CS 112 Fall 2023

Brandeis University

Modal Logics for Language:

Alethic, Epistemic, Temporal, Spatial, Doxastic Models of Reasoning

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Modal Logics for Language

Our Team

James Pustejovsky

Jingxuan Tu

Aristotle

Saul Kripke

Dr. Strange and Prof. Hegel

Applications of *modal logic*

Modal logic is a family of studies of modal notions with a unifying mathematical meta-theory.

philosophy	logic of possibility and necessity, epistemic (knowledge) and deontic (obligation) logics
linguistics	tense logic
economics	game theory
mathematics	provability logic, relational algebras
comp. sci.	temporal logic, dynamic logic automated soft- and hardware verification
AI	epistemic logic, temporal logic representing and reasoning about space and time, modelling complex interactive multi-agent systems

Topics covered in this course

- Review: Propositional Logic (PL), Predicate Logic (FOL), Proof Theories
- Syntax and Semantics of Basic Modal Logic (PML) for propositions
- Temporal Modal Logics: LTL, CTL, Interval Temporal Logic
- Dynamic/Action Logics: PDL, DEL, PAL, AL-STIT
- Spatial Logics: SML, RCC8
- Epistemic Logics: S4, K45, DEL,
- Deontic Logics: SDL, Deontic STIT, Multi-agent DL
- Counterfactual Logics: Lewi—Stalnaker Logic, Pearl Causal Model
- Translations: AMR, AVM, graphs into Modal structures

Learning Goals for the Course

- Understand why Modal Logic is important – it's everywhere!
- To encode and interpret linguistic, cognitive, and computational problems as modal relational structures
- To identify computational properties of the language used for modeling the problem (decidability, soundness, completeness)

Topics in this class

Slides thanks to: Eric Pacuit, Patrick Blackburn, Valentine Goranko, and the “Logic in Action” course

1. Propositional Modal Logic
2. First-Order Modal Logic
3. Non-Normal Modal Logics
4. Applications: (Dynamic) Epistemic Logic, Epistemic Temporal Logic, Logics of Knowledge and Ability

Setting the stage: Classical logic

Propositional Logic (PL)

- Language: $P \wedge Q$, $P \rightarrow (Q \vee \neg R)$, etc.
- Proof-Theory: Natural Deduction, Hilbert-style Deductions, Tableaux, etc.
- Semantics: Truth functions

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Propositional Logic (PL)

- Language: $P \wedge Q$, $P \rightarrow (Q \vee \neg R)$, etc.
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First-Order Logic (FOL)

- Language: $x = y$, $\exists x \forall y (P(x) \wedge Q(x, y))$, $\forall x \exists y (F(x) \rightarrow (G(x, y) \wedge \neg R(y)))$, etc.
- Proof-Theory: Natural Deduction, Hilbert-style Deductions, Tableaux, etc.
- Semantics: First-order structures

Reasoning with classical logic: pros and cons

Advantages:

- relatively simple syntax and well-understood semantics
- well-developed deductive systems and tools for automated reasoning

Disadvantages:

- cannot adequately represent some aspects natural language
- cannot adequately capture specific modes of reasoning
- undecidability of logical consequence and validity (for FOL)

Modal Logic

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Modal Logic

- Modal logic has a long, distinguished history (from Aristotle).
- Until the late 1950s, it largely consisted of a collection of syntactic theories
- Modern modal logic started in the early 1960s with the introduction of relational semantics by Saul Kripke (although see the earlier work by McKinsey and Tarski on logic and topology and Gödel on provability logic).
- There are a wide variety of modal systems, with different interpretations of the modal operators. Modal logic is an important tool in many disciplines: philosophy, computer science, linguistics, economics

The History of Modal Logic

R. Goldblatt. *Mathematical Modal Logic: A View of its Evolution*. Handbook of the History of Logic, Vol. 7, 2006.

P. Balckburn, M. de Rijke, and Y. Venema. *Modal Logic*. Section 1.7, Cambridge University Press, 2001.

R. Ballarin. *Modern Origins of Modal Logic*. Stanford Encyclopedia of Philosophy, 2010.

What is a modal?

A modality is any word or phrase that can be applied to a statement S to create a new statement that makes an assertion that *qualifies* the truth of S.

Types of Modal Logics

Alethic logic: Necessary and possible truths.

Temporal logic: Temporal reasoning.

Spatial logics: Reasoning about spatial relations.

Epistemic logics: Reasoning about knowledge.

Doxastic logics: Reasoning about beliefs.

Deontic logics: Reasoning about obligations and permissions.

Types of Modal Logics

Logics of multiagent systems: Reasoning about many agents and their knowledge, beliefs, goals, actions, strategies, etc.

Description logics: Reasoning about ontologies.

Logics of programs: Reasoning about program executions.

Logics of computations: Specification of transition systems.

Provability logic: Reasoning about proofs

Introducing Modal Logic

Modern Modal Logic began with C.I. Lewis' dissatisfaction with the material conditional ($\rightarrow$).

- Irrelevance/non-causality:
  If the Sun is hot, then $2 + 2 = 4$.
- False antecedents:
  If $2 + 2 = 5$ then the Moon is made of cheese.
- Monotonicity:
  If I put sugar in my coffee, then it will taste good. Therefore, if I put sugar and I put oil in my coffee then it will taste good.

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C.I. Lewis' idea: Interpret 'If A then B' as 'It **must** be the case that A implies B', or 'It is **necessarily** the case that A implies B'

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Prosecutor: $G \to A$
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Judge: $\neg(G \to A)$ $\Leftrightarrow G \wedge \neg A$, therefore G!

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Prosecutor: $\Box(G \to A)$ (It must be the case that ...)
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Judge: $\neg\Box(G \to A)$ (*What can the Judge conclude?*)

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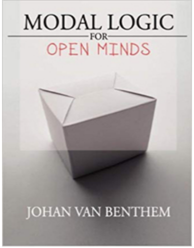
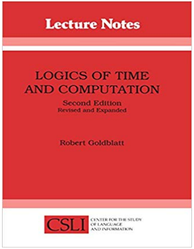
Introducing Modal Logic

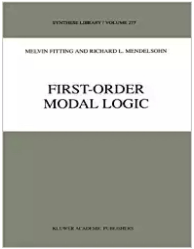
Gradually, the study of the modalities themselves became dominant, with the study of “conditionals” developing into a separate topic.

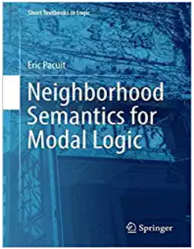
Books

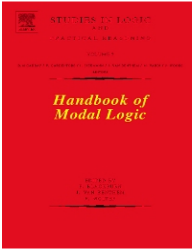

Modal Logic
Patrick Blackburn, Maarten de Rijke and Yde Venema


MODAL LOGIC FOR OPEN MINDS
JOHAN VAN BENTHEM

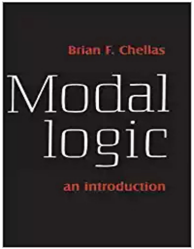

Lecture Notes
LOGICS OF TIME AND COMPUTATION
Second Edition
Revised and Expanded
Robert Goldblatt
CSLI
CENTER FOR THE STUDY OF LANGUAGE AND INFORMATION

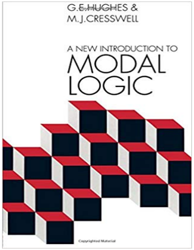

SYNTHESE LIBRARY / VOLUME 277
MELVIN FITTING AND RICHARD L. MENDELSOHN
FIRST-ORDER MODAL LOGIC
KLUWER ACADEMIC PUBLISHERS

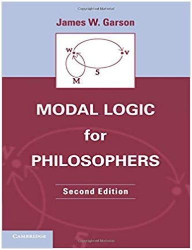

Short Textbooks in Logic
Eric Pacuit
Neighborhood Semantics for Modal Logic
Springer

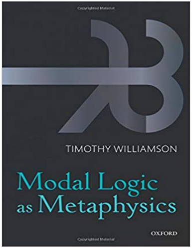

Handbook of Modal Logic

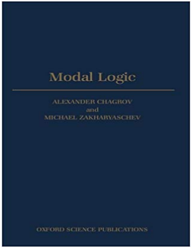
Books


Brian F. Chellas
Modal logic
an introduction


G.E.HUGHES &
M.J.CRESSWELL
A NEW INTRODUCTION TO
MODAL LOGIC


James W. Garson
MODAL LOGIC
for
PHILOSOPHERS
Second Edition
CAMBRIDGE


TIMOTHY WILLIAMSON
Modal Logic
as Metaphysics
OXFORD


Modal Logic
ALEXANDER CHAGROV
and
MICHAEL ZAKHARYASCHEV
OXFORD SCIENCE PUBLICATIONS

Modal Languages

Modal languages extend some logical language (e.g., propositional logic, first-order logic, second-order logic, etc.) with (at least) two new symbols '$\Box$' and '$\Diamond$'.

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$\Box\varphi$: "it is *necessary* that φ is true"

$\Diamond\psi$: "it is *possible* that φ is true"

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$\Box\varphi$: "it is *knowing* that φ is true"

$\Diamond\psi$: "it is *consistent with everything that is known* that φ is true"

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Modal languages extend some logical language (e.g., propositional logic, first-order logic, second-order logic, etc.) with (at least) two new symbols '$\Box$' and '$\Diamond$'.

$\Box\varphi$: "it is *will always be* that φ is true"

$\Diamond\psi$: "it is *will sometimes be* that φ is true"

Modal Languages

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$\Box\varphi$: "it is *ought to be* that φ is true"

$\Diamond\psi$: "it is *permissible* that φ is true"

Modal Languages

Modal languages extend some logical language (e.g., propositional logic, first-order logic, second-order logic, etc.) with (at least) two new symbols '$\Box$' and '$\Diamond$'.

$\Box\varphi$: "it is ______ that φ is true"

$\Diamond\psi$: "it is ______ that φ is true"

Modal Languages

The symbols '$\Box$' and '$\Diamond$' are *sentential operators* the transform sentences into more complex sentences (similar to the negation operator).

An alternative approach treats modals as *predicates* that apply to terms (that are Gödel numbers of sentences)

J. Stern. *Toward Predicate Approaches to Modality*. Springer, 2016.

Modal Languages

More generally, $\triangle(\varphi_1, \ldots, \varphi_n)$ is an ***n*-ary modality**.

Definition 1.11 of [BdRV]: A **modal similarity type** is a pair $\tau = (O, \rho)$ where O is a non-empty set and $\rho : O \to \mathbb{N}$. The elements of O are the modal operator and ρ assigns to each modality an arity.

Narrow vs. Wide Scope

"If you do p, you must also do q"

- $p \rightarrow \Box q$
- $\Box(p \rightarrow q)$

de dicto vs. de re

"I know that someone appreciates me"

- $\Box\exists x A(x, e)$ (*de dicto*)
- $\exists x \Box A(x, e)$ (*de re*)

Iterations of Modal Operators

$\Box\varphi \to \Box\Box\varphi$: If I know, do I know that I know?

$\neg\Box\varphi \to \Box\neg\Box\varphi$: If I don't know, do I know that I don't know?

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What about: $\Diamond\Box\varphi \to \Box\Diamond\varphi$, $\Box\Diamond\varphi \to \Diamond\Box\varphi$, $\varphi \to \Box\Diamond\varphi$, $\Diamond\Box(\varphi \wedge \psi) \to \Diamond\Box\varphi \wedge \Diamond\Box\psi$, $\ldots$?

Propositional Modal Language

Language: Let At be a set of atomic propositions. The set of propositional modal formulas, denoted $\mathcal{L}(\mathsf{At})$, is the smallest set of formulas generated by the following grammar:

$$p \mid \bot \mid \neg\varphi \mid (\varphi \vee \psi) \mid \Diamond\varphi$$

where $p \in \mathsf{At}$.

Propositional Modal Language

A formula of Modal Logic is defined *inductively*:

1. Any element of At (called atomic propositions or propositional variables) is a formula
2. $\bot$ is a formula
3. If φ and ψ are formula, then so are $\neg\varphi$ and $\varphi \vee \psi$
4. If φ is a formula, then so is $\Diamond\varphi$
5. Nothing else is a formula

Eg., $\Box(p \to \Diamond q) \vee \Box\Diamond\neg r$; $\neg\Diamond\neg\bot$

Propositional Modal Language

The other Boolean connectives ($\wedge$, $\rightarrow$, and $\leftrightarrow$) are defined as usual

$\top$ is defined as $\neg\bot$.

