Computer-Aided Reasoning for Software

CSE507

Finite Model Finding

courses.cs.washington.edu/courses/cse507/14au/

Emina Torlak
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Today

Today

Last lecture

- The DPPL(T) framework for deciding quantifier-free SMT formulas

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- The DPPL(T) framework for deciding quantifier-free SMT formulas

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- Finite model finding for quantified FOL and beyond

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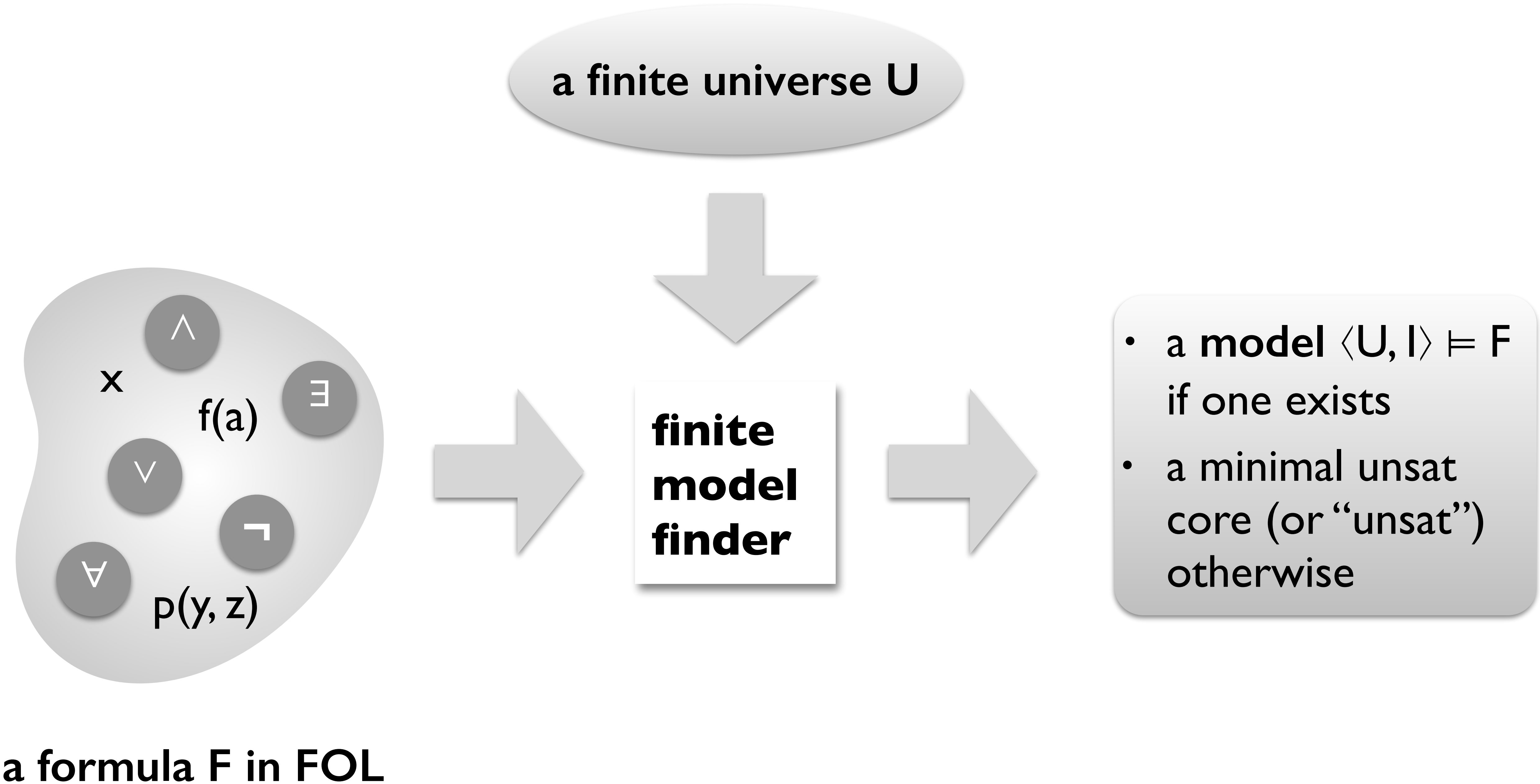
- Finite model finding for quantified FOL and beyond

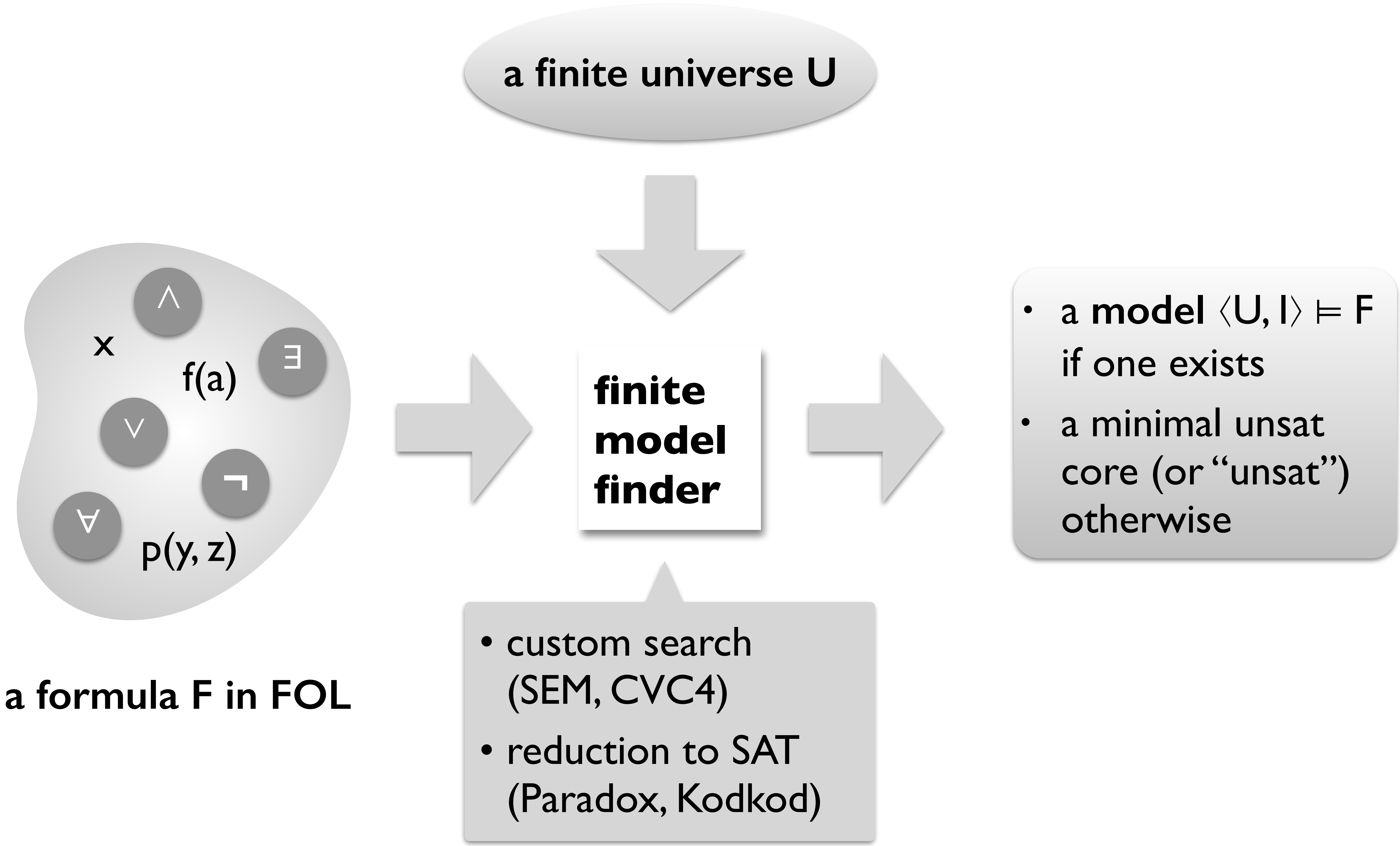
Announcements

- Due date for Homework 2 moved to October 30 at 11pm

Finite model finding



Finite model finding



Some applications of finite model finding

Proving theorems in finite algebras (Finder, SEM, MACE)

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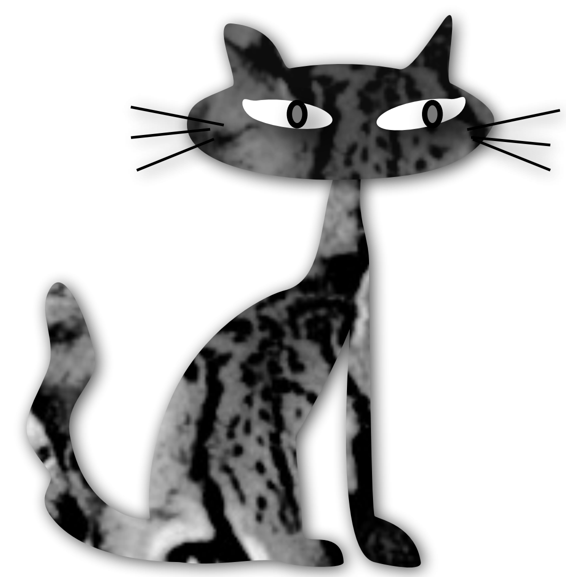
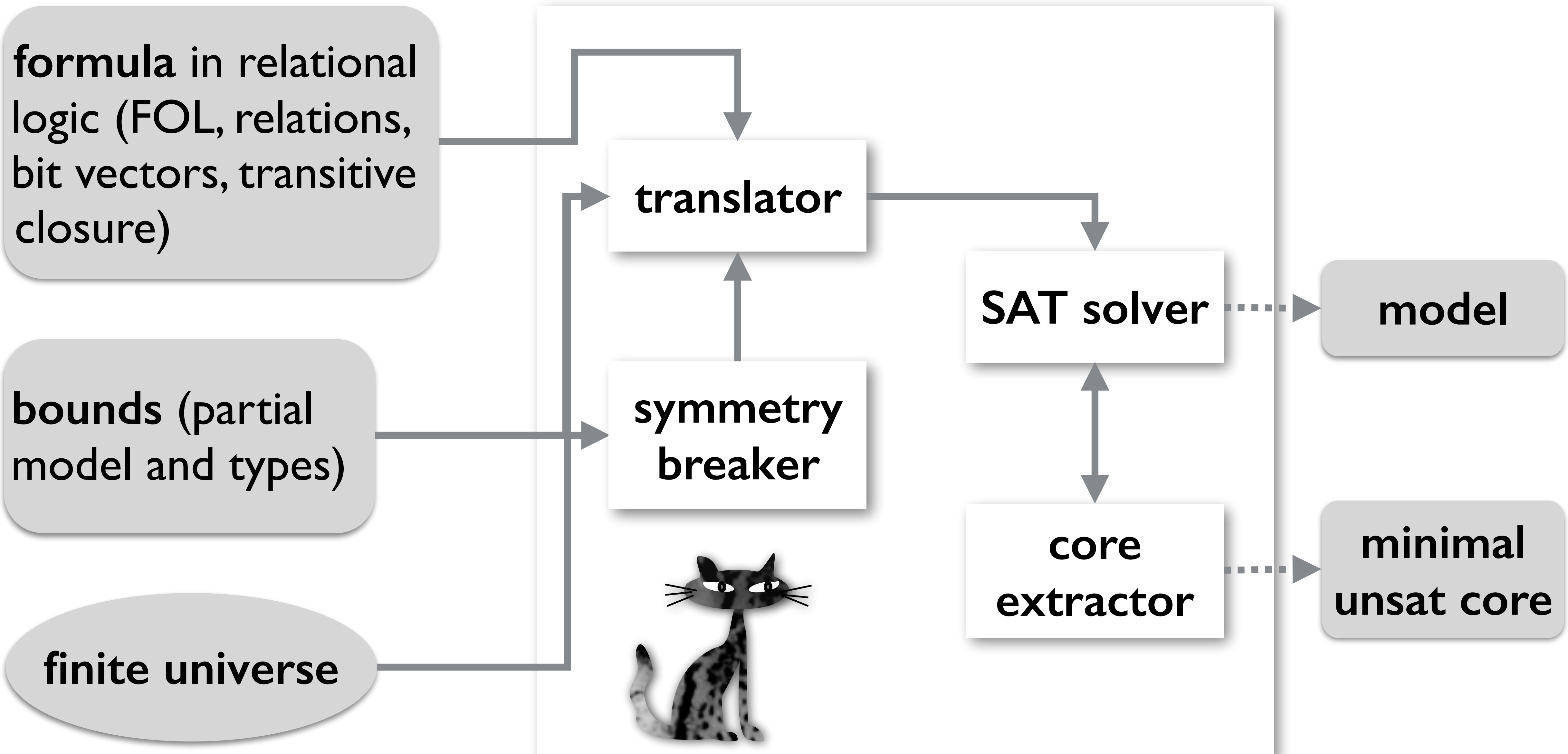


