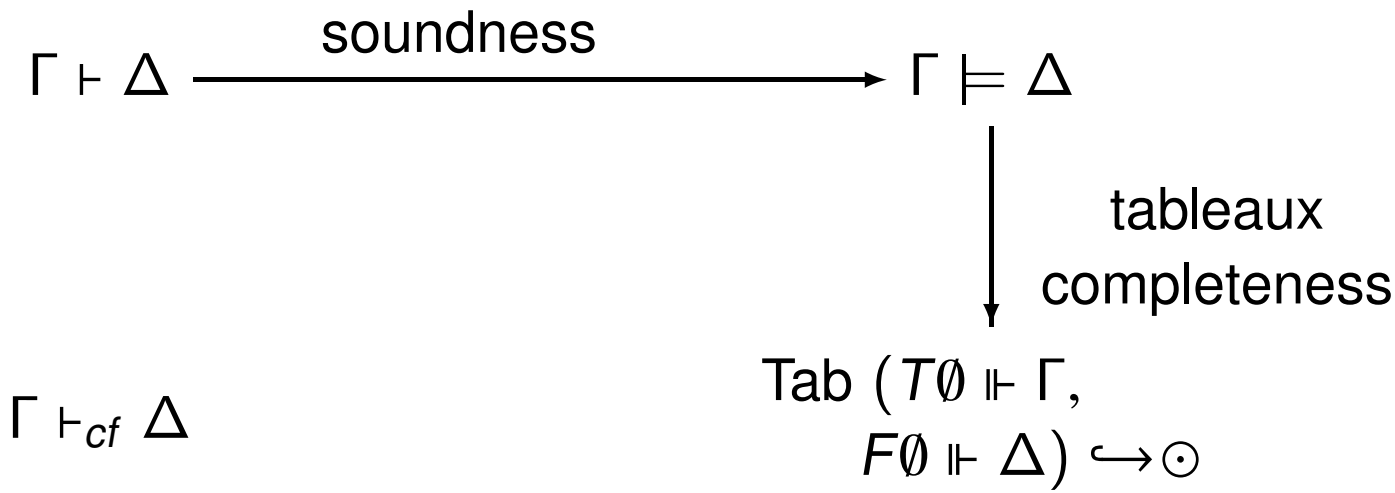
$\Gamma \vdash \Delta$
soundness
$\Gamma \models \Delta$
tableaux
completeness
$\Gamma \vdash_{cf} \Delta$
Tab $(T\emptyset \Vdash \Gamma,$
$F\emptyset \Vdash \Delta) \hookrightarrow \odot$

Tableaux soundness

We show the following theorem:

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If a tableau starting with $T\emptyset \Vdash \Gamma, F\emptyset \Vdash P$ is closed, then we can transform it into a proof of $\Gamma \vdash_{cf} P$.

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- Without the cut rule, we show the lemma (by a double induction):

$$\Gamma_1 \vdash_{cf} A \vee B \qquad \Gamma_2 \vdash_{cf} A \vee C$$
$$\text{then} \qquad \Gamma_1, \Gamma_2 \vdash_{cf} A \vee (B \wedge C)$$

Computational content: what kind of algorithm ?

Let's reconsider the rule:

$$R \in R \to \forall y\ (\forall x(y \in x \Rightarrow R \in x) \Rightarrow (y \in R \Rightarrow (A \Rightarrow A)))$$