$\Box\varphi$ is defined as $\neg\Diamond\neg\varphi$

$\Box p \rightarrow p$ is the formula $\neg\neg\Diamond\neg p \vee p$

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$\Diamond\varphi \ := \ \neg\Box\neg\varphi$

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$$p \mid \bot \mid \neg\varphi \mid (\varphi \vee \psi) \mid (\varphi \wedge \psi) \mid (\varphi \to \psi) \mid \Diamond\varphi \mid \Box\varphi$$

where $p \in \mathrm{At}$.

Notation

- Sometimes we'll use lowercase letters $p, q, r, \ldots$ for atomic propositions and other times we'll use uppercase letters $A, B, C, \ldots$
- The choice of which modal operator is part of the syntax and which is defined is largely conventional. We will use whatever is most convenient.
- When there are multiple modal operators in the language, we will use subscripts $\Box_a$, $\Diamond_a$ or place them "inside" the operators: $[a]$, $\langle a \rangle$

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"This practice is not very consistent, but most readers should agree that it is nice to have different clothes to wear, depending on one's mood"
(van Benthem, pg. 11)

Substitution

A function $\sigma : \mathsf{At} \to \mathcal{L}(\mathsf{At})$. Extended to all formulas $\overline{\sigma} : \mathcal{L}(\mathsf{At}) \to \mathcal{L}(\mathsf{At})$:

1. $\overline{\sigma}(p) = \sigma(p)$
2. $\overline{\sigma}(\neg\varphi) = \neg\overline{\sigma}(\varphi)$
3. $\overline{\sigma}(\varphi \vee \psi) = \overline{\sigma}(\varphi) \vee \overline{\sigma}(\psi)$
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For simplicity, identify σ and $\overline{\sigma}$ and write φ^{σ} for $\sigma(\varphi)$.

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For example, if $\sigma(p) = \Box\Diamond(p \wedge q)$ and $\sigma(q) = p \wedge \Box q$, then

$$(\Box(p \wedge q) \to \Box p)^\sigma = \Box((\Box\Diamond(p \wedge q)) \wedge (p \wedge \Box q)) \to \Box(\Box\Diamond(p \wedge q)).$$

Interpreting Modal Languages: Some Warm-up Questions

1. Is $(A \rightarrow B) \vee (B \rightarrow A)$ **true** or **false**?

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2. Is $A \to (B \to \neg A)$ **true** or **false**?

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4. Is $\Box A \to (B \to \Box A)$ **true** or **false**?

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5. Is $\neg\Box A \wedge \neg(\Diamond B \vee \neg\Box A)$ **true** or **false**?

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6. Is $\neg\Box A \wedge \neg(\Diamond B \vee \Diamond\neg A)$ **true** or **false**? false.
   (**tricky:** $\neg\Diamond\neg A$ **is equivalent to** $\Box A$**.**)

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7. Is $\Box A \rightarrow A$ **true** or **false**?

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6. Is $\neg\Box A \wedge \neg(\Diamond B \vee \Diamond\neg A)$ **true** or **false**? false.
   (**tricky: $\neg\Diamond\neg A$ is equivalent to $\Box A$.**)
7. Is $\Box A \to A$ **true** or **false**? It depends!

A few questions to keep you up at night...

- Is $A \to \Box B$ equivalent to $\Box(A \to B)$?
- Is $\Box A \to A$ valid? What about $\Box A \to \Box\Box A$?
- Can we give a truth-table semantics for the basic modal language?

  Hint: there are only 4 truth-functions for a unary operator. Suppose we want $\Box A \to A$ to be valid, but not $A \to \Box A$ and $\neg\Box A$.

Semantics for Propositional Modal Logic

1. Relational semantics (i.e., Kripke semantics)
2. Neighborhood models
3. Algebraic semantics (BAO: Boolean algebras with operators)
4. Possibility structures
5. Topological semantics (Closure algebras)
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Mathematical Background: sets, relations, functions, basic logic, etc.

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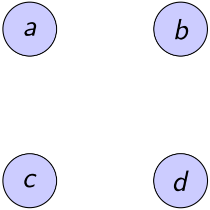

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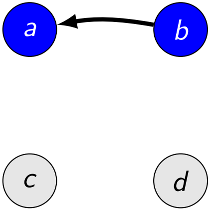

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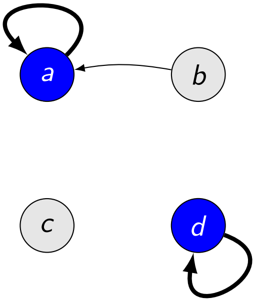

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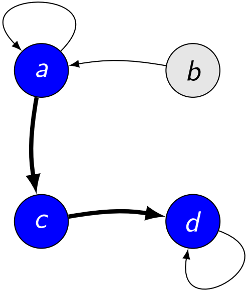

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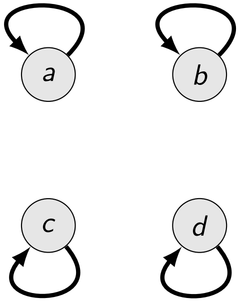

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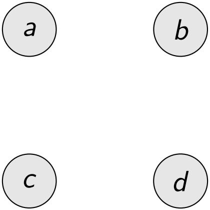

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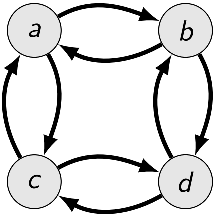

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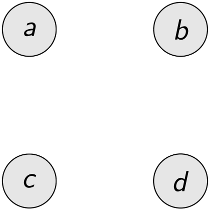

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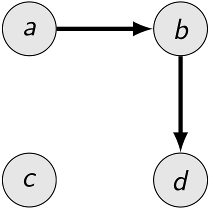

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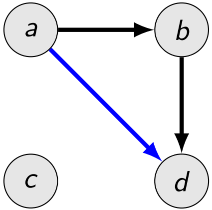

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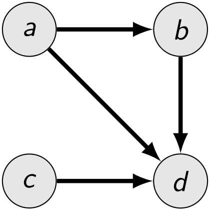

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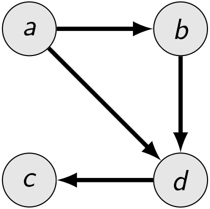

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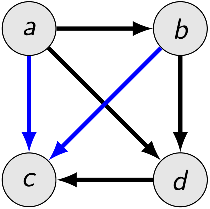

Suppose that $R \subseteq W \times W$ is a relation.

- R is *reflexive* provided that for all $w \in W$, wRw.
- R is *irreflexive* provided that for all $w \in W$, it is not the case that wRw.
- R is *symmetric* provided that for all $w, v \in W$, if wRv then vRw.
- R is *transitive* provided that for all $w, v, x \in W$, if wRv and vRx then wRx.

Suppose that $R \subseteq W \times W$ is a relation.

- R is *complete* provided that for all $w, v \in W$, wRv or vRw (or both).
- R is *serial* provided that for all $w \in W$, there is a $v \in W$ such that wRv
- R is *anti-symmetric* provided that for all $w, v \in W$, if wRv and vRw, then $w = v$.
- R is *Euclidean* provided that for all $w, v, x \in W$, if wRv and wRx then vRx.

Relational Structure

A **relational structure** is a tuple $\langle W, R\rangle$ where $W \neq \emptyset$ and $R \subseteq W \times W$ is a relation.

- Elements of the domain W are called *states*, *possible worlds*, *points*, or *nodes*.
- R is called the *accessibility relation* or the *edge relation*. When wRv we say "w can see v" or "v is accessible from w".
- For $w \in W$, let $R(w) = \{v \mid wRv\}$.

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Warning: Although a relational structure with labels is just a relational structure (with a binary relation and multiple unary relations), they have a specific interpretation in the theory of modal logic.

Examples

- Epistemic models
- Temporal models
- Transition systems
- Social networks
- Other examples (see [ML], Section 1.1)

Muddy Children

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Assume:

- There are three children: Ann, Bob and Charles.
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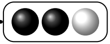
state-of-affairs



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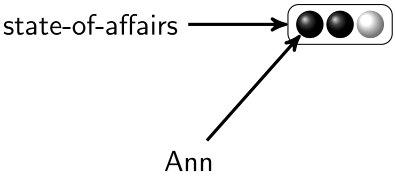

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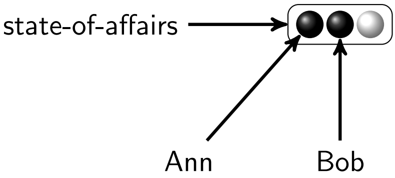

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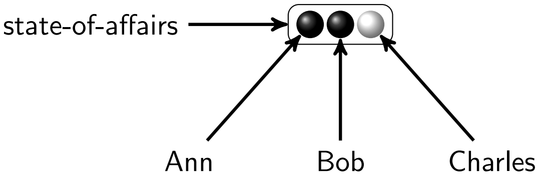

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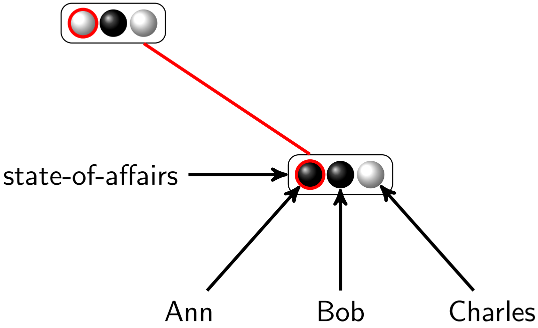

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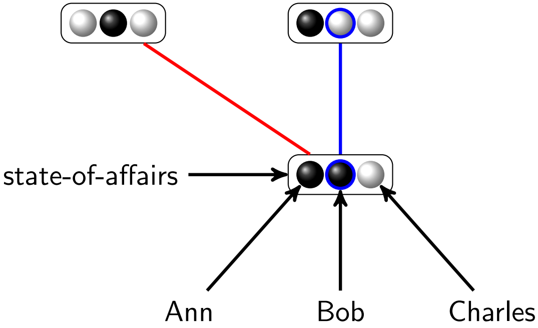

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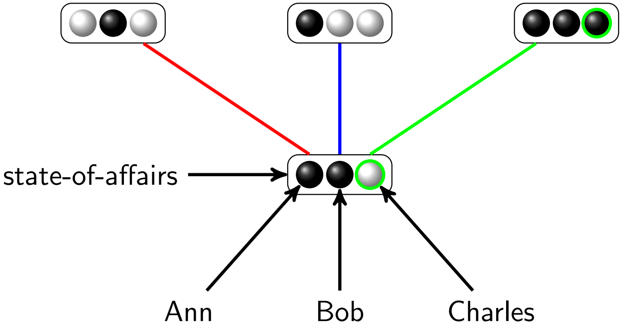

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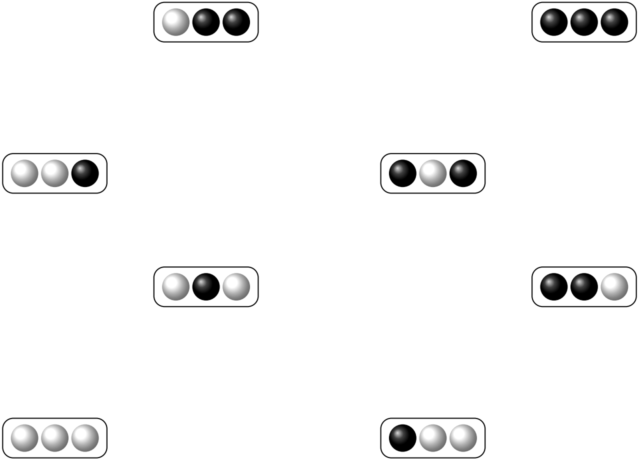
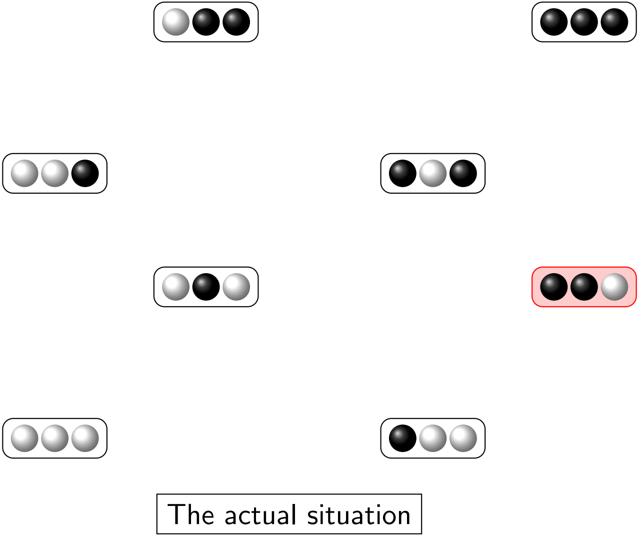