KODKOD

Overview of Kodkod



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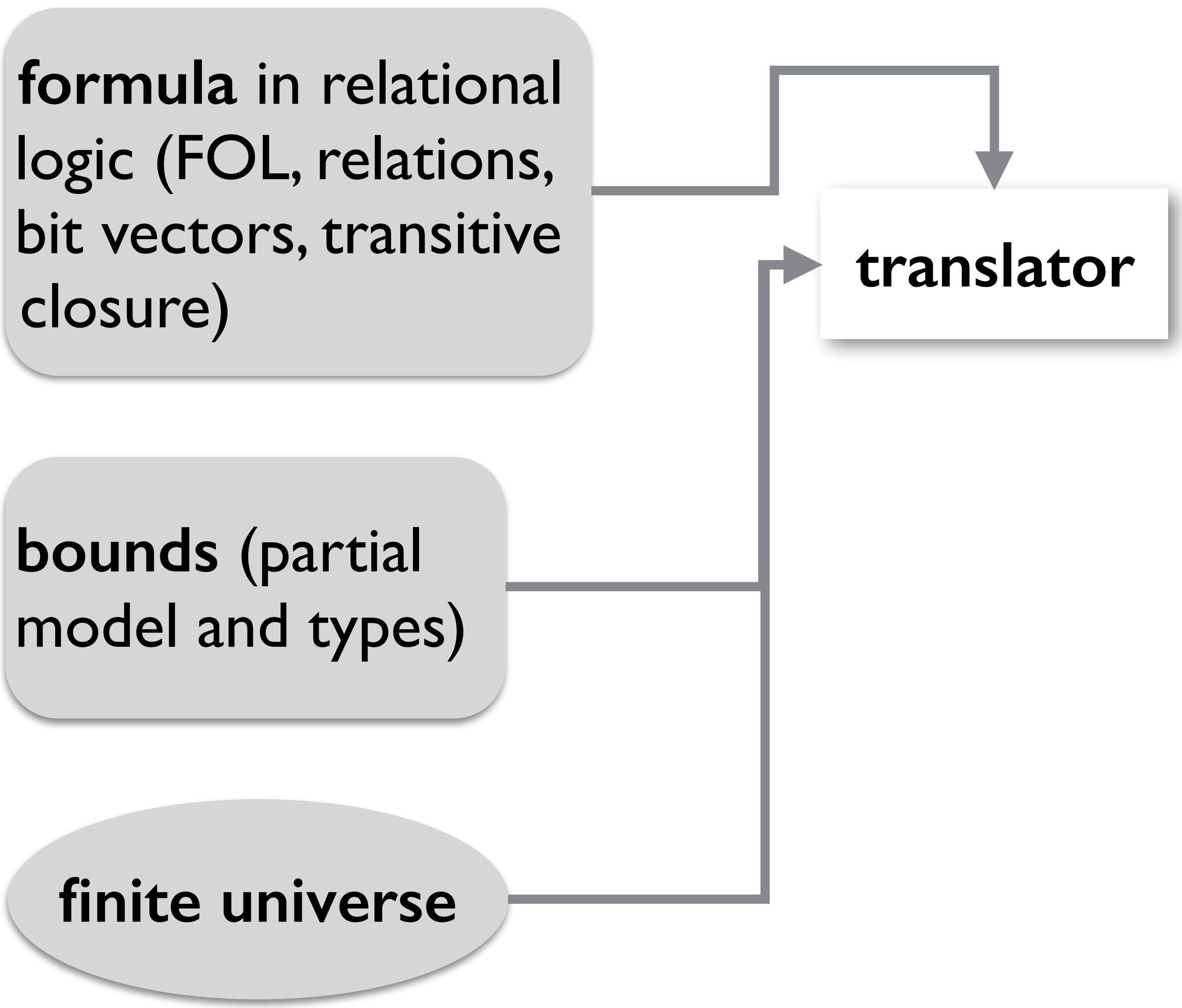

Relational logic by example

a minimalistic formal specification of a filesystem

Relational logic by example

Root ⊆ Dir

- The root of a filesystem hierarchy is a directory.

Relational logic by example

$Root \subseteq Dir$

$contents \subseteq Dir \times (File \cup Dir)$

- The root of a filesystem hierarchy is a directory.
- Directories may contain files or directories.

Relational logic by example

$Root \subseteq Dir$

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$(File \cup Dir) \subseteq Root.{*}contents$

- The root of a filesystem hierarchy is a directory.
- Directories may contain files or directories.
- All directories and files are reachable from the root.

Relational logic by example

$\text{Root} \subseteq \text{Dir}$

$\text{contents} \subseteq \text{Dir} \times (\text{File} \cup \text{Dir})$

$(\text{File} \cup \text{Dir}) \subseteq \text{Root}.{*}\text{contents}$

$\forall\ d: \text{Dir} \mid \neg\ (d \subseteq d.\hat{}\text{contents})$

- The root of a filesystem hierarchy is a directory.
- Directories may contain files or directories.
- All directories and files are reachable from the root.
- The contents relation is acyclic.

Bounded relational logic by example

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

{ **R**, **D_1**, **D_2**, **F_1**, **F_2** }

Finite universe of interpretation.

Bounded relational logic by example

$Root \subseteq Dir$

$contents \subseteq Dir \times (File \cup Dir)$

$(File \cup Dir) \subseteq Root.{*}contents$

$\forall\, d: Dir \mid \neg\, (d \subseteq d.\hat{}contents)$

$\{\ \mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\ \}$

Finite universe of interpretation.

$\{\langle \mathbf{R} \rangle\} \subseteq Root \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq Dir \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

$\{\} \subseteq File \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

$\{\} \subseteq contents \subseteq \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}\} \times \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\}$

Bounds for each relation:

- Tuples it *must* contain (partial model).
- Tuples it *may* contain (type).

Bounded relational logic by example

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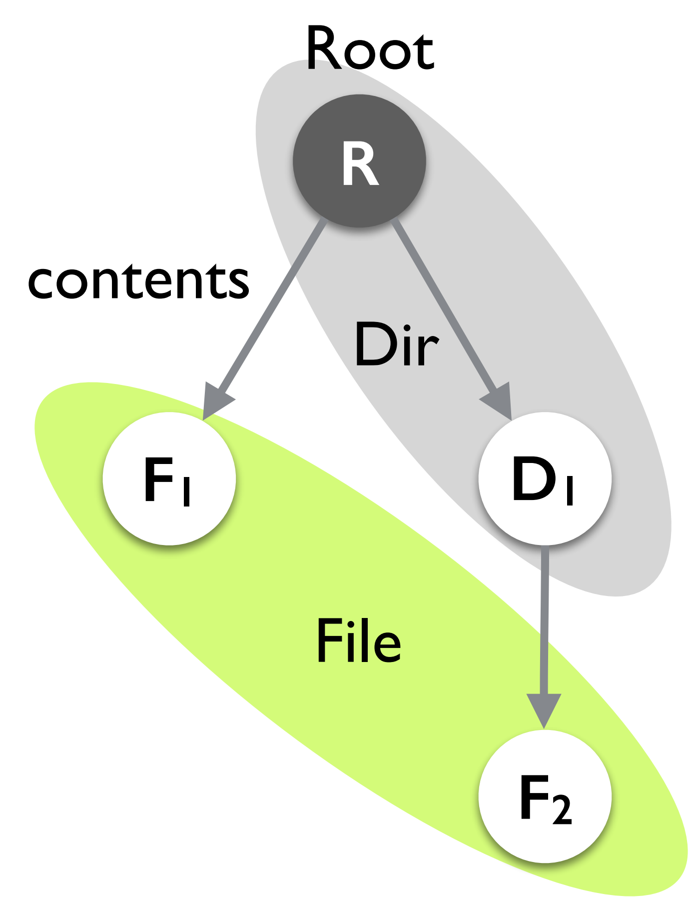

Translation by example

$Root \subseteq Dir$

$contents \subseteq Dir \times (File \cup Dir)$

$(File \cup Dir) \subseteq Root.{}^{*}contents$

$\forall\ d: Dir \mid \neg\ (d \subseteq d.{}^{\wedge}contents)$

$\{\ \mathbf{R}, \mathbf{D}_1, \mathbf{D}_2, \mathbf{F}_1, \mathbf{F}_2\ \}$

$\{\langle \mathbf{R} \rangle\} \subseteq Root \subseteq \{\langle \mathbf{R} \rangle\}$

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$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

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Encode

- relational constants as boolean matrices
- relational expressions as matrix operations
- formulas as constraints over matrix entries

Relational constants as boolean matrices

Relational constants as boolean matrices

R	D_1	D_2	F_1	F_2
1	0	0	0	0

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

Relational constants as boolean matrices

R	D_1	D_2	F_1	F_2
1	0	0	0	0

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

R	D_1	D_2	F_1	F_2
d_0	d_1	d_2	0	0

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

Relational constants as boolean matrices

R	D_1	D_2	F_1	F_2	
1	0	0	0	0	$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$
d_0	d_1	d_2	0	0	$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$
0	0	0	f_0	f_1	$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

Relational constants as boolean matrices

	R	D_1	D_2	F_1	F_2
	1	0	0	0	0

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

d_0	d_1	d_2	0	0

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

0	0	0	f_0	f_1

$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

R	c_0	c_1	c_2	c_3	c_4
D_1	c_5	c_6	c_7	c_8	c_9
D_2	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
F_1	0	0	0	0	0
F_2	0	0	0	0	0

$\{\} \subseteq \text{contents} \subseteq \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}\} \times \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\}$

Relational expressions as matrix operations

File ∨ Dir = File ∪ Dir

File				
0	0	0	f_0	f_1

∨

Dir				
d_0	d_1	d_2	0	0

=

File ∪ Dir				
d_0	d_1	d_2	f_0	f_1

Dir
d_0
d_1
d_2
0
0

×

File ∪ Dir				
d_0	d_1	d_2	f_0	f_1

=

Dir × (File ∪ Dir)

$d_0 \wedge d_0$	$d_0 \wedge d_1$	$d_0 \wedge d_2$	$d_0 \wedge f_0$	$d_0 \wedge f_1$
$d_1 \wedge d_0$	$d_1 \wedge d_1$	$d_1 \wedge d_2$	$d_1 \wedge f_0$	$d_1 \wedge f_1$
$d_2 \wedge d_0$	$d_2 \wedge d_1$	$d_2 \wedge d_2$	$d_2 \wedge f_0$	$d_2 \wedge f_1$
0	0	0	0	0
0	0	0	0	0

Formulas as constraints over matrix entries

contents

c_0	c_1	c_2	c_3	c_4
c_5	c_6	c_7	c_8	c_9
c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
0	0	0	0	0
0	0	0	0	0

$\Rightarrow$

Dir × (File ∪ Dir)

$d_0 \wedge d_0$	$d_0 \wedge d_1$	$d_0 \wedge d_2$	$d_0 \wedge f_0$	$d_0 \wedge f_1$
$d_1 \wedge d_0$	$d_1 \wedge d_1$	$d_1 \wedge d_2$	$d_1 \wedge f_0$	$d_1 \wedge f_1$
$d_2 \wedge d_0$	$d_2 \wedge d_1$	$d_2 \wedge d_2$	$d_2 \wedge f_0$	$d_2 \wedge f_1$
0	0	0	0	0
0	0	0	0	0

=

contents ⊆ Dir × (File ∪ Dir)

$(c_0 \Rightarrow d_0 \wedge d_0) \wedge$

$(c_1 \Rightarrow d_0 \wedge d_1) \wedge$

$(c_2 \Rightarrow d_0 \wedge d_2) \wedge$

$(c_3 \Rightarrow d_0 \wedge f_0) \wedge$

$(c_4 \Rightarrow d_0 \wedge f_1) \wedge$

$(c_5 \Rightarrow d_1 \wedge d_0) \wedge$

...

