Countermodels for non-normal modal logics via nested sequents

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SYSMICS, Amsterdam
Jan 24, 2019

Modal logics: A success story

Fact

Many problems in Computer Science are modelled in Modal Logic.

Examples

- Epistemic logics: $\mathcal{K}(A)$ . . . “the agent knows A is the case”
- Deontic logics: $\mathcal{O}(A)$ . . . “A ought to be the case”
- . . .

In particular, modal logics often have nice reasoning systems a.k.a. calculi with strong connections to

- Syntax: useful for proving theorems
- Semantics: useful for finding countermodels.

Modal logics: A success story (normally?)

... But not all applications might satisfy normality:

Epistemic logics: $\mathcal{K}(A)$ ... "the agent knows that A is the case"

- $\mathcal{K}(\top)$ ... "the agent knows all tautologies"

Deontic logics: $\mathcal{O}(A)$ ... "A ought to be the case"

- $\mathcal{O}(\text{go}) \wedge \mathcal{O}(\neg\text{go}) \rightarrow \mathcal{O}(\text{go} \wedge \neg\text{go})$ ... "in presence of conflicting obligations, $\bot$ ought to be the case"

So...

Can we find good calculi for non-normal modal logics?

Monotone modal logic

The formulae of monotone modal logic M are given by

$$p \in \mathsf{Var} \mid \bot \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid \varphi \to \varphi \mid \langle\exists\forall]\varphi$$

A neighbourhood frame $\mathcal{F} = (W, \mathcal{N})$ has a neighbourhood function satisfying $\mathcal{N}(w) \subseteq \mathcal{P}(W)$ for every $w \in W$.
Valuations σ satisfy:

- local clauses for $\wedge, \vee, \to, \bot$.
- $\mathcal{F}, \sigma, w \Vdash \langle\exists\forall]A$ iff $\exists \alpha \in \mathcal{N}(w)\, \forall v \in \alpha.\ \mathcal{F}, \sigma, v \Vdash A$

The axiomatisation of M is given by propositional logic and the rule

$$\frac{\vdash A \to B}{\vdash \langle\exists\forall]A \to \langle\exists\forall]B}$$

Reasoning in monotone modal logic

There are some calculi for M:

Syntactical calculi:

- Sequent calculi [Lavendhomme, Lucas:2000, Indrzejczak:2005]
- (Labelled Tableaux [Indrzejczak:2007])

Pro: Good for reasoning, formula interpretation

Con: Bad for countermodels

Semantical calculi:

- Labelled sequent calculi [Negri:2017, Dalmonte et al:2018]

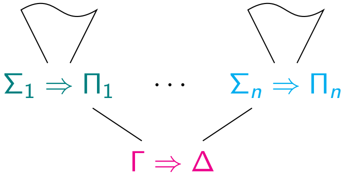
Pro: Good for countermodels

Con: Bad for reasoning, no formula interpretation

But we want syntax and semantics to meet!

Nested sequents to the rescue!

Nested sequents are trees of (multi-set based) sequents:



interpreted in normal modal logics as

$$\bigwedge\Gamma \to \bigvee\Delta \vee \Box(\bigwedge\Sigma_1 \to \bigvee\Pi_1^*) \vee \cdots \vee \Box(\bigwedge\Sigma_n \to \bigvee\Pi_n^*).$$

A bit of history:

- Precursors: [Bull:'92], [Kashima:'94], [Masini:'92]
- Current form in modal logics: [Brünnler:'09], [Poggiolesi:'09]
- For intuitionistic modal logics: [Straßburger et al:'12 - now]
- Adapted to intuitionistic logic in [Fitting:'14]

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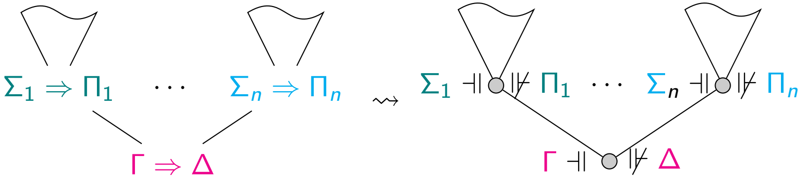

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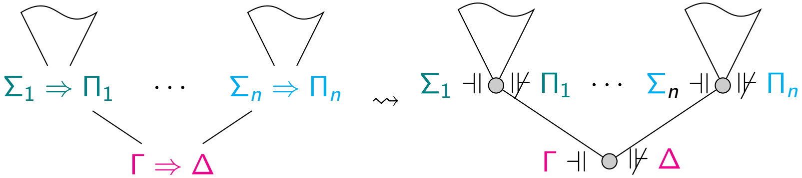

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Nested sequents give rise to models for normal modal logic.