All 8 possible situations

Muddy Children



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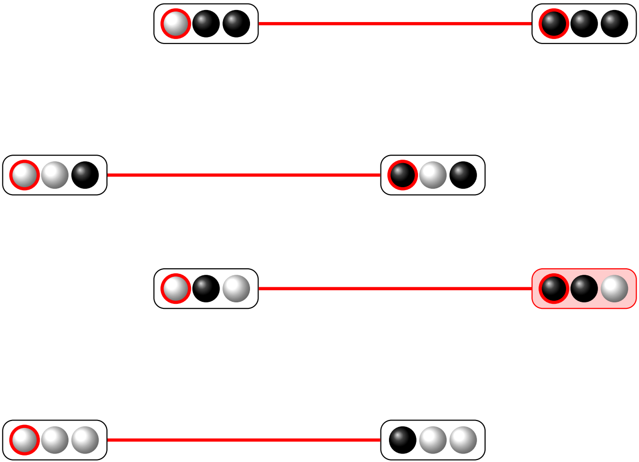
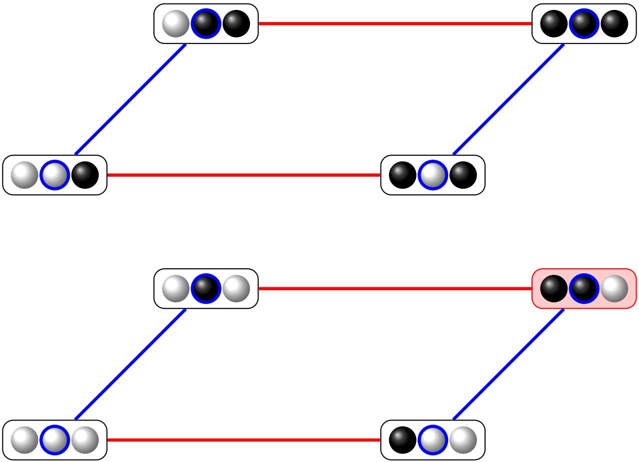


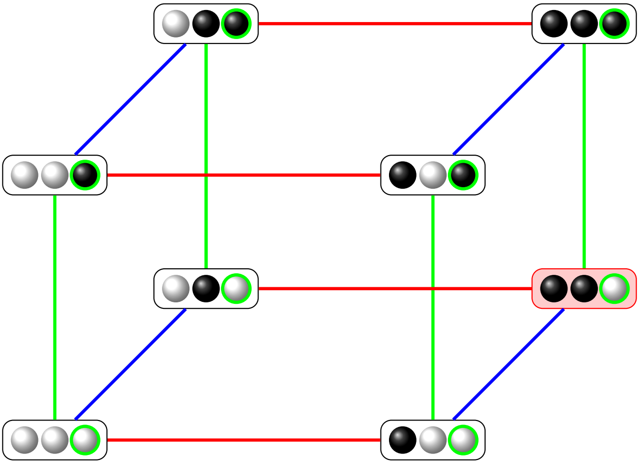
Ann's uncertainty

Muddy Children



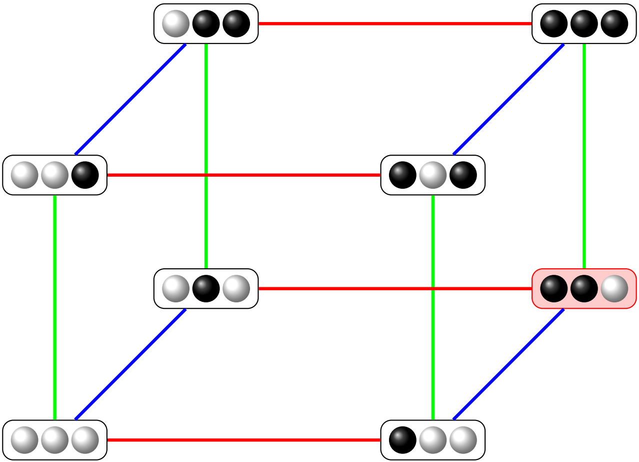
Bob's uncertainty

Muddy Children



Charles' uncertainty

Muddy Children



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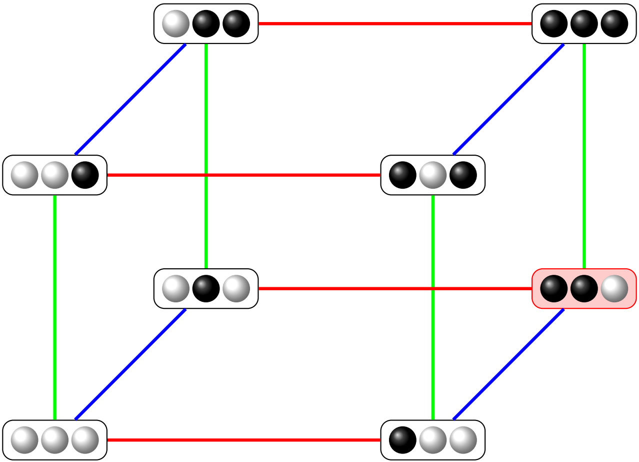

None of the children know if they are muddy

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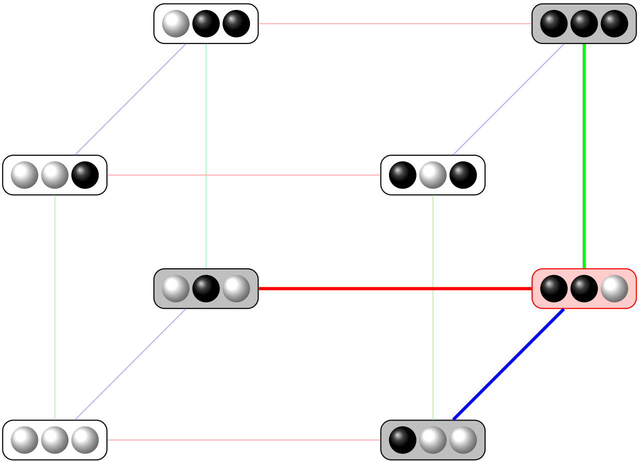

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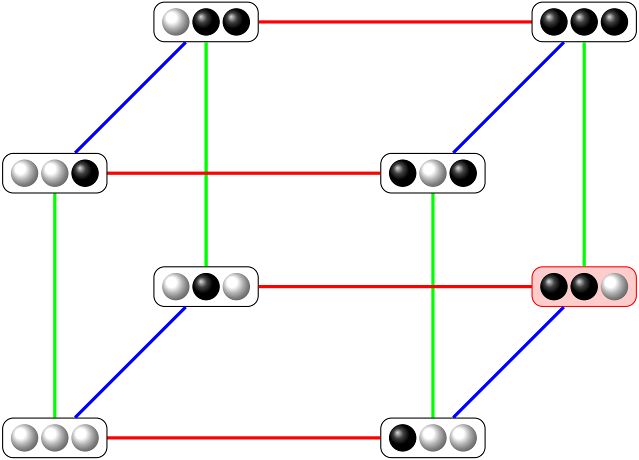
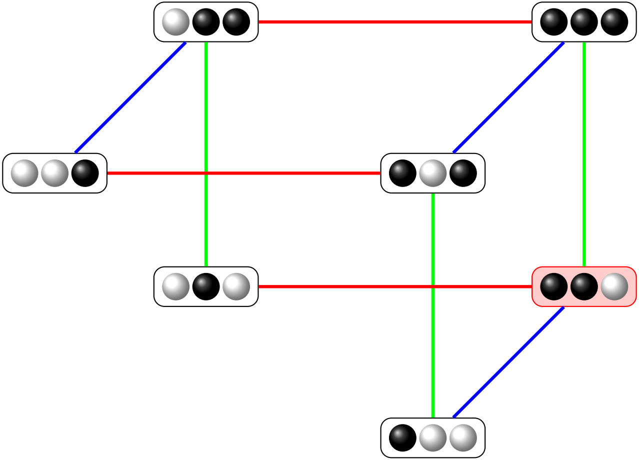


“At least one has mud on their forehead.”

Muddy Children



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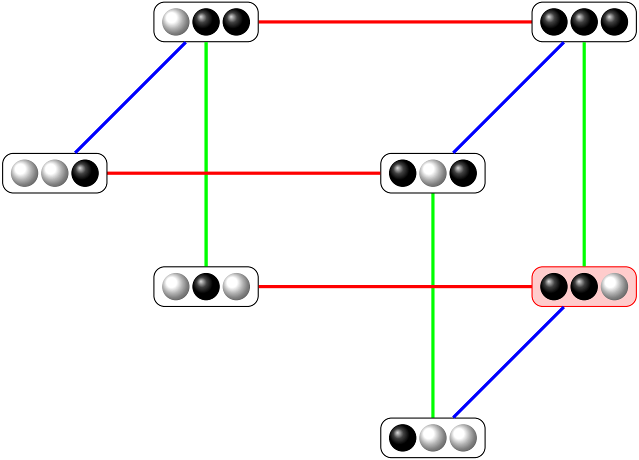

“Who has mud on their forehead?”

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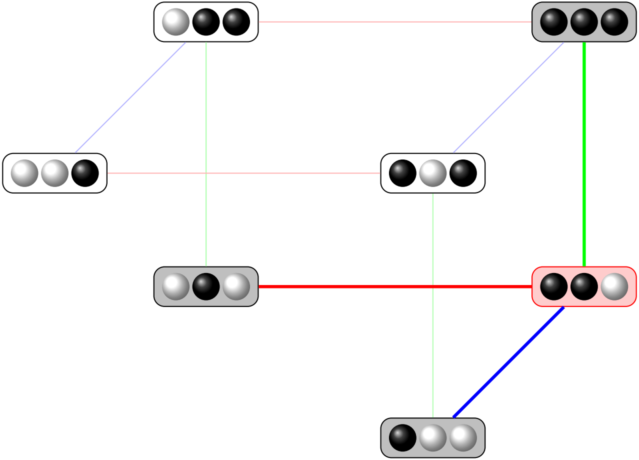

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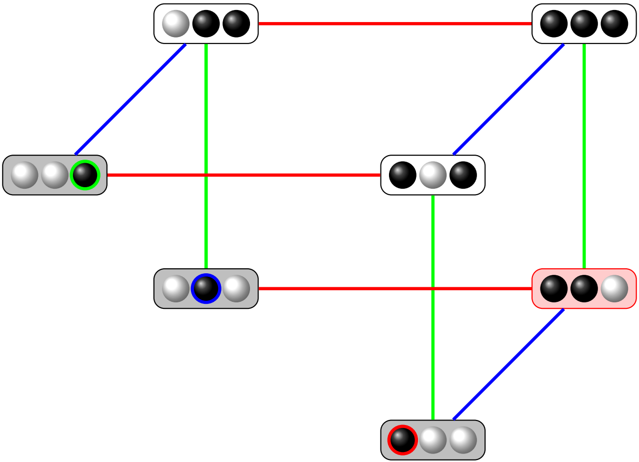
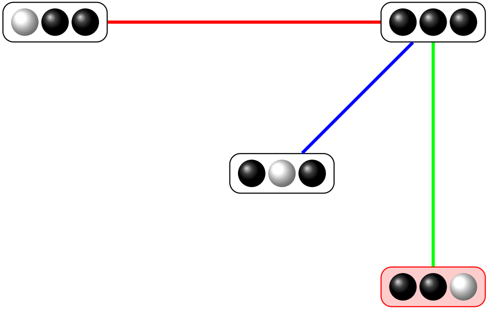


No one steps forward.

Muddy Children



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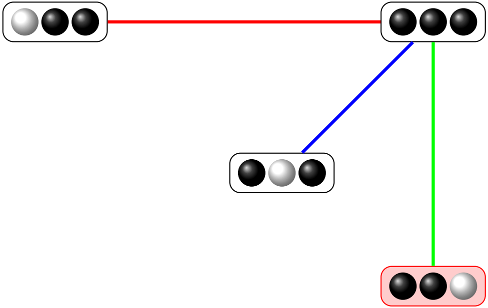

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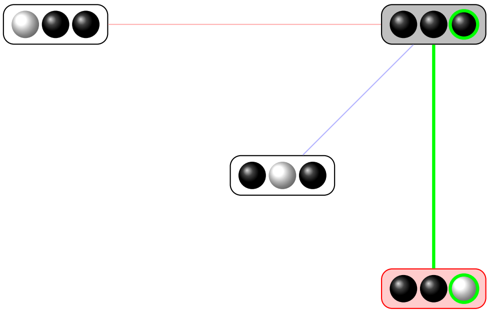
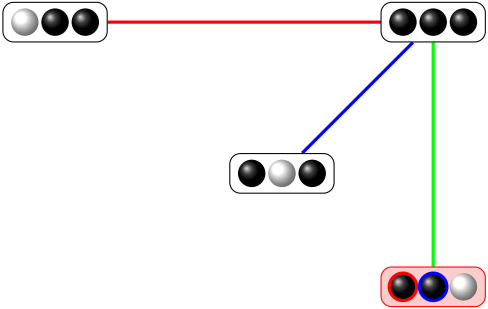


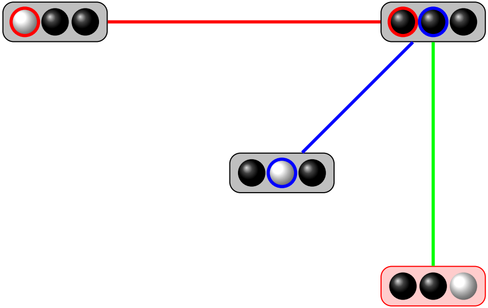
Charles does not know he is clean.