$(c_{14} \Rightarrow d_2 \wedge f_1)$

Dealing with sparseness and redundancy

Dir × (File ∪ Dir)

$d_0 \wedge d_0$	$d_0 \wedge d_1$	$d_0 \wedge d_2$	$d_0 \wedge f_0$	$d_0 \wedge f_1$
$d_1 \wedge d_0$	$d_1 \wedge d_1$	$d_1 \wedge d_2$	$d_1 \wedge f_0$	$d_1 \wedge f_1$
$d_2 \wedge d_0$	$d_2 \wedge d_1$	$d_2 \wedge d_2$	$d_2 \wedge f_0$	$d_2 \wedge f_1$
0	0	0	0	0
0	0	0	0	0

Dealing with sparseness and redundancy

Dir × (File ∪ Dir)

$d_0 \wedge d_0$	$d_0 \wedge d_1$	$d_0 \wedge d_2$	$d_0 \wedge f_0$	$d_0 \wedge f_1$
$d_1 \wedge d_0$	$d_1 \wedge d_1$	$d_1 \wedge d_2$	$d_1 \wedge f_0$	$d_1 \wedge f_1$
$d_2 \wedge d_0$	$d_2 \wedge d_1$	$d_2 \wedge d_2$	$d_2 \wedge f_0$	$d_2 \wedge f_1$
0	0	0	0	0
0	0	0	0	0

Empty regions in matrices (exponential w.r.t. relation arity).

Dealing with sparseness and redundancy

Dir × (File ∪ Dir)

$d_0 \wedge d_0$	$d_0 \wedge d_1$	$d_0 \wedge d_2$	$d_0 \wedge f_0$	$d_0 \wedge f_1$
$d_1 \wedge d_0$	$d_1 \wedge d_1$	$d_1 \wedge d_2$	$d_1 \wedge f_0$	$d_1 \wedge f_1$
$d_2 \wedge d_0$	$d_2 \wedge d_1$	$d_2 \wedge d_2$	$d_2 \wedge f_0$	$d_2 \wedge f_1$
0	0	0	0	0
0	0	0	0	0

Different circuits for the same formula.

Empty regions in matrices (exponential w.r.t. relation arity).

Dealing with sparseness and redundancy

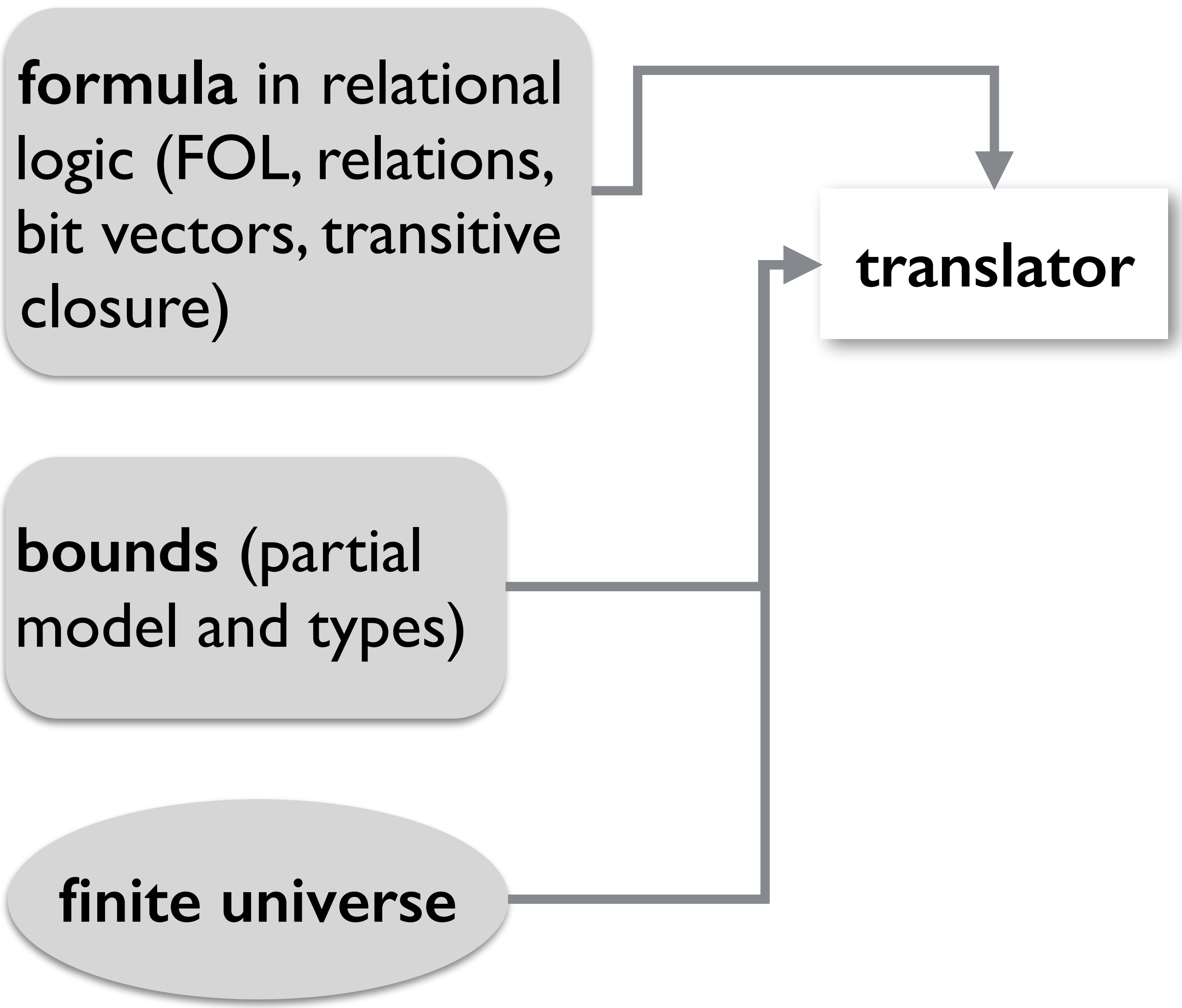
Dir × (File ∪ Dir)

$d_0 \wedge d_0$	$d_0 \wedge d_1$	$d_0 \wedge d_2$	$d_0 \wedge f_0$	$d_0 \wedge f_1$
$d_1 \wedge d_0$	$d_1 \wedge d_1$	$d_1 \wedge d_2$	$d_1 \wedge f_0$	$d_1 \wedge f_1$
$d_2 \wedge d_0$	$d_2 \wedge d_1$	$d_2 \wedge d_2$	$d_2 \wedge f_0$	$d_2 \wedge f_1$
0	0	0	0	0
0	0	0	0	0

Compact Boolean Circuits (CBCs).

Sparse matrices represented as interval trees.

Overview of Kodkod



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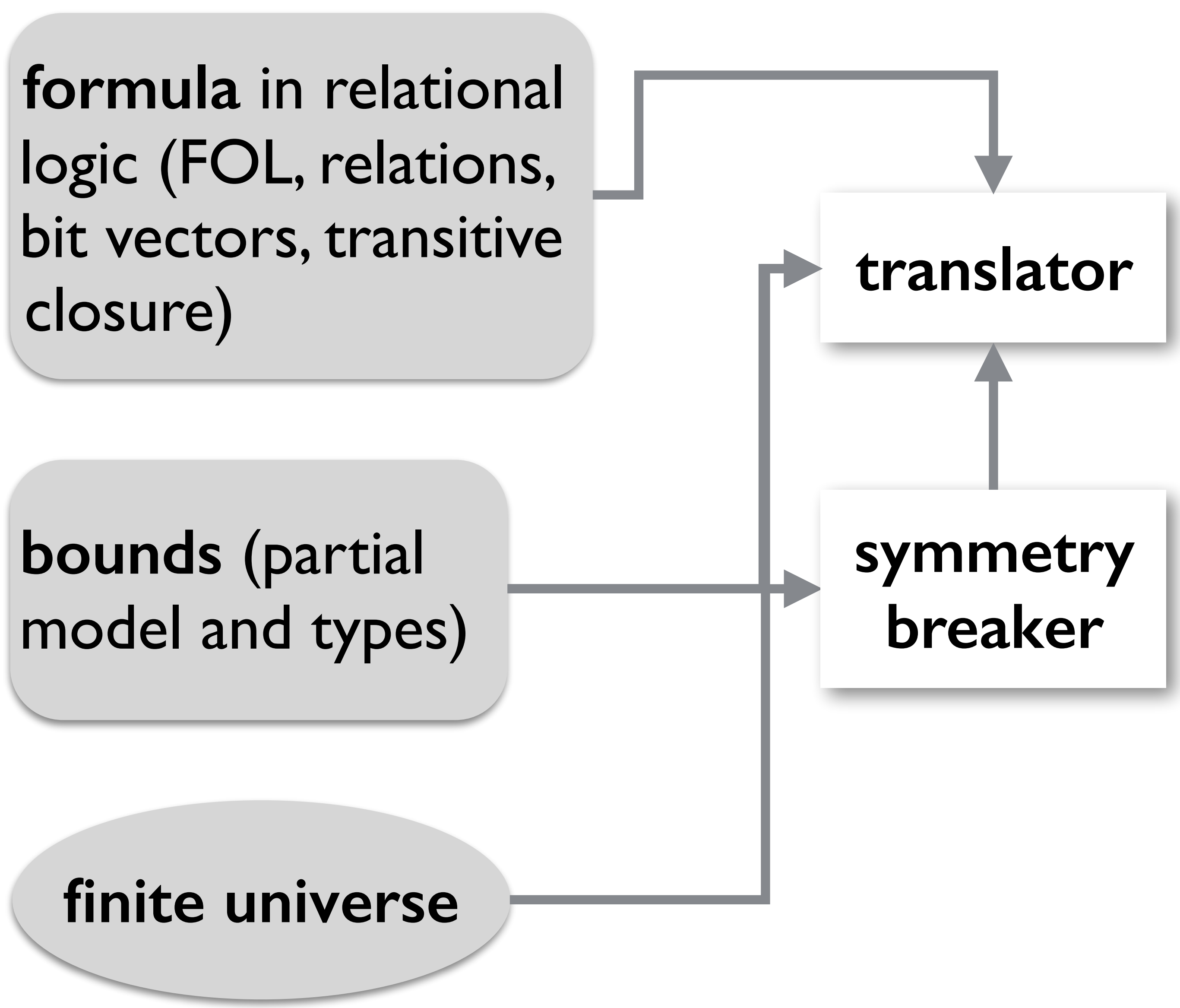


Symmetry by example

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

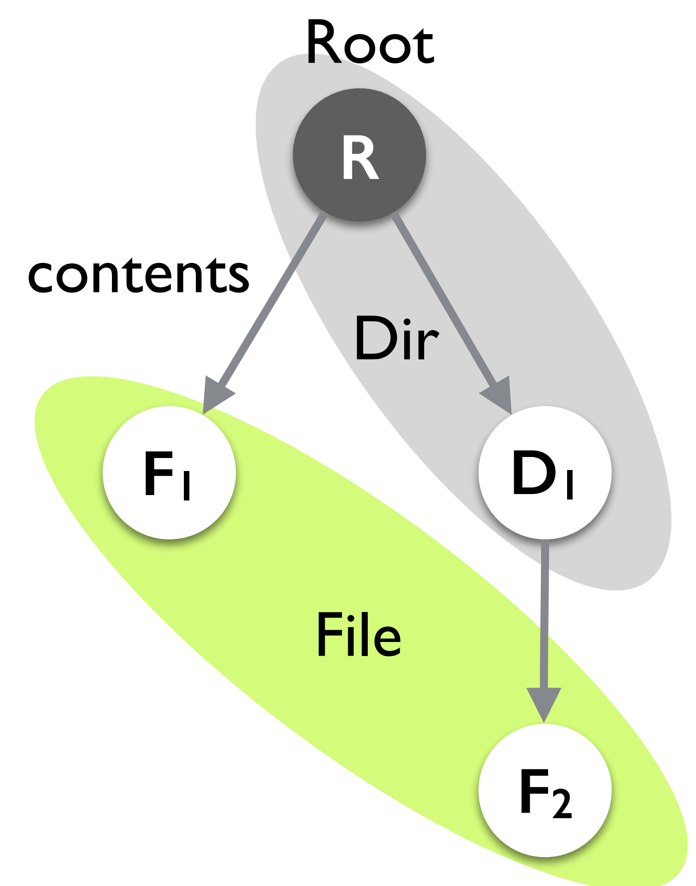
{ $\mathbf{R}$, $\mathbf{D_1}$, $\mathbf{D_2}$, $\mathbf{F_1}$, $\mathbf{F_2}$ }