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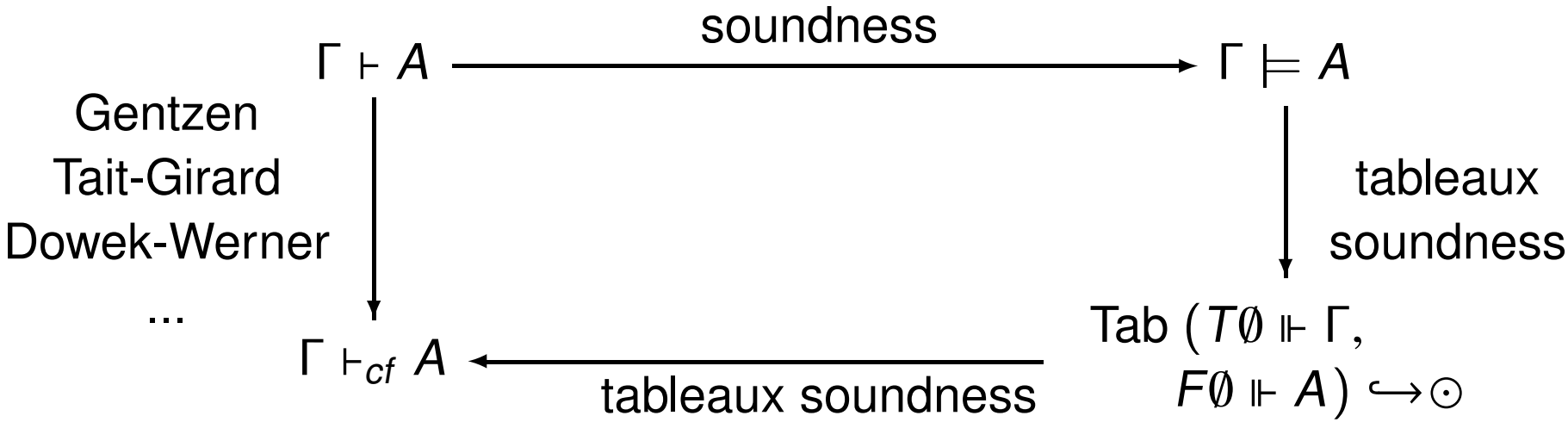
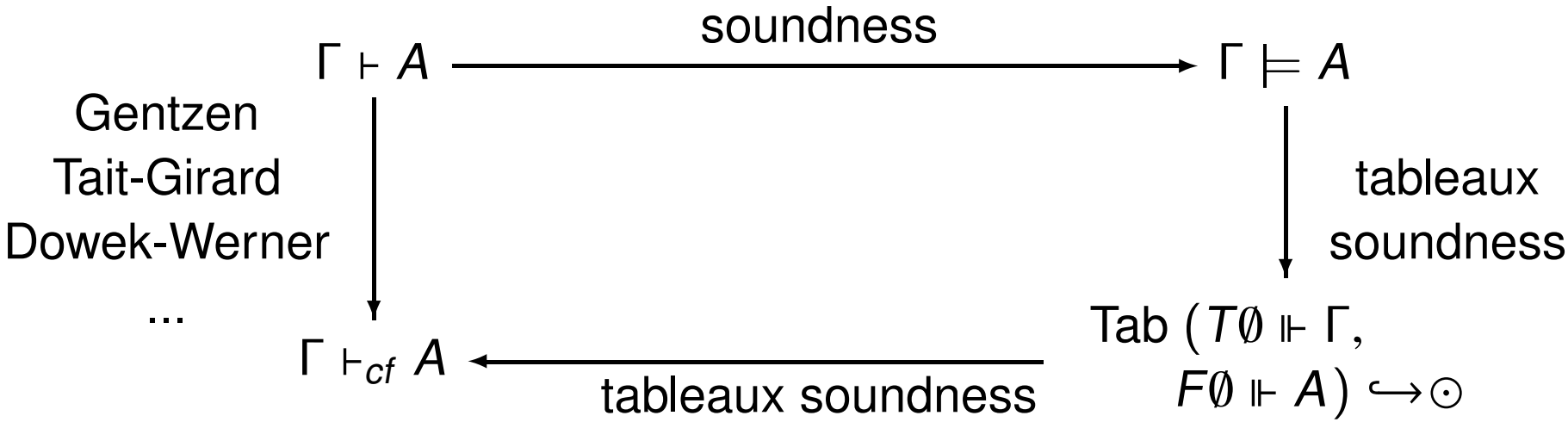
- this can not be a normalization algorithm.
- it is more or less the tableau method described here.



- This diagram does not commute.



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- But: normalization methods “generate” a certain kind of semantical cut elimination proof [Dowek - Hermant].