Muddy Children



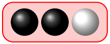
Ann and Bob step forward.

Muddy Children



Now, Charles knows he is clean.

Muddy Children



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Time

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Many variations

- discrete or continuous
- branching or linear
- point based or interval based

V. Goranko and A. Galton. *Temporal Logic*. Stanford Encyclopedia of Philosophy: `http://plato.stanford.edu/entries/logic-temporal/`.

I. Hodkinson and M. Reynolds. *Temporal Logic*. Handbook of Modal Logic, 2008.

Models of Time

$\mathcal{T} = \langle T, < \rangle$ where

- T is a set of **time points** (or **moments**),
- $< \subseteq T \times T$ is the **precedence relation**: $s < t$ means “time point s precedes time point t (or s occurs earlier than t)” and

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Examples: $\langle \mathbb{N}, < \rangle$, $\langle \mathbb{Z}, < \rangle$, $\langle \mathbb{Q}, < \rangle$, $\langle \mathbb{R}, < \rangle$

Other properties of $<$

- **Linearity**: for all $s, t \in T$, $s < t$ or $s = t$ of $t < s$
- **Past-linear**: for all $s, x, y \in T$, if $x < s$ and $y < s$, then either $x < y$ or $x = y$ or $y < x$
- **Denseness** for all $s, t \in T$, if $s < t$ then there is a $z \in T$ such that $s < z$ and $z < t$
- **Discreteness**: for all $s, t \in T$, if $s < t$ then there is a z such that ($s < z$ and there is no u such that $s < u$ and $u < z$)

Branching Time

Each moment $t \in T$ can be decided into the $Past(t) = \{s \in T \mid s < t\}$ and the $Future(t) = \{s \in T \mid t < s\}$

Typically, it is assumed that the past is linear, but the future may be branching.

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$F\varphi$: "it will be the case that φ"

φ will be the case "in the case in the actual course of events" or "no matter what course of events"

Branching Time Logics

A **branch** b in $\langle T, < \rangle$ is a maximal linearly ordered subset of T

$s \in T$ is **on a branch** b **of** T provided $s \in b$ (we also say "b is a branch going through t").

Temporal Logics

Temporal Logics

- *Linear Time Temporal Logic*: Reasoning about computation paths:

  $F\varphi$: φ is true some time in *the* future.

A. Pnuelli. *A Temporal Logic of Programs*. in *Proc. 18th IEEE Symposium on Foundations of Computer Science* (1977).

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- *Branching Time Temporal Logic*: Allows quantification over paths:

  $\exists F\varphi$: there is a path in which φ is eventually true.

E. M. Clarke and E. A. Emerson. *Design and Synthesis of Synchronization Skeletons using Branching-time Temporal-logic Specifications*. In *Proceedings Workshop on Logic of Programs*, LNCS (1981).

Interval Values

J. Allen and G. Ferguson. *Actions and Events in Interval Temporal Logics*. Journal of Logic and Computation, 1994.

J. Halpern and Y. Shoham. *A Propositional Modal Logic of Time Intervals*. Journal of the ACM, 38:4, pp. 935 - 962, 1991.

J. van Benthem. *Logics of Time*. Kluwer, 1991.

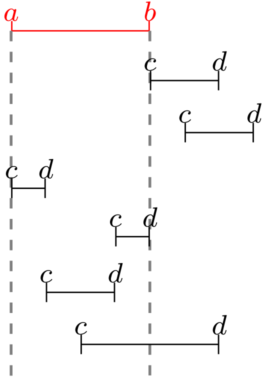
Interval Temporal Logics

Let $\mathcal{T} = \langle T, < \rangle$ be a frame and $I(\mathcal{T}) = \{[a, b] \mid a, b \in T \text{ and } a \leq b\}$ be the set of intervals over T

Interval-based relational structure: $\langle I(\mathcal{T}), \{R_X\} \rangle$ where $R_X \subseteq I(\mathcal{T}) \times I(\mathcal{T})$.

Interval Temporal Logics

$\langle A \rangle$	$[a,b] R_A [c,d] \Leftrightarrow b = c$
$\langle L \rangle$	$[a,b] R_L [c,d] \Leftrightarrow b < c$
$\langle B \rangle$	$[a,b] R_B [c,d] \Leftrightarrow a = c, d < b$
$\langle E \rangle$	$[a,b] R_E [c,d] \Leftrightarrow b = d, a < c$
$\langle D \rangle$	$[a,b] R_D [c,d] \Leftrightarrow a < c, d < b$
$\langle O \rangle$	$[a,b] R_O [c,d] \Leftrightarrow a < c < b < d$



Actions

1. Actions as *transitions between states, or situations*:

Actions

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$$s \xrightarrow{a} t$$

Actions

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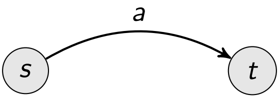
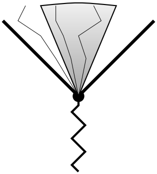
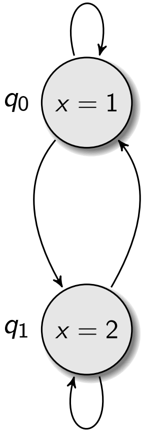
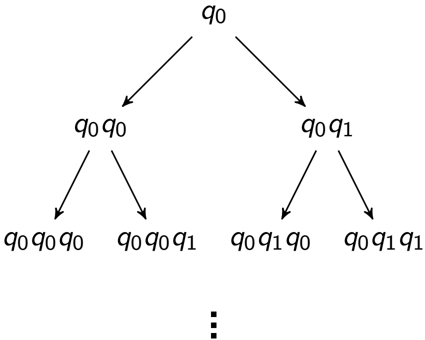


2. Actions *restrict* the set of possible future histories.



Computational vs. Behavioral Structures

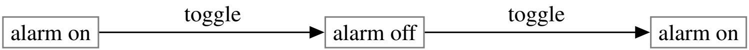




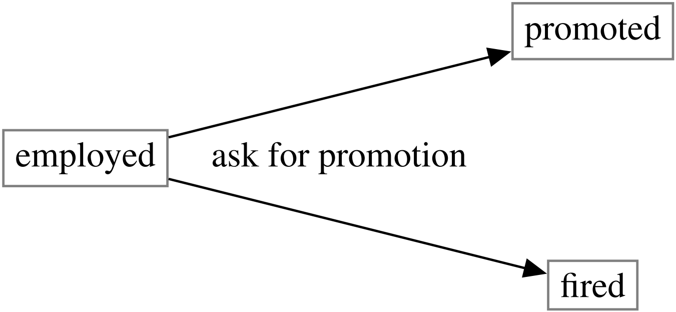
Examples

Examples


alarm on
toggle
alarm off


alarm on
toggle
alarm off
toggle
alarm on

Examples



Programs

Act is a set of *primitive actions*, or *programs*

A program is generated by the following grammar:

$$a \mid \alpha;\beta \mid \alpha \cup \beta \mid \alpha^*$$

- $\alpha;\beta$: concatenation, do α then β
- $\alpha \cup \beta$: non-deterministic choice: choose to execute α or β
- α^*: iteration: execute α some finite number of times.

Propositional Dynamic Logic

$\langle W, \{R_a\}_{a \in \mathsf{Act}} \rangle$

If α is a program, then $R_\alpha \subseteq W \times W$ where $wR_\alpha v$ means executing α in state w leads to state v.

Propositional Dynamic Logic

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If α is a program, then $R_\alpha \subseteq W \times W$ where $wR_\alpha v$ means executing α in state w leads to state v.

$R_{\alpha;\beta} = R \circ R = \{(w, v) \mid \text{ there is a } u \text{ such that } wR_\alpha u \text{ and } uR_\beta v\}$

$R_{\alpha \cup \beta} = R_\alpha \cup R_\beta$

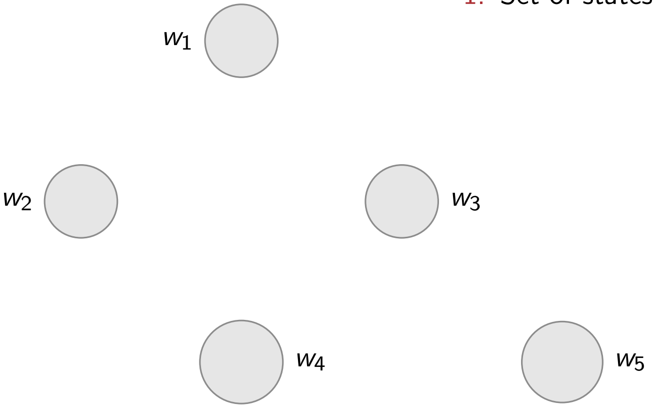
$R_{\alpha^*} = \cup_{n \geq 1} R_\alpha^n$, where $R^1 = R$ and $R^{n+1} = R \circ R^n$

D. Harel, D. Kozen and Tiuryn. *Dynamic Logic*. 2001.

Examples

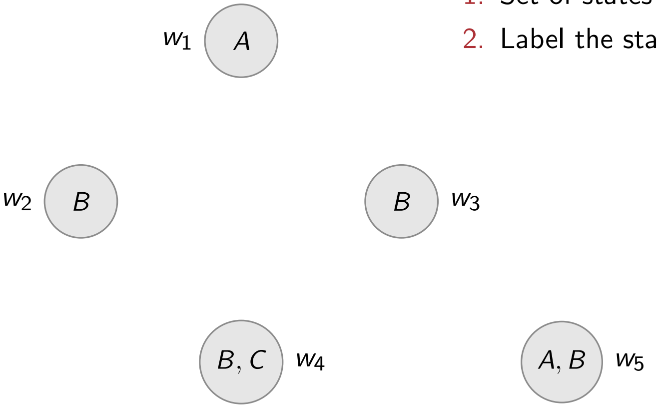
- ✓ Epistemic models
- ✓ Temporal models
- ✓ Transition systems
- Social networks
- Other examples (see [ML], Section 1.1)

Relational Model



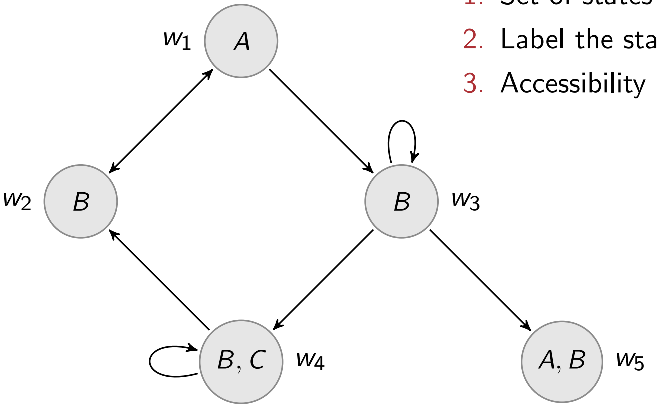
1. Set of states

Relational Model



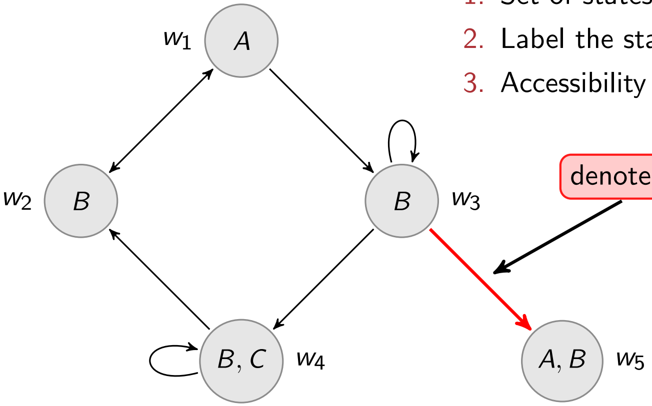
1. Set of states
2. Label the states

Relational Model



1. Set of states
2. Label the states
3. Accessibility relation

Relational Model



1. Set of states
2. Label the states
3. Accessibility relation

denoted $w_3 R w_5$

Frame: $\langle W, R\rangle$, where $W \neq \emptyset$ and $R \subseteq W \times W$

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Model: Suppose that $\mathcal{F} = \langle W, R \rangle$ is a frame. The tuple $\langle W, R, V \rangle$ is a **model based on** $\mathcal{F}$ where $V : \mathrm{At} \to \wp(W)$ is a **valuation function**.