{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨$\mathbf{D_1}$⟩, ⟨$\mathbf{D_2}$⟩}

{} ⊆ File ⊆ {⟨$\mathbf{F_1}$⟩, ⟨$\mathbf{F_2}$⟩}

{} ⊆ contents ⊆ {**R**, $\mathbf{D_1}$, $\mathbf{D_2}$} × {**R**, $\mathbf{D_1}$, $\mathbf{D_2}$, $\mathbf{F_1}$, $\mathbf{F_2}$}



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∀ d: Dir | ¬ (d ⊆ d.^contents)

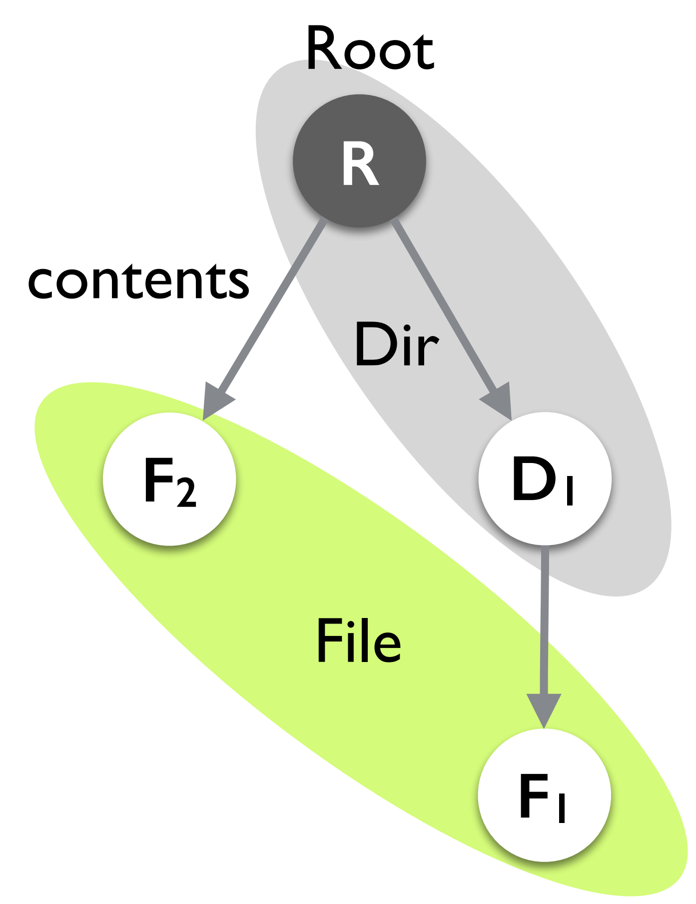
{ **R**, **D**$_1$, **D**$_2$, **F**$_1$, **F**$_2$ }

{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨**D**$_1$⟩, ⟨**D**$_2$⟩}

{} ⊆ File ⊆ {⟨**F**$_1$⟩, ⟨**F**$_2$⟩}

{} ⊆ contents ⊆ {**R**, **D**$_1$, **D**$_2$} × {**R**, **D**$_1$, **D**$_2$, **F**$_1$, **F**$_2$}



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$\forall\ d: \text{Dir} \mid \neg\ (d \subseteq d.\text{^contents})$

$\{\ \mathbf{R}, \mathbf{D_1}\ \mathbf{D_2}\ \mathbf{F_1}, \mathbf{F_2}\ \}$

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

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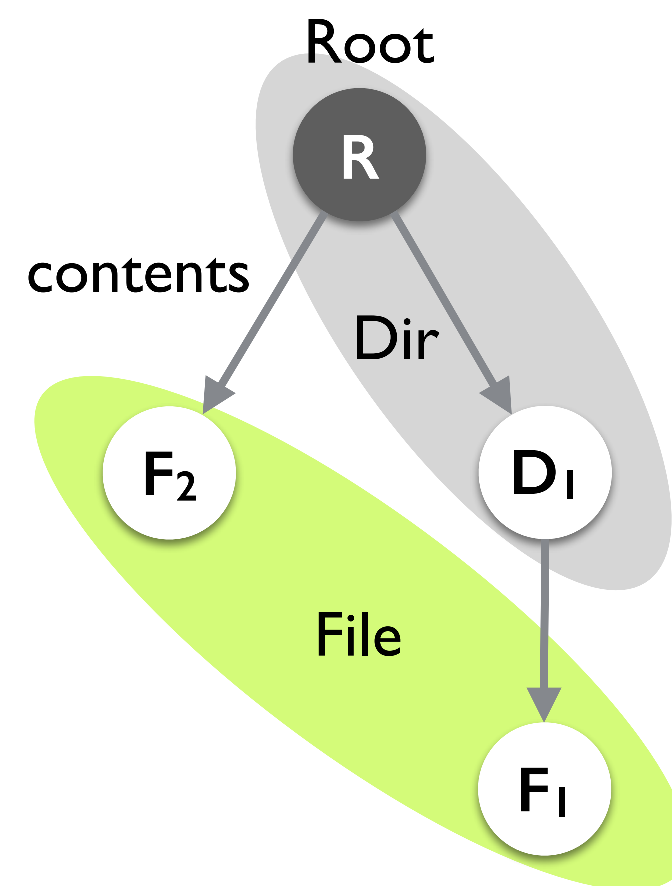

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(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

{ **R**, $\mathbf{D_1}$, $\mathbf{D_2}$, $\mathbf{F_1}$, $\mathbf{F_2}$ }

{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨$\mathbf{D_1}$⟩, ⟨$\mathbf{D_2}$⟩}

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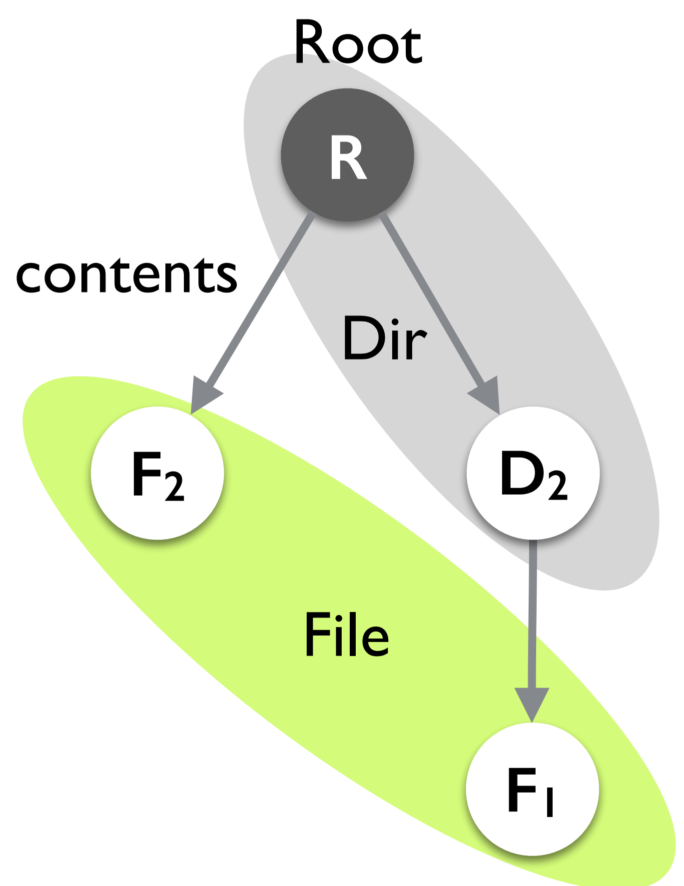