But:

- "deep applicability" of the rules implies normality of the formula interpretation.
- How to construct countermodels for non-normal logics?

monotone modal logic

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Bimodal monotone modal logic

The formulae of bimodal monotone modal logic aka. Brown's Ability Logic are given by

$$p \in \mathsf{Var} \mid \bot \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid \varphi \to \varphi \mid \langle\exists\forall]\varphi \mid [\forall\forall]\varphi$$

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Valuations σ satisfy:

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- $\mathcal{F}, \sigma, w \Vdash [\forall\forall]A$ iff $\forall \alpha \in \mathcal{N}(w)\, \forall v \in \alpha.\, \mathcal{F}, \sigma, v \Vdash A$

Brown's ability interpretation [Brown:'88]:

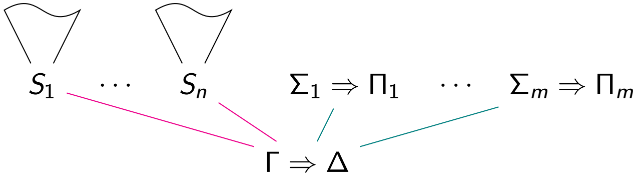
$\langle\exists\forall]A$: "The agent can reliably bring about A"
$[\forall\forall]A$: "The agent will bring about A"

Bimodal nested sequents

A bimodal nested sequent is a structure

$$\Gamma \Rightarrow \Delta, [S_1], \ldots, [S_n], \langle \Sigma_1 \Rightarrow \Pi_1 \rangle, \ldots, \langle \Sigma_m \Rightarrow \Pi_m \rangle$$

with $n, m \geq 0$ where the S_i are bimodal nested sequents.
As a tree:



Its formula interpretation ι is

$$\bigwedge\Gamma \to \bigvee\Delta \ \vee \ \bigvee_{i=1}^{n} [\forall\forall]\iota(S_i) \ \vee \ \bigvee_{j=1}^{m} \langle\exists\forall](\bigwedge\Sigma_j \to \bigvee\Pi_j)$$

The calculus for bimodal M

The calculus contains the (classical) propositional rules plus:

$$\frac{\Gamma \Rightarrow \Delta, [\Rightarrow A]}{\Gamma \Rightarrow \Delta, [\forall\forall]A}\ [\forall\forall]_R \qquad \frac{\Gamma \Rightarrow \Delta, [\Sigma, A \Rightarrow \Pi]}{\Gamma, [\forall\forall]A \Rightarrow \Delta, [\Sigma \Rightarrow \Pi]}\ [\forall\forall]_L$$

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Rules are applied anywhere except inside $\langle . \rangle$.

Theorem

The rules are sound wrt. the formula interpretation.

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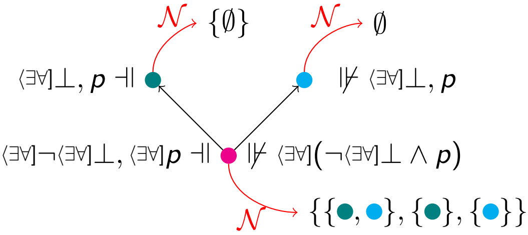
Bonus: Restricting the language specifies the calculus to the standard (linear) nested sequent calculus for modal logic K or the (linear) nested sequent calculus for monomodal M

What about countermodels?

Using an annotated version of the calculus, underivable sequents give rise to countermodels: E.g.

$$\langle\exists\forall]\neg\langle\exists\forall]\bot, \langle\exists\forall]p \Rightarrow \langle\exists\forall]\big(\neg\langle\exists\forall]\bot \wedge \langle\exists\forall]p\big),\ [\,\langle\exists\forall]\bot, p \Rightarrow\,],\ [\,\Rightarrow \langle\exists\forall]\bot, p\,]$$

yields



Theorem

The calculus for bimodal M *is cut-free complete and failed proof search yields a countermodel.*

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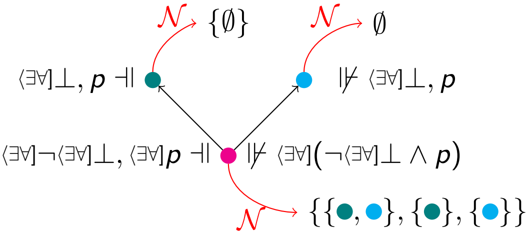

Corollary (Bonus)

The calculi for K *and monomodal* M *are cut-free complete and failed proof search yields a countermodel.*

What do derivations look like?