- $w \in V(p)$ means that p is true at w.

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Pointed Model Suppose that $\mathcal{M} = \langle W, R, V\rangle$ is a model. If $w \in W$, then $(\mathcal{M}, w)$ is called a **pointed model**.

Truth of Modal Formulas

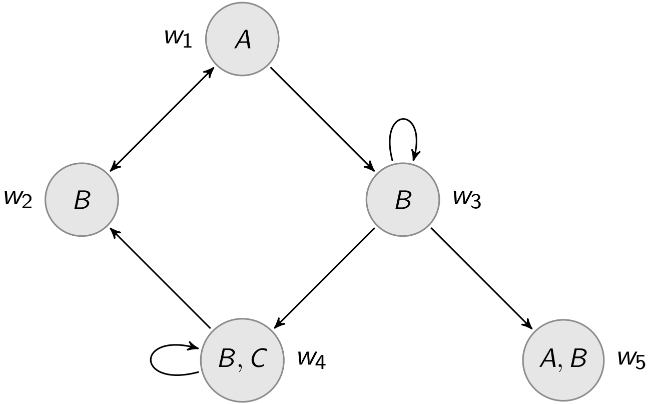
Suppose that $\mathcal{M} = \langle W, R, V \rangle$ is a model. Truth of a modal formula $\varphi \in \mathcal{L}(\mathrm{At})$ at a state w in $\mathcal{M}$, denoted $\mathcal{M}, w \models \varphi$, is defined as follows:

- $\mathcal{M}, w \models p$ iff $w \in V(p)$ (where $p \in \mathrm{At}$)
- $\mathcal{M}, w \not\models \bot$
- $\mathcal{M}, w \models \neg\varphi$ iff $\mathcal{M}, w \not\models \varphi$
- $\mathcal{M}, w \models \varphi \vee \psi$ iff $\mathcal{M}, w \models \varphi$ or $\mathcal{M}, w \models \psi$
- $\mathcal{M}, w \models \Diamond\varphi$ iff there is a $v \in W$ such that wRv and $\mathcal{M}, v \models \varphi$

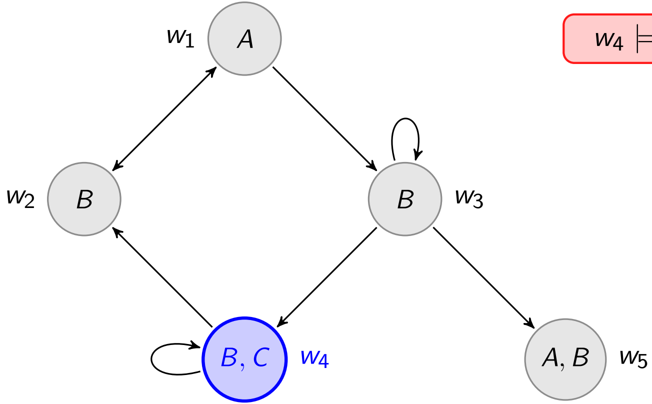
Truth of Modal Formulas

- $\mathcal{M}, w \models \varphi \wedge \psi$ iff $\mathcal{M}, w \models \varphi$ and $\mathcal{M}, w \models \psi$
- $\mathcal{M}, w \models \varphi \rightarrow \psi$ iff if $\mathcal{M}, w \models \varphi$, then $\mathcal{M}, w \models \psi$ iff either $\mathcal{M}, w \not\models \varphi$ or $\mathcal{M}, w \models \psi$
- $\mathcal{M}, w \models \Box\varphi$ iff for all $v \in W$, if wRv then $\mathcal{M}, v \models \varphi$

Example

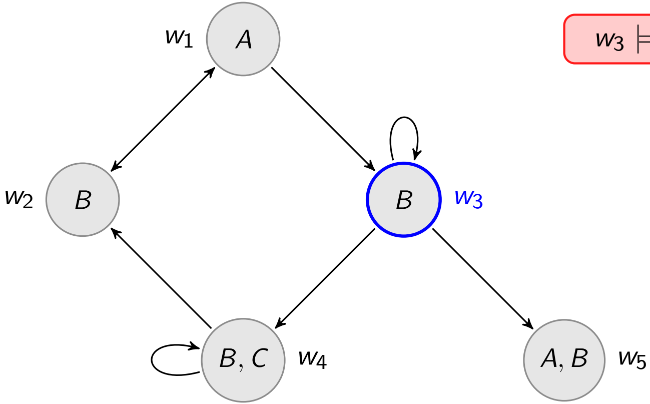


Example



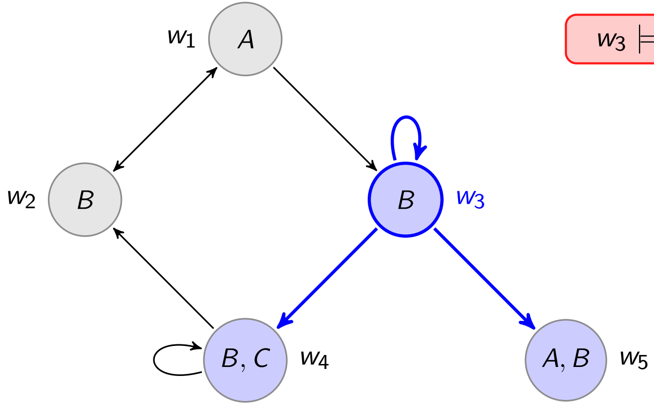
$w_4 \models B \wedge C$

Example



$w_3 \models \Box B$

Example



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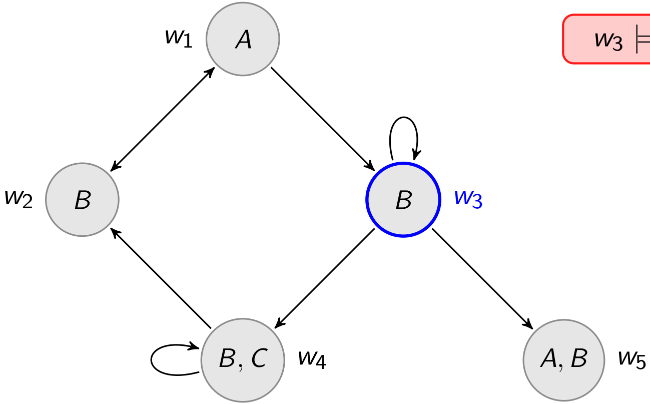
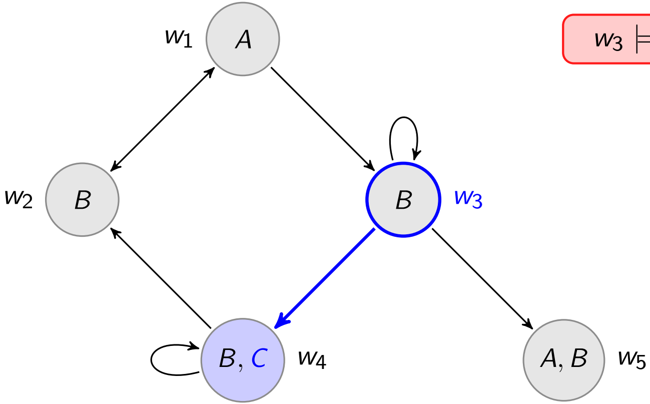
Example



$w_3 \models \Diamond C$

Example



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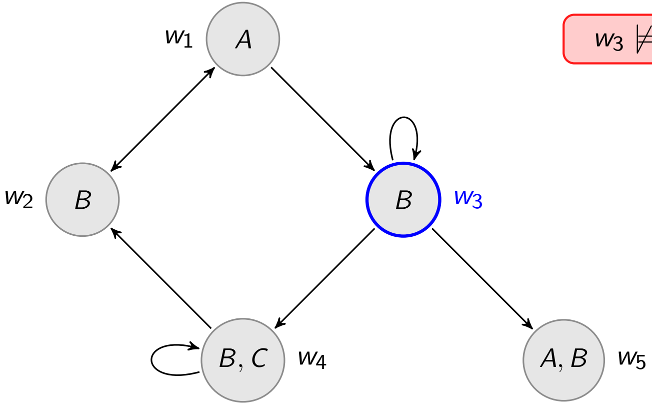
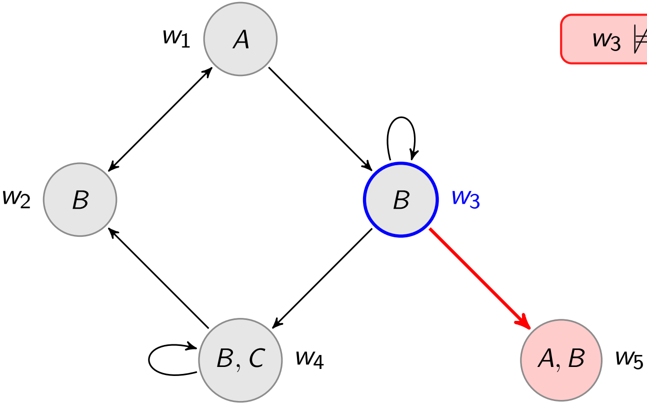
Example