Symmetries between models

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

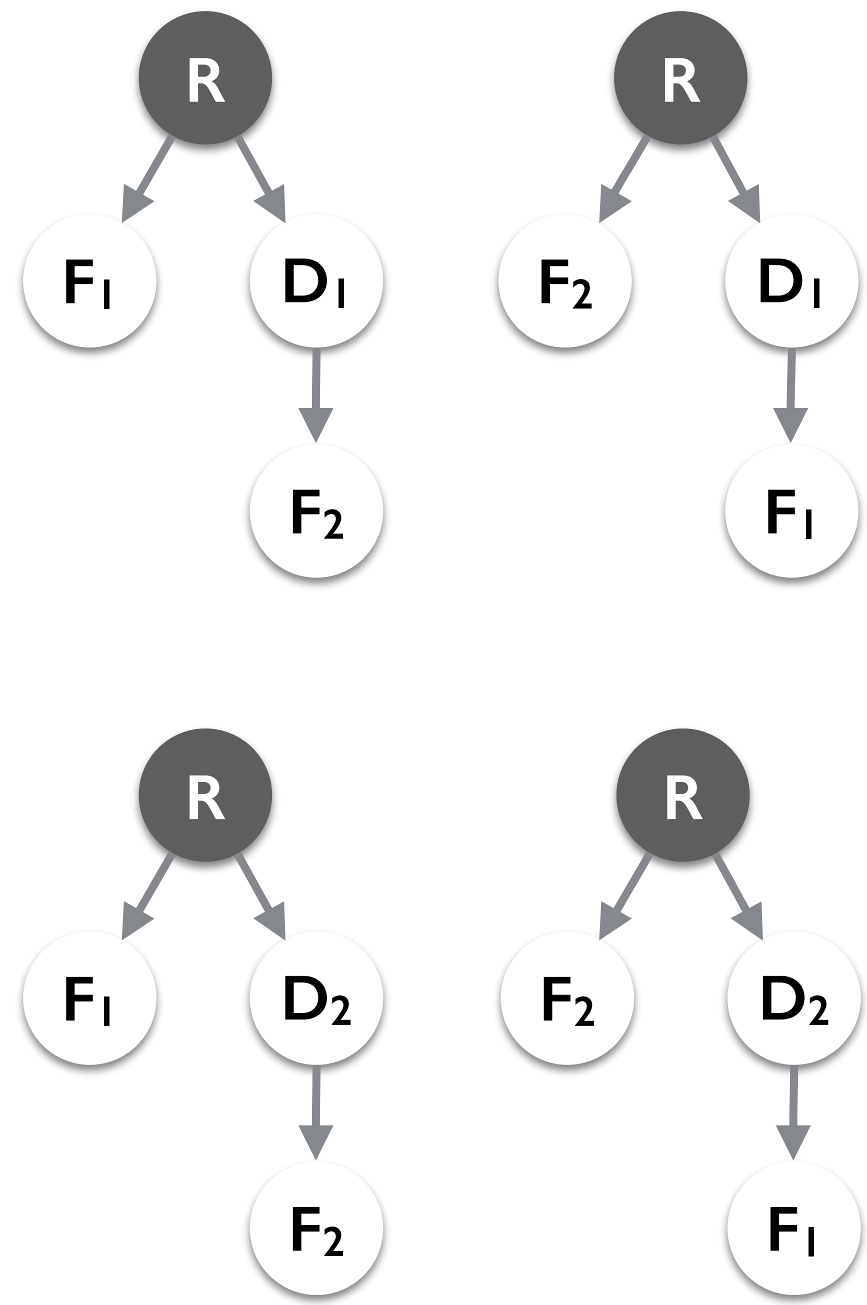
{ R, D_1, D_2, F_1, F_2 }

{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨**D_1**⟩, ⟨**D_2**⟩}

{} ⊆ File ⊆ {⟨**F_1**⟩, ⟨**F_2**⟩}

{} ⊆ contents ⊆ {R, D_1, D_2} × {R, D_1, D_2, F_1, F_2}



Symmetries between non-models

$\text{Root} \subseteq \text{Dir}$

$\text{contents} \subseteq \text{Dir} \times (\text{File} \cup \text{Dir})$

$(\text{File} \cup \text{Dir}) \subseteq \text{Root.*contents}$

$\forall\ d: \text{Dir} \mid \neg\ (d \subseteq d.\hat{}\text{contents})$

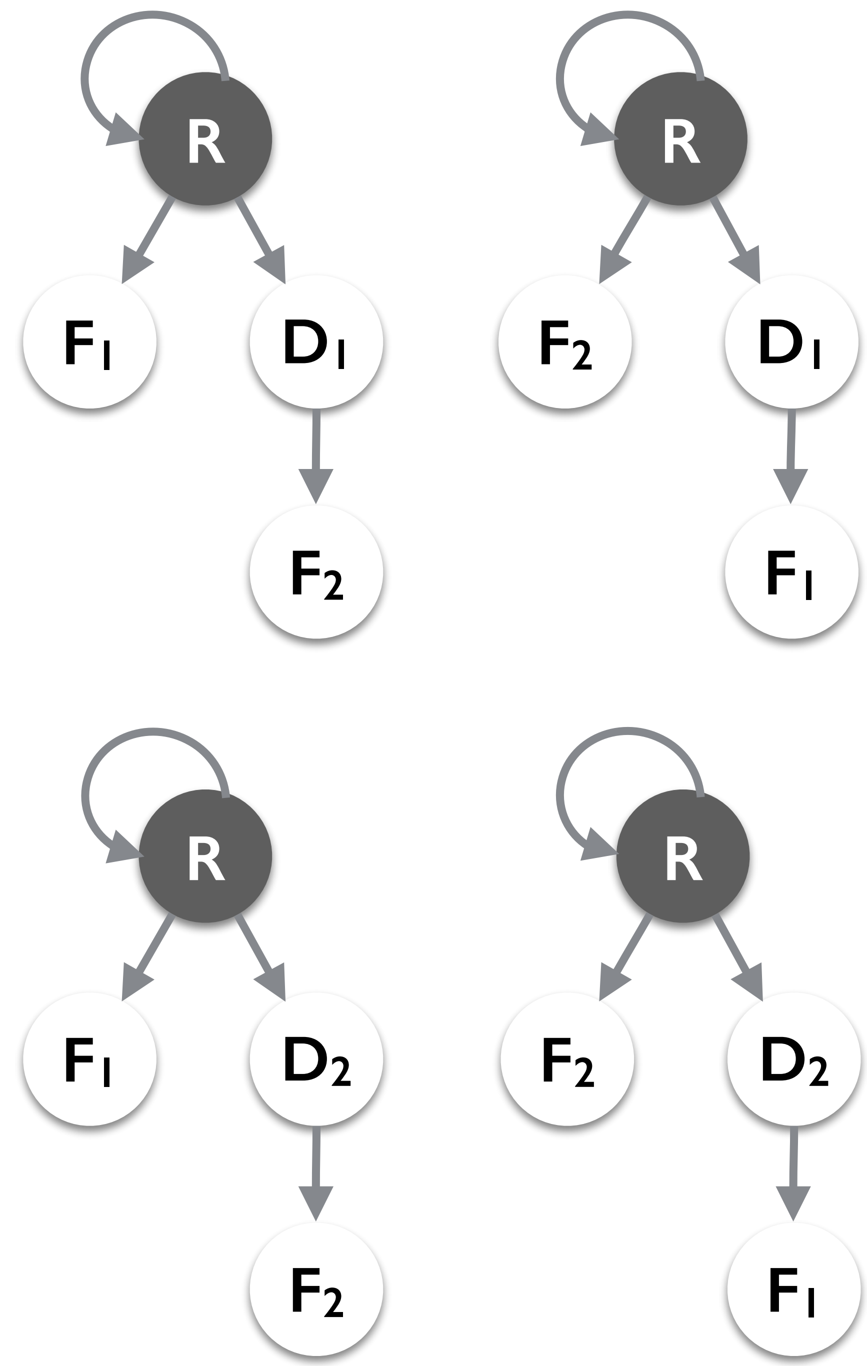
$\{\ R, D_1, D_2, F_1, F_2\ \}$

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

$\{\} \subseteq \text{contents} \subseteq \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}\} \times \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\}$



Symmetries induce equivalence classes

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

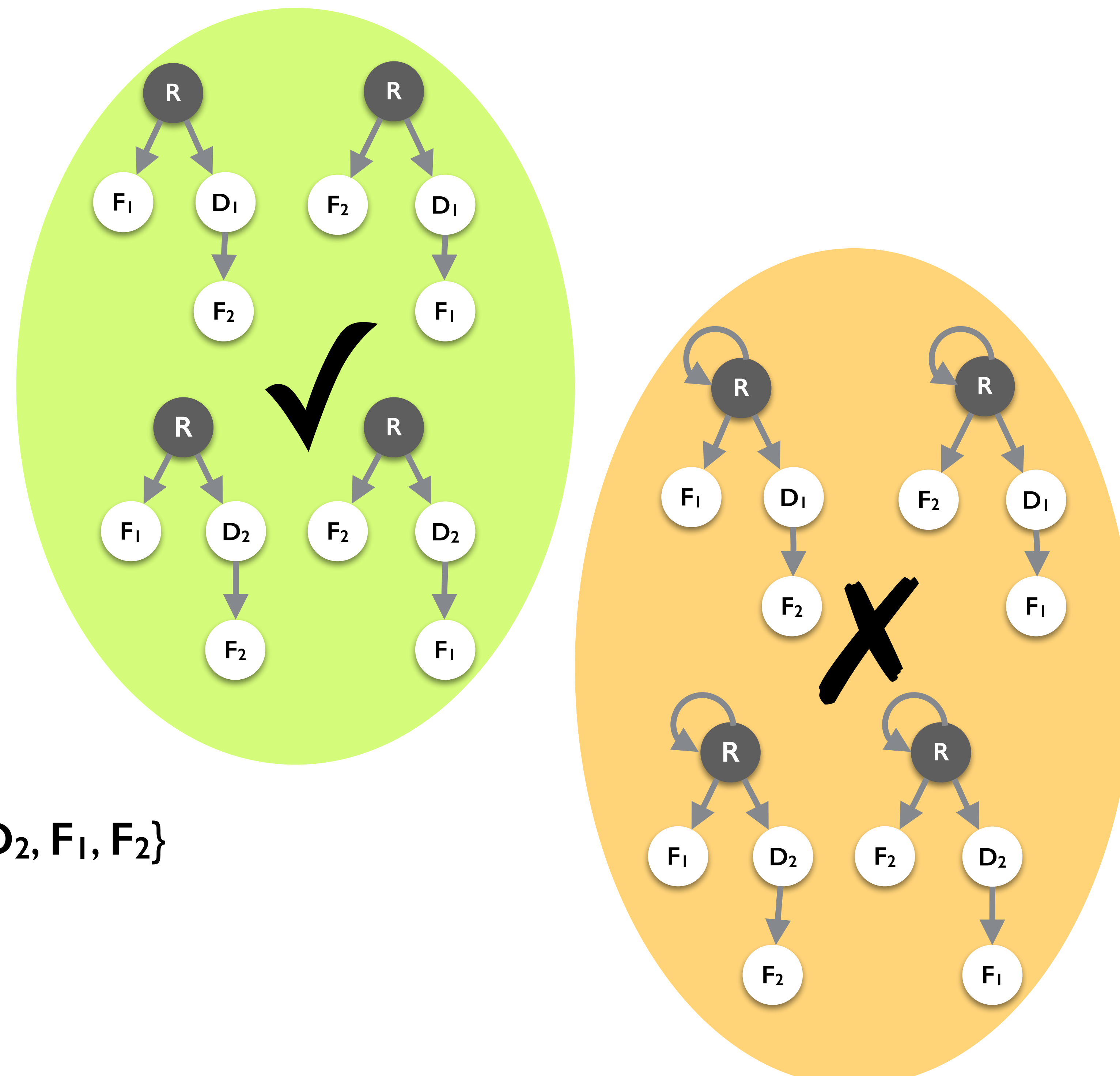
{ **R**, **D**$_{\mathbf{1}}$, **D**$_{\mathbf{2}}$, **F**$_{\mathbf{1}}$, **F**$_{\mathbf{2}}$ }

{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨**D**$_{\mathbf{1}}$⟩, ⟨**D**$_{\mathbf{2}}$⟩}

{} ⊆ File ⊆ {⟨**F**$_{\mathbf{1}}$⟩, ⟨**F**$_{\mathbf{2}}$⟩}

{} ⊆ contents ⊆ {**R**, **D**$_{\mathbf{1}}$, **D**$_{\mathbf{2}}$} × {**R**, **D**$_{\mathbf{1}}$, **D**$_{\mathbf{2}}$, **F**$_{\mathbf{1}}$, **F**$_{\mathbf{2}}$}



Symmetries induce equivalence classes

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

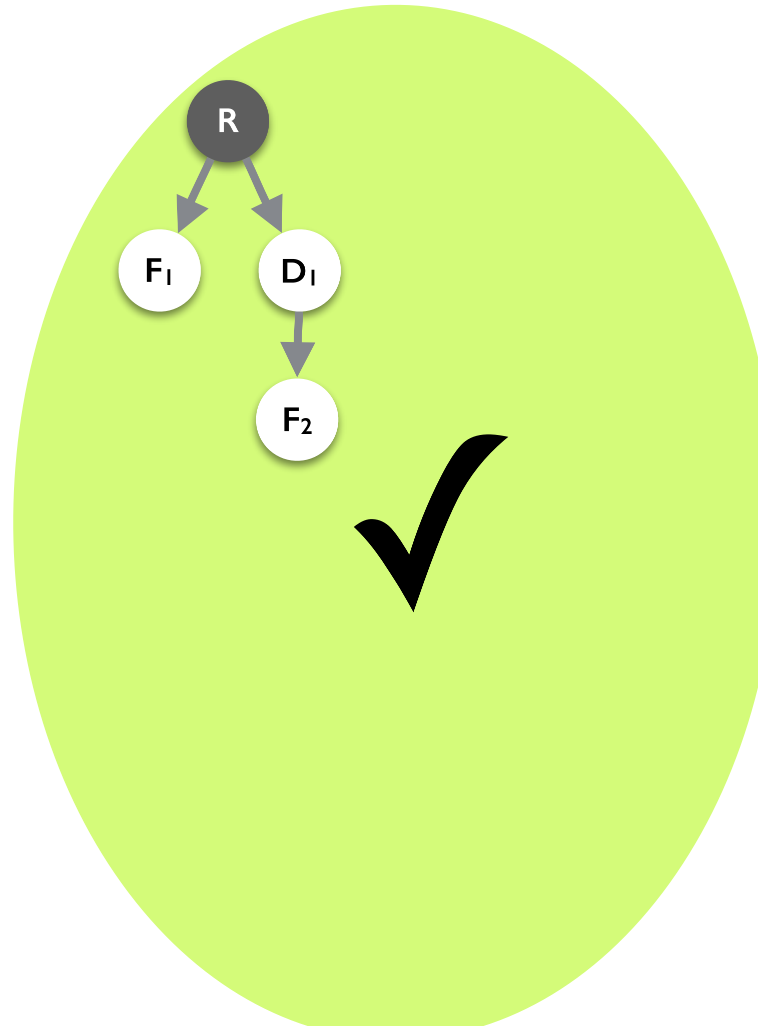
{ **R**, **D_1**, **D_2**, **F_1**, **F_2** }

{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

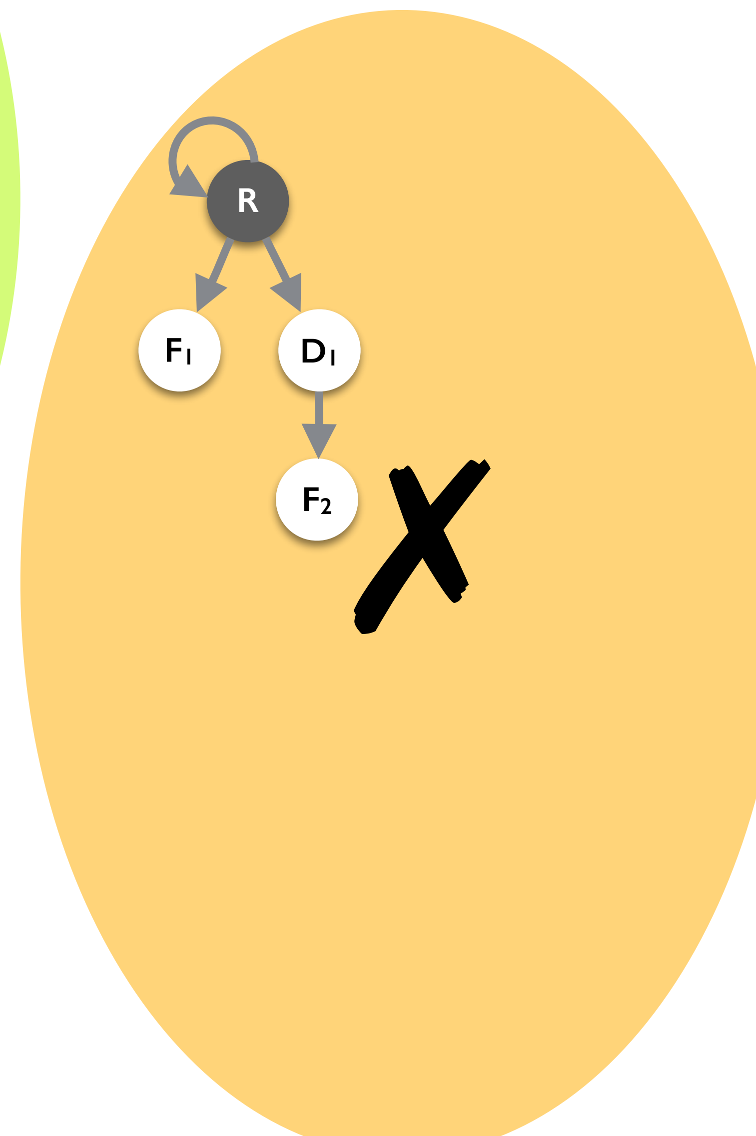
{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨**D_1**⟩, ⟨**D_2**⟩}