…Let the implementation work that out!

(`http://subsell.logic.at/bprover/nnProver/`)

Input sequent: $\Rightarrow (([\forall\forall](a \to b) \wedge \langle\exists\forall\rangle a) \to \langle\exists\forall\rangle b)$

Derivation found!

$$
\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{}{[\forall\forall](a \to b), \langle\exists\forall\rangle a \Rightarrow \langle a \Rightarrow b\rangle^{\mathsf{f}}, \langle\Rightarrow b\rangle^{\mathsf{u}}, \langle\exists\forall\rangle b\,[b, a \overset{a}{\Rightarrow} b]}\;\mathsf{init} \qquad \dfrac{}{[\forall\forall](a \to b), \langle\exists\forall\rangle a \Rightarrow \langle a \Rightarrow b\rangle^{\mathsf{f}}, \langle\Rightarrow b\rangle^{\mathsf{u}}, \langle\exists\forall\rangle b\,[(a \to b), a \overset{a}{\Rightarrow} a, b]}\;\mathsf{init}}{[\forall\forall](a \to b), \langle\exists\forall\rangle a \Rightarrow \langle a \Rightarrow b\rangle^{\mathsf{f}}, \langle\Rightarrow b\rangle^{\mathsf{u}}, \langle\exists\forall\rangle b\,[(a \to b), a \overset{a}{\Rightarrow} b]}\;\to_L}{[\forall\forall](a \to b), \langle\exists\forall\rangle a \Rightarrow \langle a \Rightarrow b\rangle^{\mathsf{f}}, \langle\Rightarrow b\rangle^{\mathsf{u}}, \langle\exists\forall\rangle b\,[a \overset{a}{\Rightarrow} b]}\;[\forall\forall]_L}{[\forall\forall](a \to b), \langle\exists\forall\rangle a \Rightarrow \langle a \Rightarrow b\rangle^{\mathsf{f}}, \langle\Rightarrow b\rangle^{\mathsf{u}}, \langle\exists\forall\rangle b}\;\mathsf{jump}}{[\forall\forall](a \to b), \langle\exists\forall\rangle a \Rightarrow \langle\Rightarrow b\rangle^{\mathsf{u}}, \langle\exists\forall\rangle b}\;\langle\exists\forall\rangle_L}{[\forall\forall](a \to b), \langle\exists\forall\rangle a \Rightarrow \langle\exists\forall\rangle b}\;\langle\exists\forall\rangle_R}{([\forall\forall](a \to b) \wedge \langle\exists\forall\rangle a) \Rightarrow \langle\exists\forall\rangle b}\;\wedge_L}{\Rightarrow (([\forall\forall](a \to b) \wedge \langle\exists\forall\rangle a) \to \langle\exists\forall\rangle b)}\;\to_R
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Input sequent:

$$\Rightarrow (((\langle\exists\forall\rangle(((\langle\exists\forall\rangle c \wedge d) \rightarrow ([\forall\forall]a \vee (\langle\exists\forall\rangle b \vee f))) \wedge (\langle\exists\forall\rangle(\langle\exists\forall\rangle m \rightarrow (k \vee (\langle\exists\forall\rangle l \vee \langle\exists\forall\rangle n))) \wedge [\forall\forall]((\langle\exists\forall\rangle x \wedge [\forall\forall]y) \rightarrow \langle\exists\forall\rangle(\langle\exists\forall\rangle z \wedge \langle\exists\forall\rangle w)))) \rightarrow ([\forall\forall](g \vee [\forall\forall]h) \vee (\langle\exists\forall\rangle\langle\exists\forall\rangle\langle\exists\forall\rangle\langle\exists\forall\rangle i \vee \langle\exists\forall\rangle([\forall\forall]o \rightarrow \langle\exists\forall\rangle p))))$$

Countermodel found!

Suming up

Bimodal nested sequents for monotone modal logic yield:

- an internal calculus;
- support for countermodel construction;
- the basis for a general treatment of non-normal modal logics;
- an implementation including countermodel generation