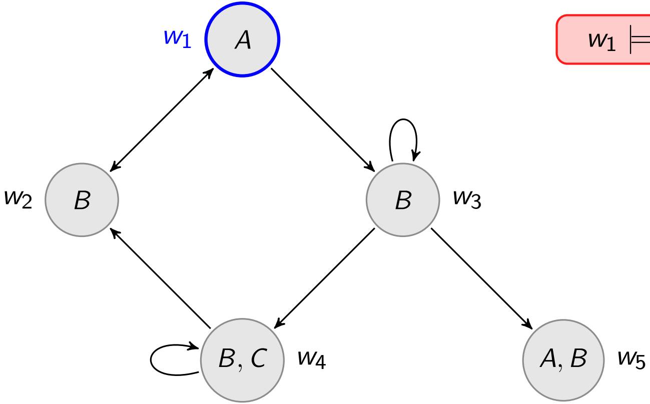
$w_3 \not\models \Box C$

Example



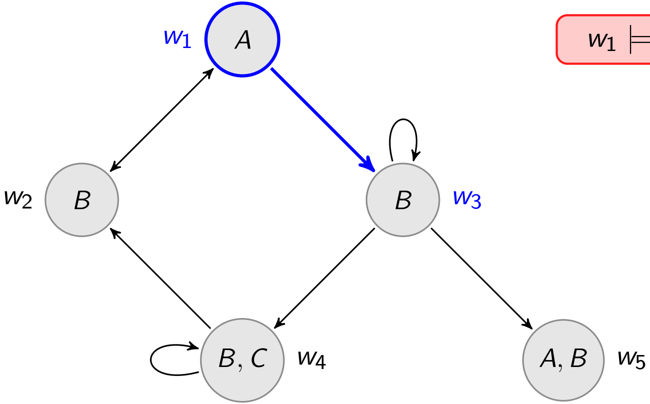
$w_3 \not\models \Box C$

Example



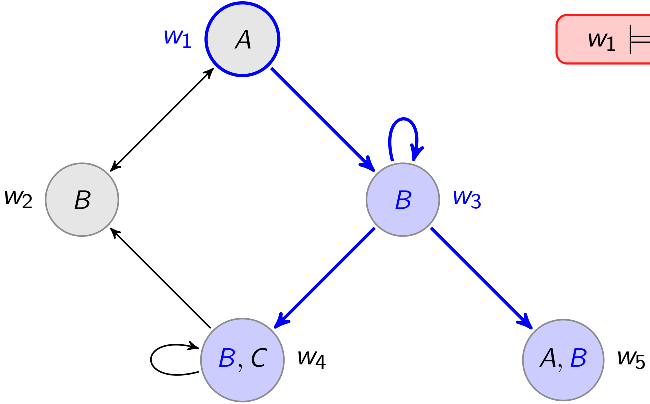
$w_1 \models \Diamond\Box B$

Example



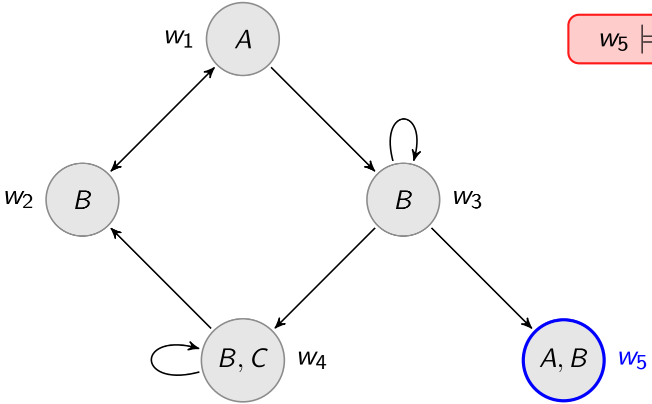
$w_1 \models \Diamond\Box B$

Example



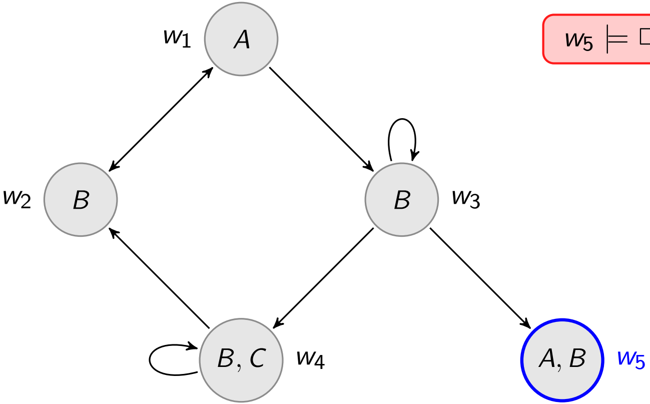
$w_1 \models \Diamond \Box B$

Example



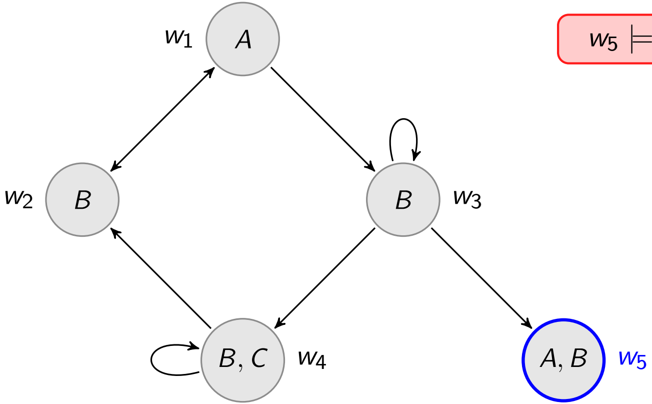
$w_5 \models \Box C$

Example

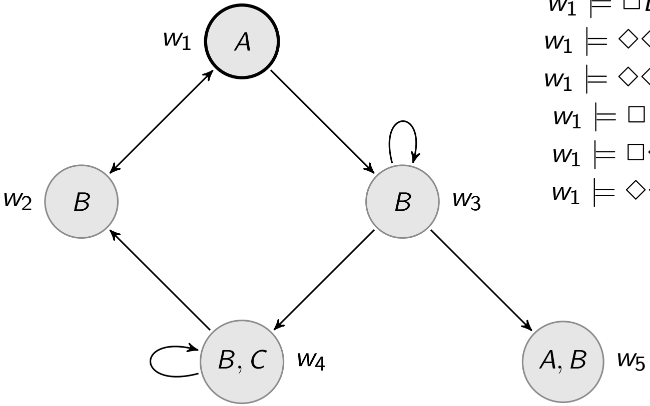


$w_5 \models \Box(B \wedge \neg B)$

Example



$w_5 \models \neg\Diamond B$



$w_1 \models \Box B \wedge B$?

$w_1 \models \Diamond\Diamond B$?

$w_1 \models \Diamond\Diamond\Diamond B$?

$w_1 \models \Box\Box B$?

$w_1 \models \Box\Diamond C$?

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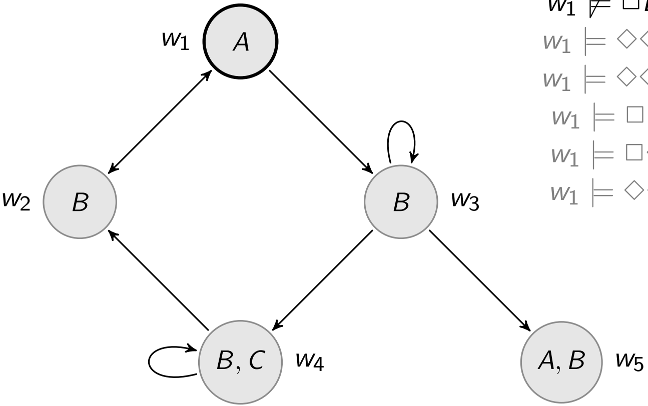

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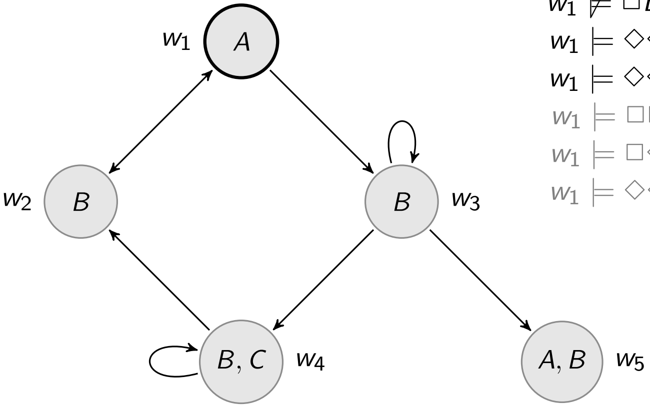

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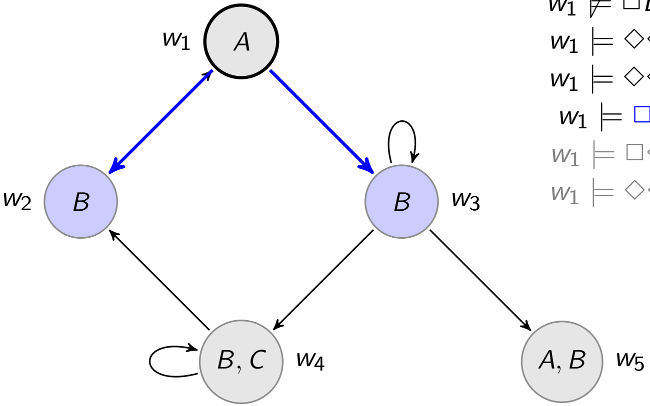

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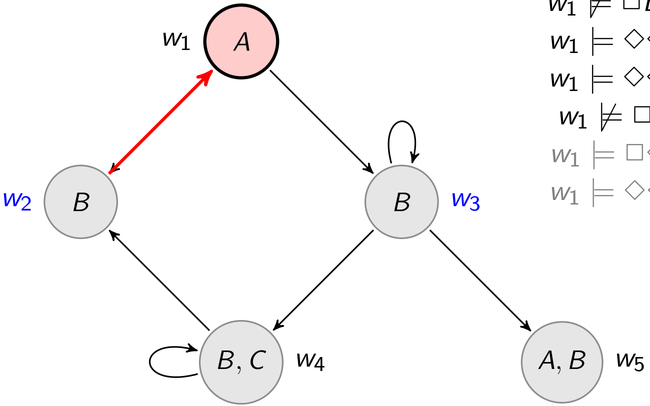

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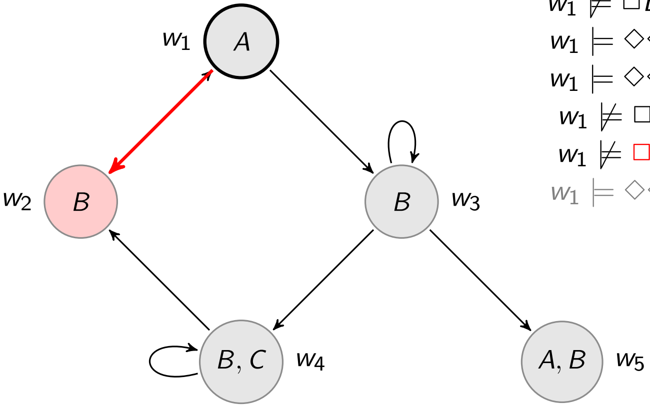

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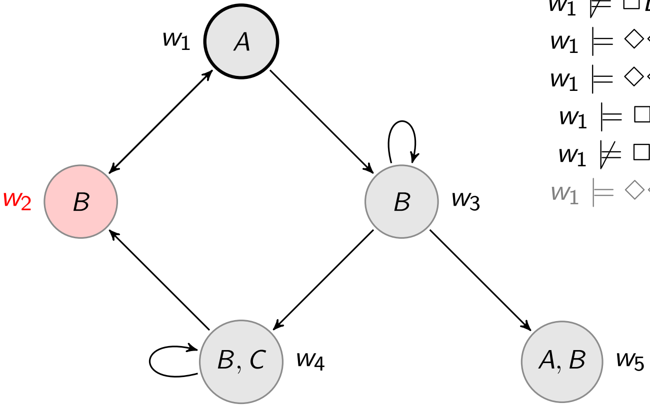

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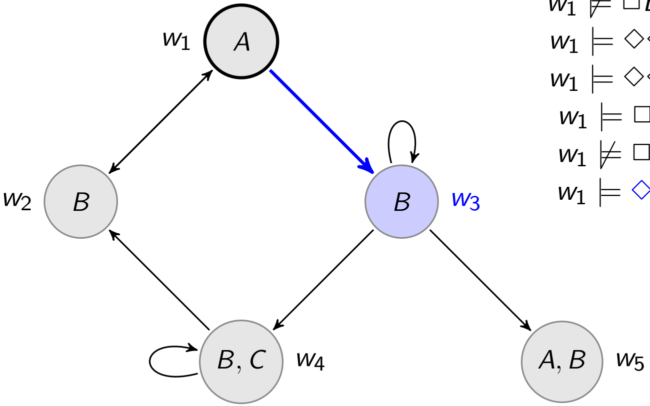

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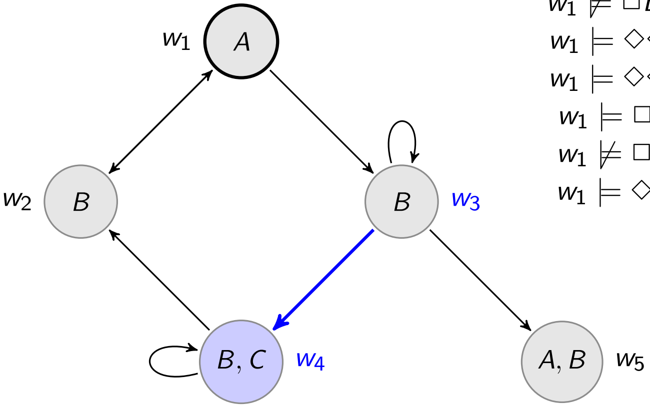

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$w_1 \not\models \Box\Diamond C$

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φ is **satisfiable** means that there is a model $\mathcal{M} = \langle W, R, V \rangle$ and $w \in W$ such that $\mathcal{M}, w \models \varphi$.