{} ⊆ File ⊆ {⟨**F_1**⟩, ⟨**F_2**⟩}

{} ⊆ contents ⊆ {**R**, **D_1**, **D_2**} × {**R**, **D_1**, **D_2**, **F_1**, **F_2**}



sufficient to test one binding per equivalence class



Symmetry detection

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

{ **R**, $\mathbf{D_1}$, $\mathbf{D_2}$, $\mathbf{F_1}$, $\mathbf{F_2}$ }

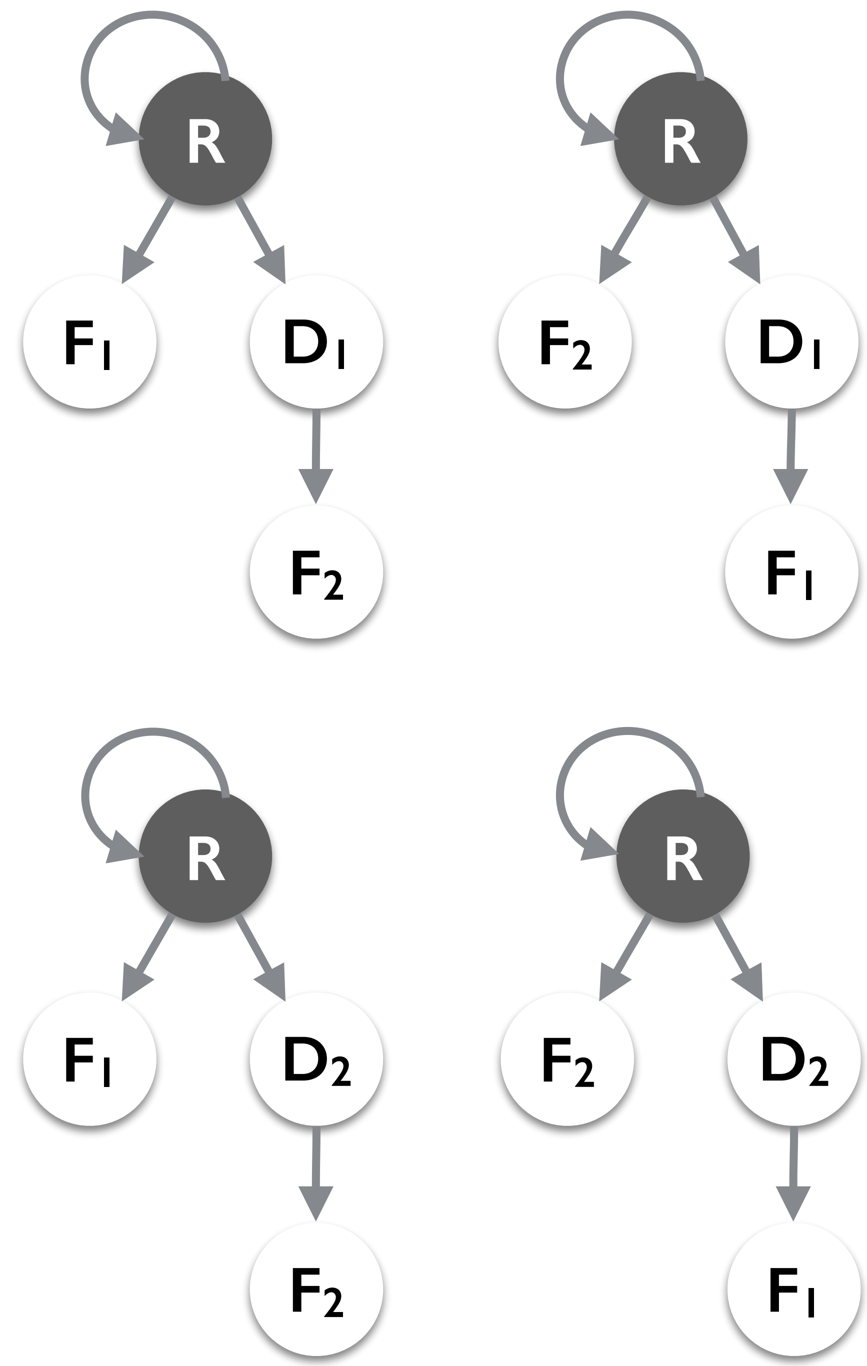
{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨$\mathbf{D_1}$⟩, ⟨$\mathbf{D_2}$⟩}

{} ⊆ File ⊆ {⟨$\mathbf{F_1}$⟩, ⟨$\mathbf{F_2}$⟩}

{} ⊆ contents ⊆ {**R**, $\mathbf{D_1}$, $\mathbf{D_2}$} × {**R**, $\mathbf{D_1}$, $\mathbf{D_2}$, $\mathbf{F_1}$, $\mathbf{F_2}$}

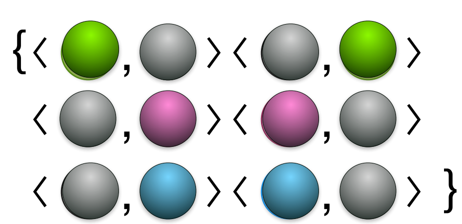
Assignment symmetries = bound symmetries

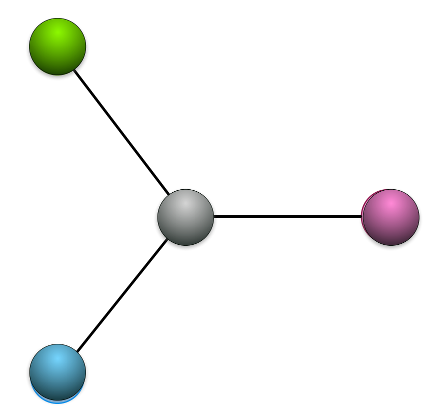


Detecting symmetries is hard ...

Assignment symmetries
= bound symmetries

Graph automorphism
detection





But only a few symmetries needed in practice

Greedy algorithm that partitions the universe into equivalence classes ✓

✗ Graph automorphism detection

Base partitioning: practical symmetry detection

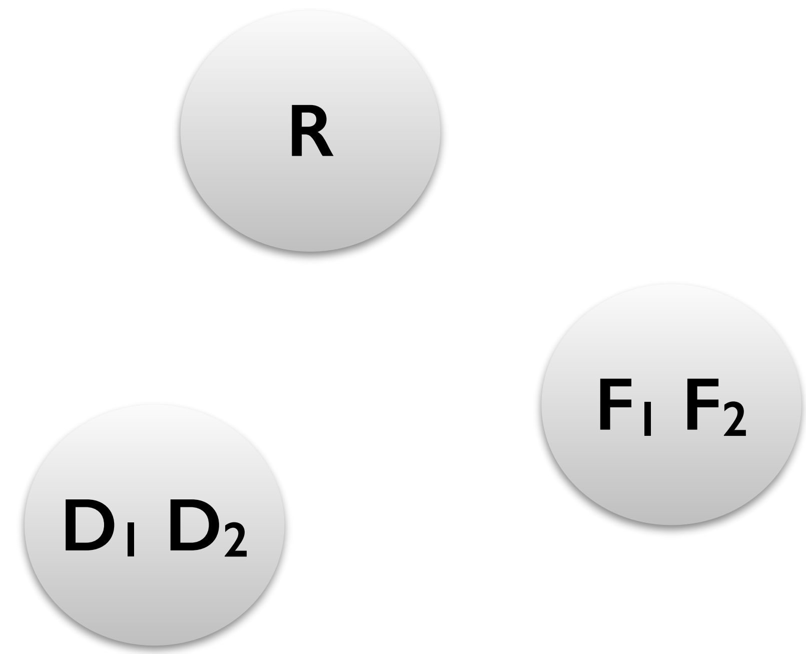
$\{ \mathbf{R}, \mathbf{D}_1, \mathbf{D}_2, \mathbf{F}_1, \mathbf{F}_2 \}$

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D}_1 \rangle, \langle \mathbf{D}_2 \rangle\}$

$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F}_1 \rangle, \langle \mathbf{F}_2 \rangle\}$

$\{\} \subseteq \text{contents} \subseteq \{\mathbf{R}, \mathbf{D}_1, \mathbf{D}_2\} \times \{\mathbf{R}, \mathbf{D}_1, \mathbf{D}_2, \mathbf{F}_1, \mathbf{F}_2\}$



The coarsest partitioning of the universe such that all non-empty bounds are expressible as unions of products of partitions.

Finding the base partitioning

$R\ D_1\ D_2\ F_1\ F_2$

start with a single partition and refine greedily for each non-empty lower and upper bound

Finding base partitioning

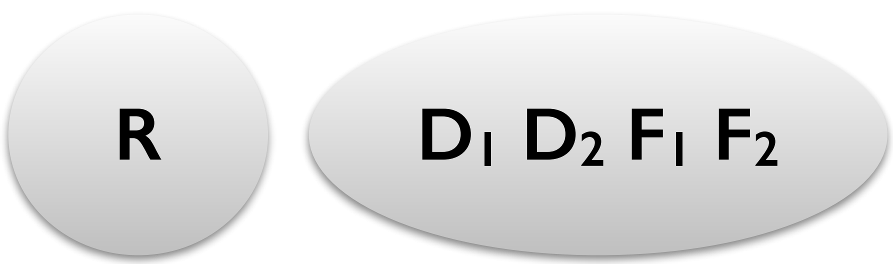
$R\ D_1\ D_2\ F_1\ F_2$

Finding base partitioning

$R\ D_1\ D_2\ F_1\ F_2$

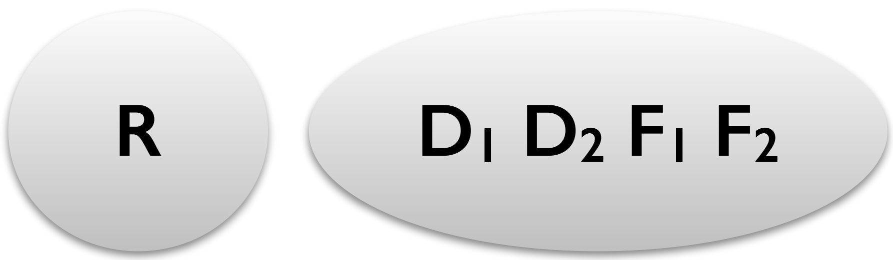
$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

Finding base partitioning



$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

Finding base partitioning



$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

Finding base partitioning

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

Finding base partitioning

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

Finding base partitioning

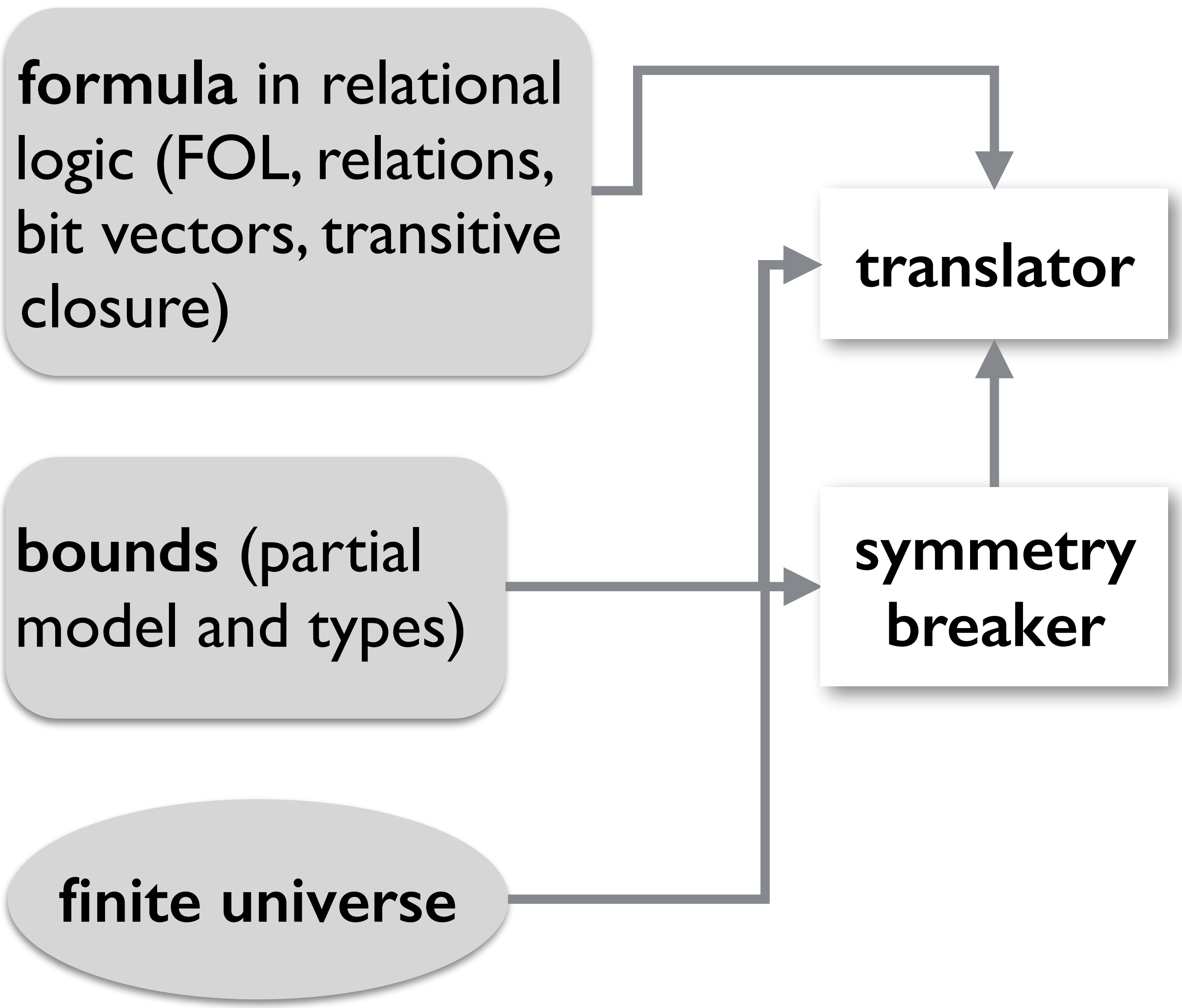
$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

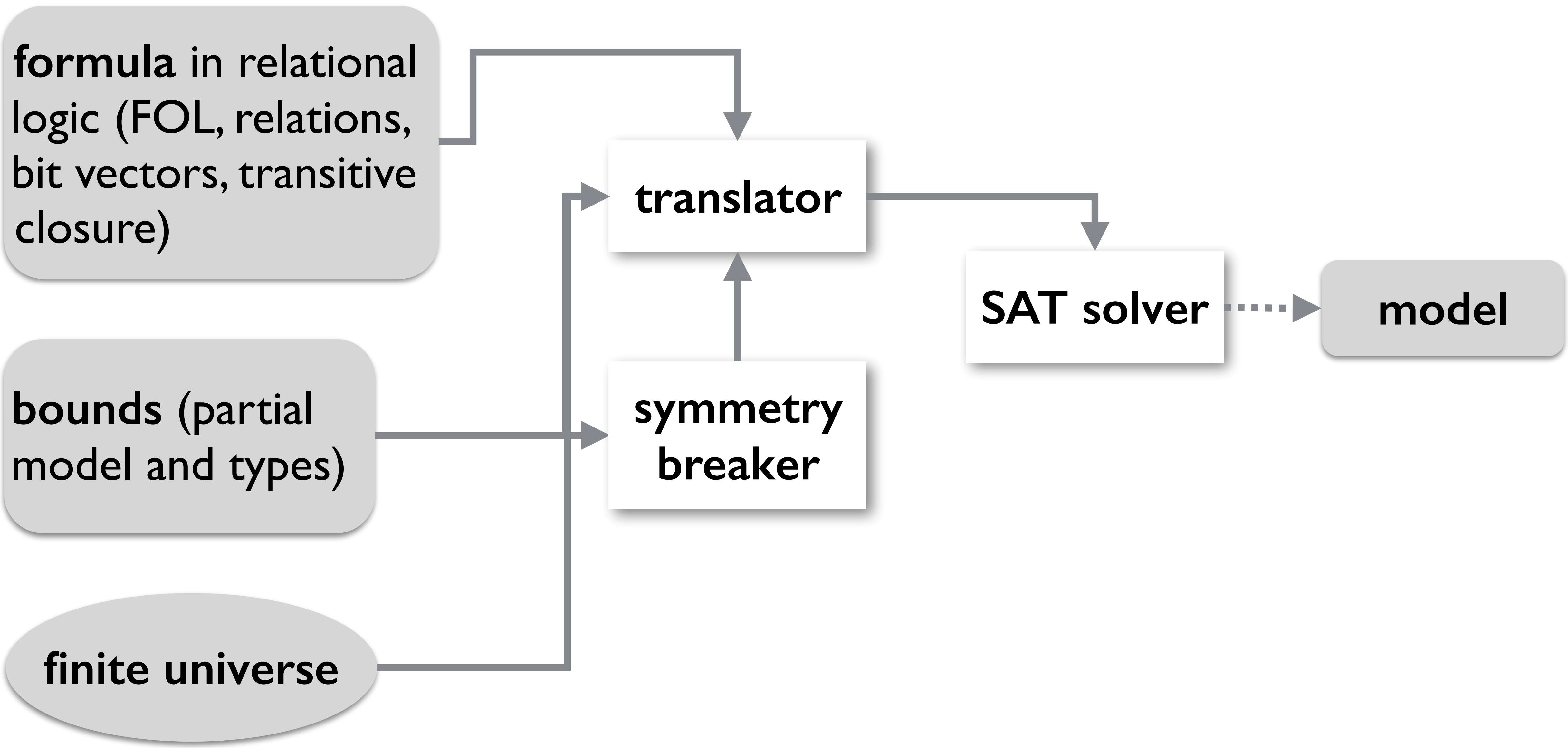
$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

$\{\} \subseteq \text{contents} \subseteq \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}\} \times \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\}$

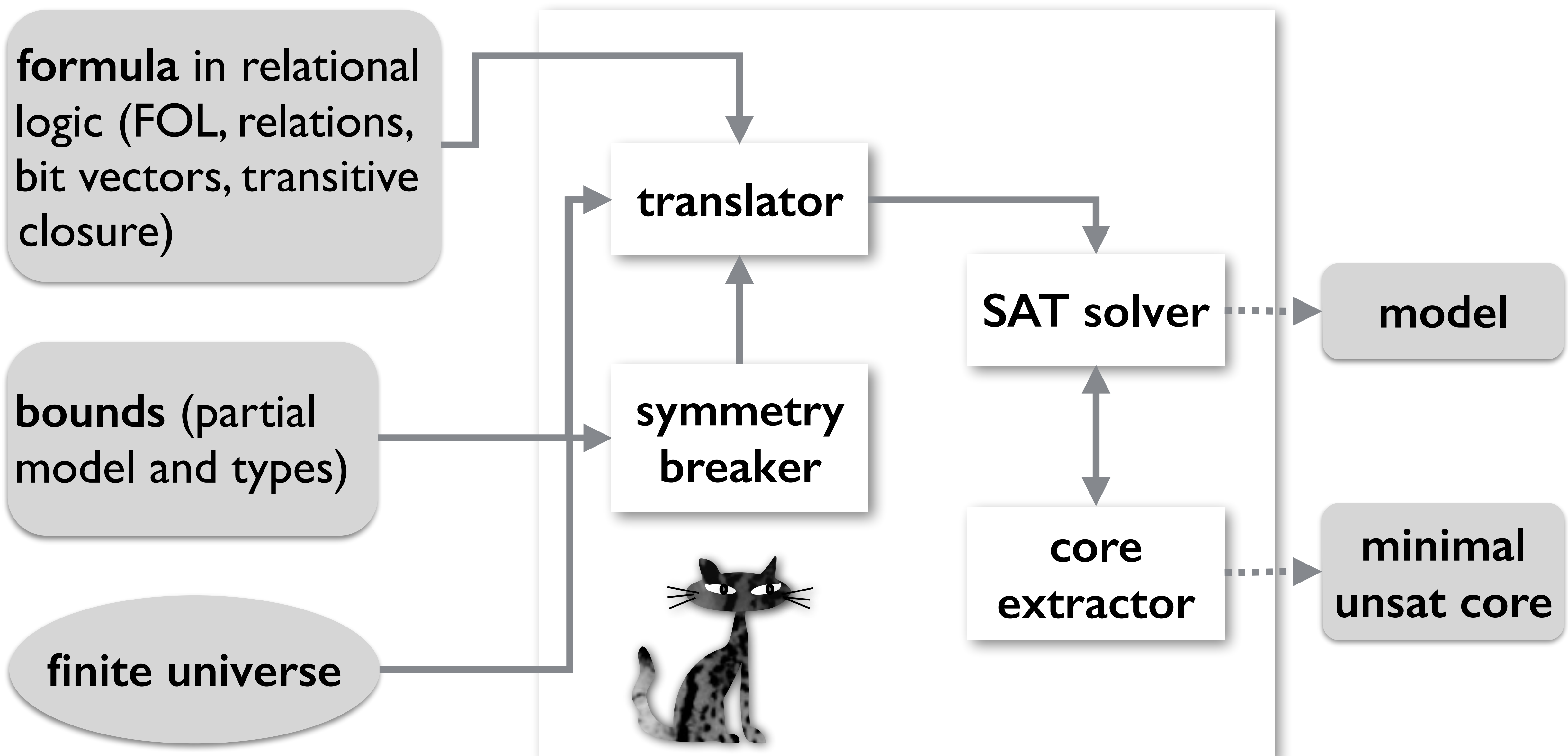
Overview of Kodkod



Overview of Kodkod



Overview of Kodkod



A bug in the tiny filesystem

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

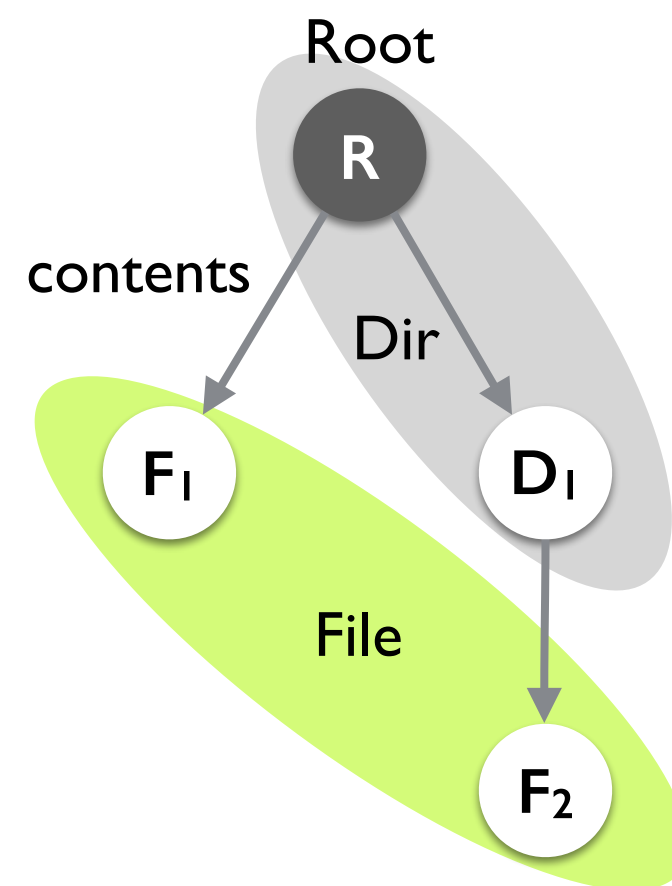
{ **R**, **D**$_1$, **D**$_2$, **F**$_1$, **F**$_2$ }