Validity

Valid on a model $\mathcal{M} = \langle W, V, R \rangle$

$\mathcal{M} \models \varphi$: for all $w \in W$, $\mathcal{M}, w \models \varphi$

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for all functions V, for all $w \in W$, $\langle W, R, V\rangle, w \models \varphi$

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for all functions V, for all $w \in W$, $\langle W, R, V \rangle, w \models \varphi$

Valid at a state on a frame $\mathcal{F} = \langle W, R \rangle$ with $w \in W$

$\mathcal{F}, w \models \varphi$: for all $\mathcal{M}$ based on $\mathcal{F}$, $\mathcal{M}, w \models \varphi$

Validity

Valid on a model $\mathcal{M} = \langle W, V, R \rangle$

$\mathcal{M} \models \varphi$: for all $w \in W$, $\mathcal{M}, w \models \varphi$

Valid on a frame $\mathcal{F} = \langle W, R \rangle$

$\mathcal{F} \models \varphi$: for all $\mathcal{M}$ based on $\mathcal{F}$, for all $w \in W$, $\mathcal{M}, w \models \varphi$
for all functions V, for all $w \in W$, $\langle W, R, V \rangle, w \models \varphi$

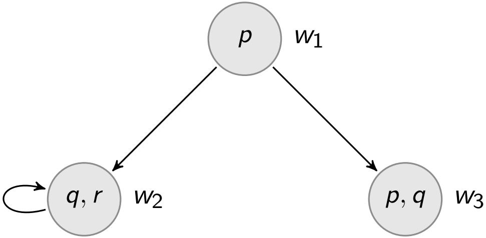
Valid at a state on a frame $\mathcal{F} = \langle W, R \rangle$ with $w \in W$

$\mathcal{F}, w \models \varphi$: for all $\mathcal{M}$ based on $\mathcal{F}$, $\mathcal{M}, w \models \varphi$

Valid in a class F of frames:

$\models_{\mathsf{F}} \varphi$: for all $\mathcal{F} \in \mathsf{F}$, $\mathcal{F} \models \varphi$

Model validity



$$\mathcal{M} \models \Box q$$

validity on a model is *not* closed under substitution ($\mathcal{M} \not\models \Box p$)

Frame validity

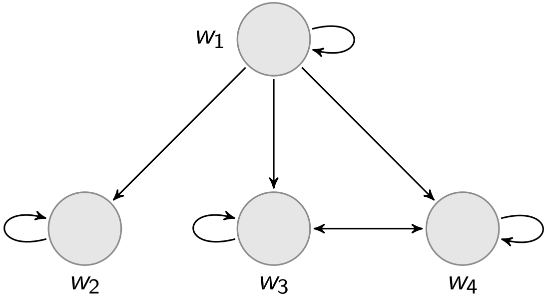
Some frame validities:

- $(\Box q \wedge \Box q) \rightarrow \Box(p \wedge q)$
- $\Box\top$
- $\Box p \leftrightarrow \neg\Diamond\neg p$
- $\Box(p \rightarrow q) \rightarrow (\Box p \rightarrow \Box q)$

Some frame non-validities:

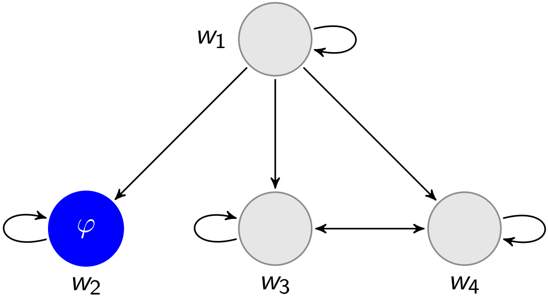
- $\Box p \vee \Box\neg p$ (compare with the validity $\Box p \vee \neg\Box p$)
- $(\Diamond p \wedge \Diamond q) \rightarrow \Diamond(p \wedge q)$
- $\Box(p \vee q) \rightarrow (\Box p \vee \Box q)$
- $\Box p \rightarrow p$

Valid at a state



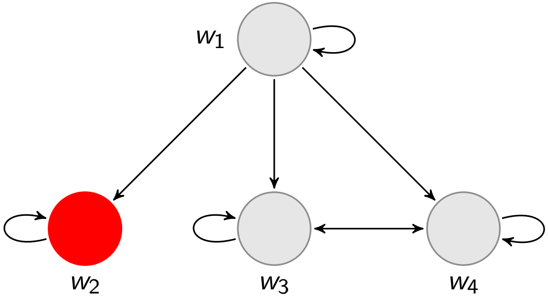
$$\mathcal{F}, w_1 \models \Box\Diamond\varphi \rightarrow \Diamond\Box\varphi$$

Valid at a state



$$\boxed{\mathcal{F}, w_1 \models \Box\Diamond\varphi \to \Diamond\Box\varphi}$$

Valid at a state



$$\mathcal{F}, w_1 \models \Box\Diamond\varphi \to \Diamond\Box\varphi$$

Propositional Dynamic Logic

Let Act be a set of atomic programs and At a set of atomic propositions.

Formulas of **PDL** have the following syntactic form:

$$\varphi := p \mid \bot \mid \neg\varphi \mid \varphi \vee \psi \mid [\alpha]\varphi$$

$$\alpha := a \mid \alpha \cup \beta \mid \alpha ; \beta \mid \alpha^* \mid \varphi ?$$

where $p \in \mathrm{At}$ and $a \in \mathrm{Act}$.

$[\alpha]\varphi$ is intended to mean "after executing the program α, φ is true"

Propositional Dynamic Logic

Semantics: $\mathcal{M} = \langle W, \{R_a \mid a \in \mathsf{P}\}, V \rangle$ where for each $a \in \mathsf{P}$, $R_a \subseteq W \times W$ and $V : \mathsf{At} \to \wp(W)$

- $R_{\alpha \cup \beta} := R_\alpha \cup R_\beta$
- $R_{\alpha;\beta} := R_\alpha \circ R_\beta$
- $R_{\alpha^*} := \cup_{n \geq 0} R_\alpha^n$
- $R_{\varphi?} = \{(w, w) \mid \mathcal{M}, w \models \varphi\}$

$$\mathcal{M}, w \models [\alpha]\varphi \text{ iff for each } v \text{, if } wR_\alpha v \text{ then } \mathcal{M}, v \models \varphi$$

Propositional Dynamic Logic

Some validities:

1. $[\alpha \cup \beta]\varphi \leftrightarrow [\alpha]\varphi \wedge [\beta]\varphi$
2. $[\alpha; \beta]\varphi \leftrightarrow [\alpha][\beta]\varphi$
3. $[\psi?]\varphi \leftrightarrow (\psi \to \varphi)$
4. $\varphi \wedge [\alpha][\alpha^*]\varphi \leftrightarrow [\alpha^*]\varphi$
5. $\varphi \wedge [\alpha^*](\varphi \to [\alpha]\varphi) \to [\alpha^*]\varphi$

Propositional Dynamic Logic

Some validities:

1. $[\alpha \cup \beta]\varphi \leftrightarrow [\alpha]\varphi \wedge [\beta]\varphi$

2. $[\alpha; \beta]\varphi \leftrightarrow [\alpha][\beta]\varphi$

3. $[\psi?]\varphi \leftrightarrow (\psi \rightarrow \varphi)$

4. $\varphi \wedge [\alpha][\alpha^*]\varphi \leftrightarrow [\alpha^*]\varphi$ (Fixed-Point Axiom)

5. $\varphi \wedge [\alpha^*](\varphi \rightarrow [\alpha]\varphi) \rightarrow [\alpha^*]\varphi$ (Induction Axiom)

Logical consequence

Suppose that Γ is a set of formulas and F is a set of frames. We write $\mathcal{M}, w \models \Gamma$ iff $\mathcal{M}, w \models \alpha$ for all $\alpha \in \Gamma$.

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Local: $\Gamma \models_{\mathsf{F}} \varphi$ iff for all frames $\mathcal{F} \in \mathsf{F}$, for all models $\mathcal{M}$ based on $\mathcal{F}$ and all states w in $\mathcal{M}$, $\mathcal{M}, w \models \Gamma$ implies $\mathcal{M}, w \models \varphi$

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Global: $\Gamma \models^{g}_{\mathsf{F}} \varphi$ iff for all frames $\mathcal{F} \in \mathsf{F}$, for all models $\mathcal{M}$ based on $\mathcal{F}$, $\mathcal{M} \models \Gamma$ implies $\mathcal{M} \models \varphi$

$$\{p\} \models^{g} \Box p \qquad\qquad \{p\} \not\models \Box p$$

Definability

Suppose that $\mathcal{M} = \langle W, R, V \rangle$ is a relational model.

$[\![\cdot]\!]_{\mathcal{M}} : \mathcal{L} \to \wp(W)$ defined as $[\![\varphi]\!]_{\mathcal{M}} = \{w \mid \mathcal{M}, w \models \varphi\}$.

$$\begin{array}{rcl}
[\![p]\!]_{\mathcal{M}} & = & V(p) \\
[\![\neg\varphi]\!]_{\mathcal{M}} & = & W - [\![\varphi]\!]_{\mathcal{M}} \\
[\![\varphi \wedge \psi]\!]_{\mathcal{M}} & = & [\![\varphi]\!]_{\mathcal{M}} \cap [\![\psi]\!]_{\mathcal{M}} \\
[\![\Box\varphi]\!]_{\mathcal{M}} & = & m_R([\![\varphi]\!]_{\mathcal{M}}) \\
 & & \text{where } m_R(X) = \{w \mid R(w) \subseteq X\}
\end{array}$$

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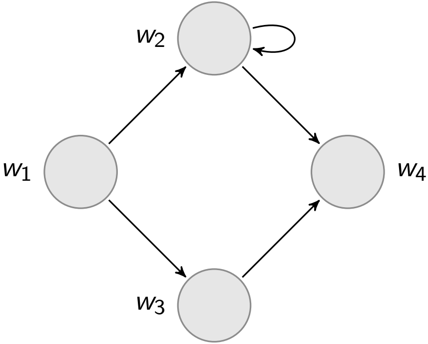
 & & \text{where } m_R(X) = \{w \mid R(w) \subseteq X\}
\end{array}
$$

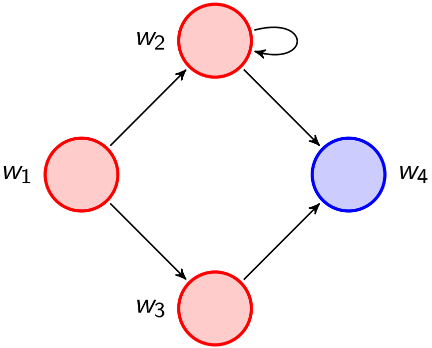
$X \subseteq W$ is **definable** by modal formula if there is some $\varphi \in \mathcal{L}$ such that $X = [\![\varphi]\!]_{\mathcal{M}}$.

Defining States



- $\{w_4\} =$
- $\{w_3\} =$
- $\{w_2\} =$
- $\{w_1\} =$

Defining States



- $\{w_4\} = [\![\Box\bot]\!]$
- $\{w_3\} =$
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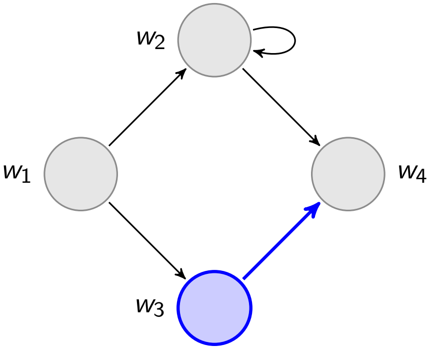
Defining States



- $\{w_4\} = [\![\Box\bot]\!]$
- $\{w_3\} = [\![\Diamond\Box\bot \wedge \Box\Box\bot]\!]$
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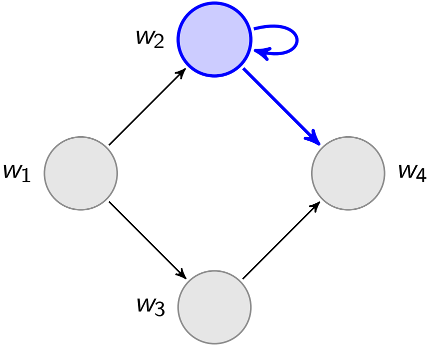
Defining States



- $\{w_4\} = [\![\Box\bot]\!]$
- $\{w_3\} = [\![\Diamond\Box\bot \land \Box\Box\bot]\!]$
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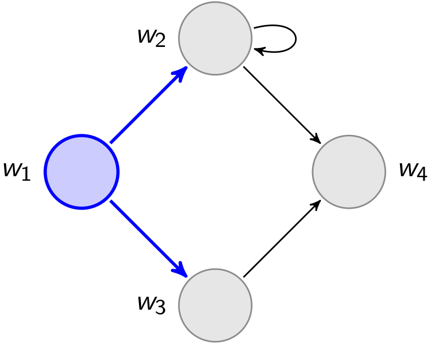
- $\{w_1\} =$

Defining States



- $\{w_4\} = [\![\Box\bot]\!]$
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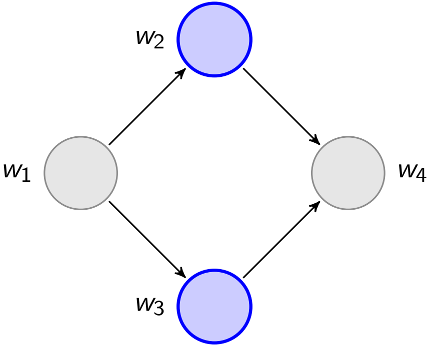
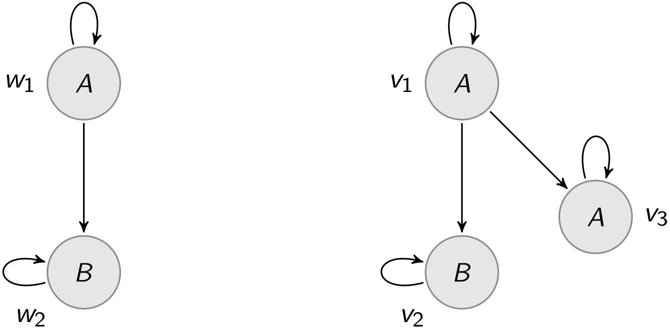
Defining States



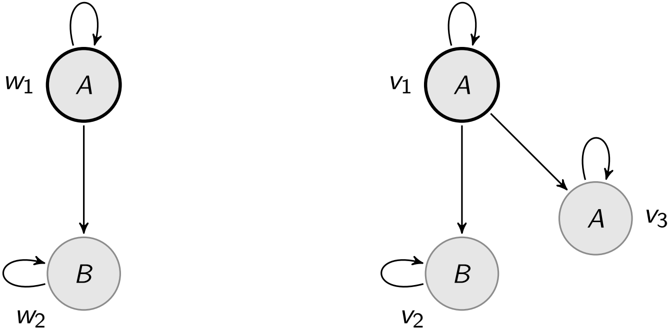
- $\{w_4\} = [\![\Box\bot]\!]$
- $\{w_2, w_3\} = [\![\Diamond\Box\bot \wedge \Box\Box\bot]\!]$
- $\{w_1\} = [\![\Diamond(\Diamond\Box\bot \wedge \Box\Box\bot)]\!]$

Distinguishing States



What is the difference between states w_1 and v_1?

Distinguishing States



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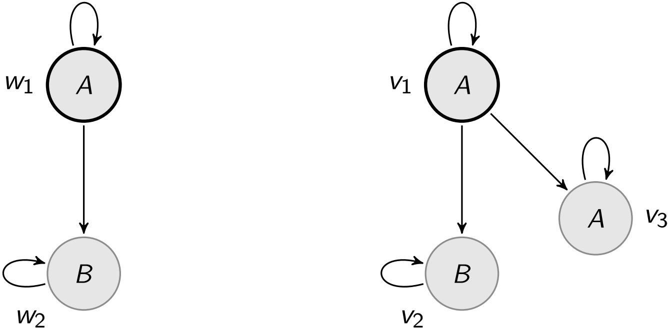
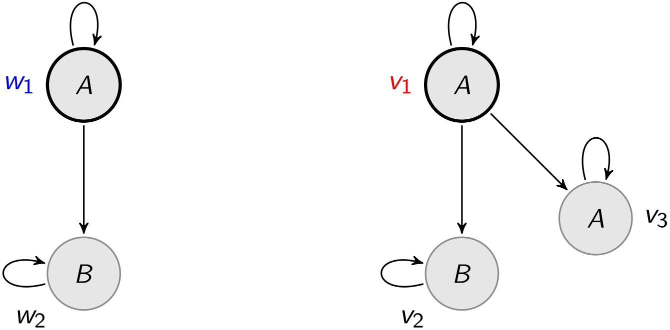


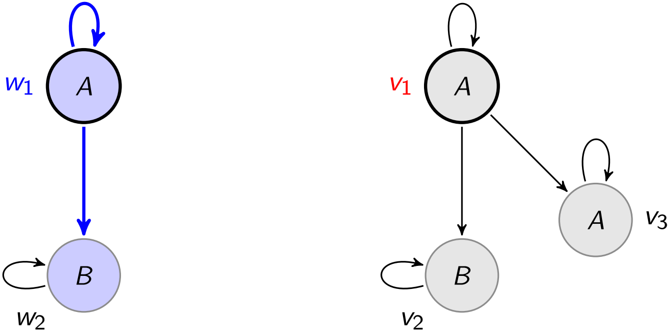
Is there a modal formula true at w_1 but not at v_1?

Distinguishing States



$w_1 \models \Box\Diamond\neg A$ but $v_1 \not\models \Box\Diamond\neg A$.

Distinguishing States



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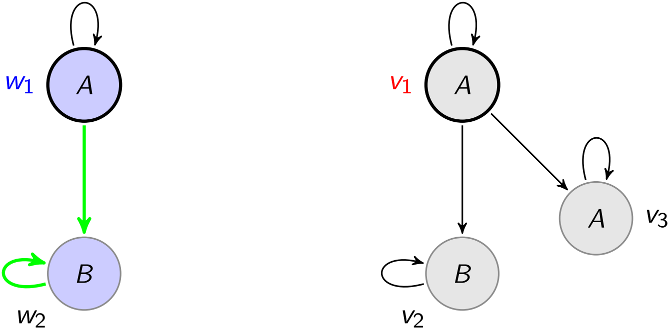

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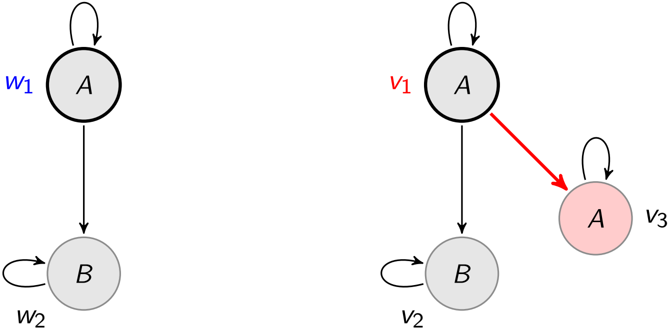

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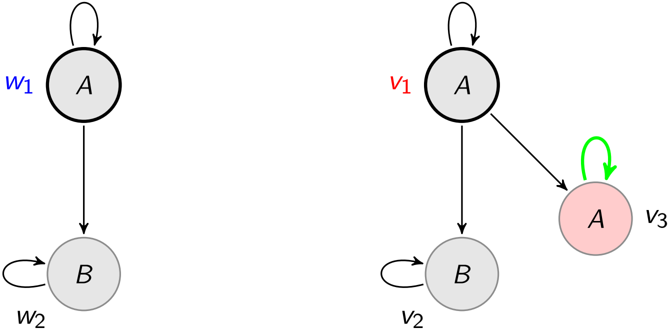

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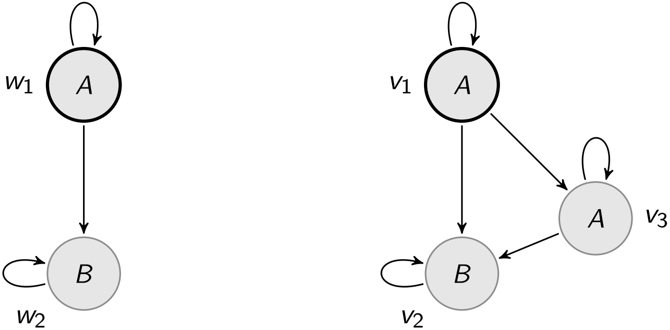
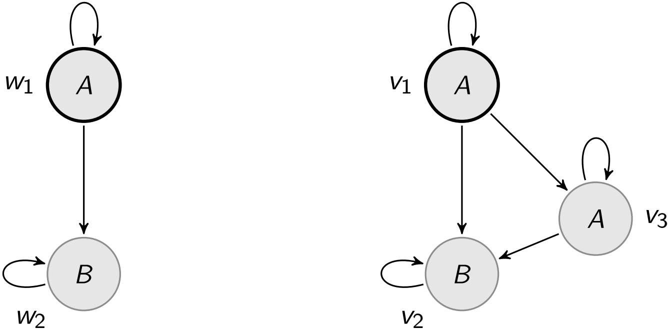


What about now? Is there a modal formula true at w_1 but not v_1?

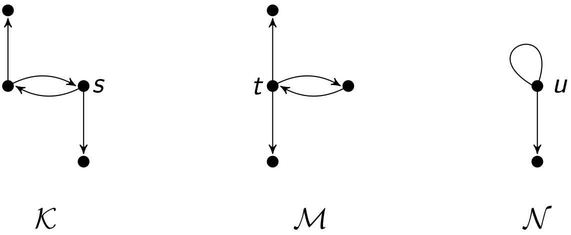
Distinguishing States



No modal formula can distinguish w_1 and v_1!

A More Complicated Example

Which pair of states cannot be distinguished by a modal formula?



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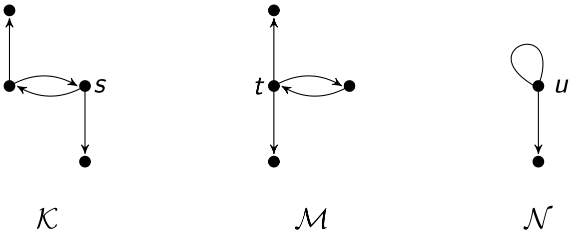

$$\Box(\Box\bot \vee \Diamond\Box\bot)$$

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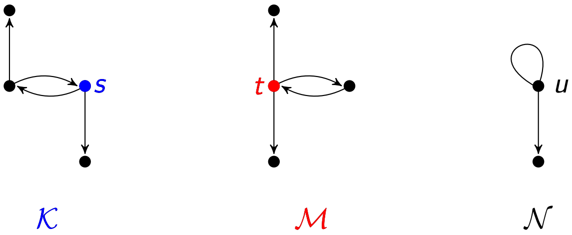

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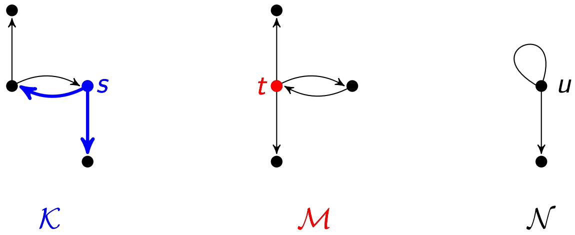

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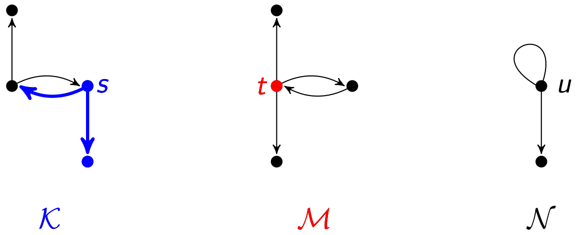

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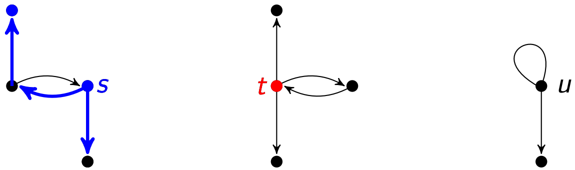
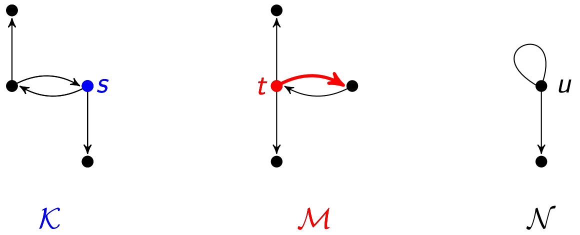


$\mathcal{K}$ $\mathcal{M}$ $\mathcal{N}$

$\Box(\Box\bot \vee \Diamond\Box\bot)$

A More Complicated Example

Which pair of states cannot be distinguished by a modal formula?



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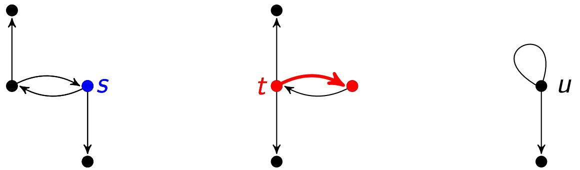

$\mathcal{K}$ $\qquad$ $\mathcal{M}$ $\qquad$ $\mathcal{N}$

$\Box(\Box\bot \vee \Diamond\Box\bot)$

A More Complicated Example

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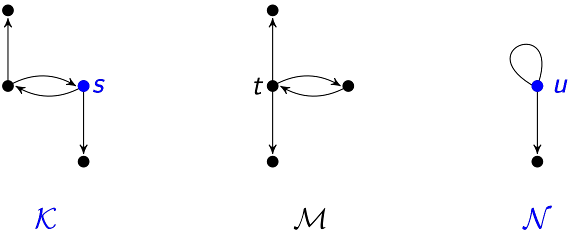

- Logical issues: expressive power; axiomatizing logical consequence; proof theory; decidability/complexity of satisfiability/model checking

- Language extensions: Hybrid logic; First-order extensions; Propositional quantifiers; Fixed-point operators

- Alternative semantics: Topological models; Neighborhood models; Algebraic models; Possibility semantics

- Applications: Temporal logic; (Dynamic) Epistemic logic

Conferences/Journals

TARK (www.tark.org): July 17-19, 2019, Toulouse, Deadline: early April

LORI (golori.org/lori2019): October 18-21, 2019, Southwest University, Chongqing, China, Deadline: May 13

LOFT (faculty.econ.ucdavis.edu/faculty/bonanno/loft.html): next conference in 2020

AiML (www.aiml.net): next conference in 2020

ESSLLI (esslli2019.folli.info): Summer school, Riga, Latvia, August 5 - 16 (also see NASSLLI)

Journals: Review of Symbolic Logic; Journal of Philosophical Logic; Journal of Logic, Language and Information; Synthese?; Journal of Symbolic Logic?