{⟨**R**⟩} ⊆ Root ⊆ {⟨**R**⟩}

{} ⊆ Dir ⊆ {⟨**R**⟩, ⟨**D**$_1$⟩, ⟨**D**$_2$⟩}

{} ⊆ File ⊆ {⟨**F**$_1$⟩, ⟨**F**$_2$⟩}

{} ⊆ contents ⊆ {**R**, **D**$_1$, **D**$_2$} × {**R**, **D**$_1$, **D**$_2$, **F**$_1$, **F**$_2$}



A bug in the tiny filesystem

$\text{Root} \subseteq \text{Dir}$

$\text{contents} \subseteq \text{Dir} \times (\text{File} \cup \text{Dir})$

$(\text{File} \cup \text{Dir}) \subseteq \text{Root}.{*}\text{contents}$

$\forall\ d: \text{Dir} \mid \neg\ (d \subseteq d.\hat{}\text{contents})$

$\{\ \mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\ \}$

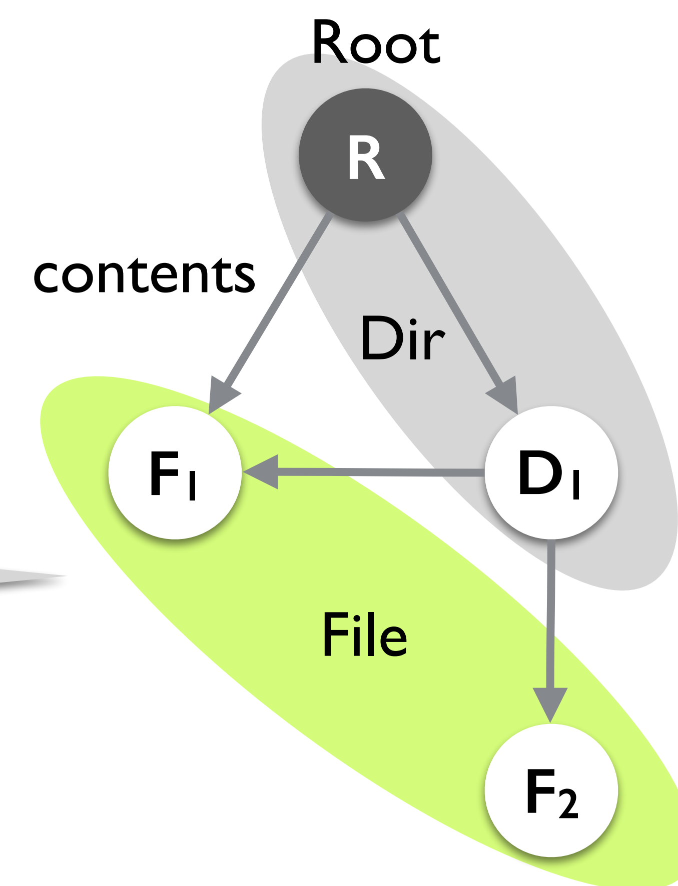
$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

$\{\} \subseteq \text{contents} \subseteq \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}\} \times \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\}$

The spec allows multiple parents.



Fixing the tiny filesystem

$Root \subseteq Dir$

$contents \subseteq Dir \times (File \cup Dir)$

$(File \cup Dir) \subseteq Root.{*}contents$

$\forall\ d: Dir \mid \neg\ (d \subseteq d.{\hat{}}contents)$

$\forall\ f: File \mid one\ contents.f$

$\forall\ d: Dir \mid one\ contents.d$

$\{\ \mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\ \}$

$\{\langle \mathbf{R} \rangle\} \subseteq Root \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq Dir \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

$\{\} \subseteq File \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

$\{\} \subseteq contents \subseteq \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}\} \times \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\}$

Fixing the tiny filesystem

Root ⊆ Dir

contents ⊆ Dir × (File ∪ Dir)

(File ∪ Dir) ⊆ Root.*contents

∀ d: Dir | ¬ (d ⊆ d.^contents)

∀ f: File | one contents.f

∀ d: Dir | one contents.d

Minimal unsatisfiable core: an unsatisfiable subset of a formula that becomes satisfiable if any of its members are removed.

$\{ \mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2} \}$

$\{\langle \mathbf{R} \rangle\} \subseteq \text{Root} \subseteq \{\langle \mathbf{R} \rangle\}$

$\{\} \subseteq \text{Dir} \subseteq \{\langle \mathbf{R} \rangle, \langle \mathbf{D_1} \rangle, \langle \mathbf{D_2} \rangle\}$

$\{\} \subseteq \text{File} \subseteq \{\langle \mathbf{F_1} \rangle, \langle \mathbf{F_2} \rangle\}$

$\{\} \subseteq \text{contents} \subseteq \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}\} \times \{\mathbf{R}, \mathbf{D_1}, \mathbf{D_2}, \mathbf{F_1}, \mathbf{F_2}\}$

Resolution-based core extraction

$Root \subseteq Dir$

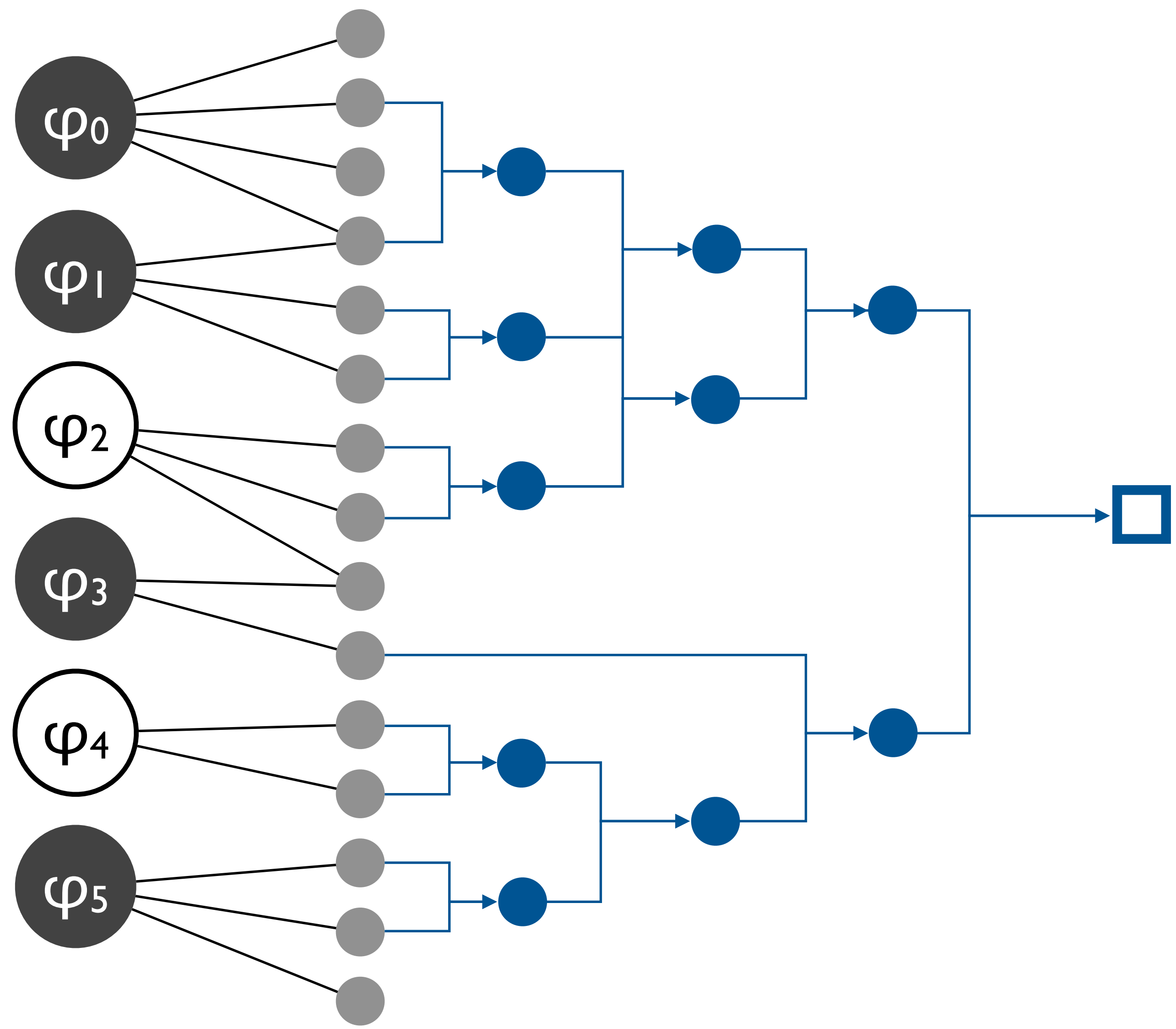
$contents \subseteq Dir \times (File \cup Dir)$

$(File \cup Dir) \subseteq Root.{*}contents$

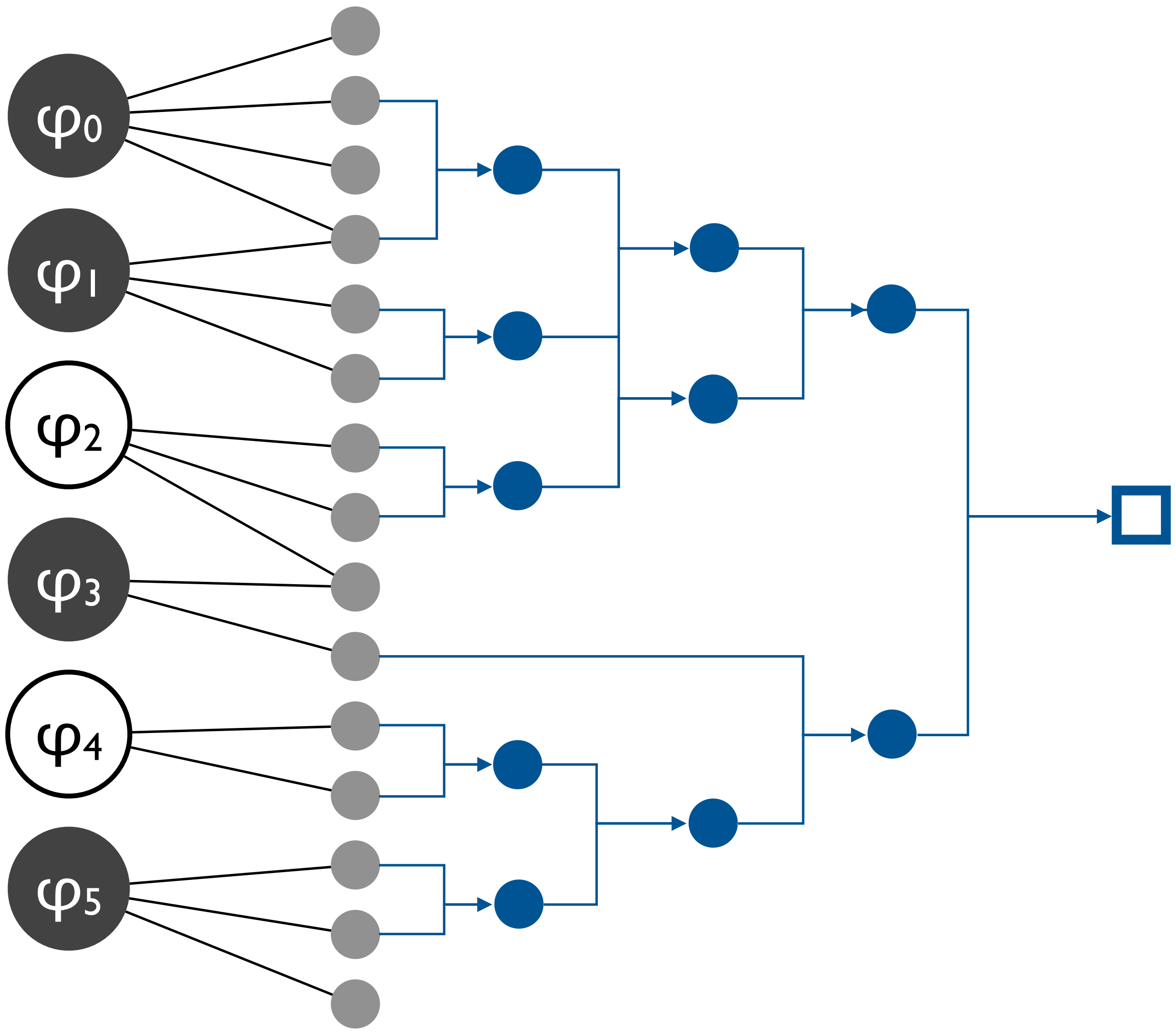
$\forall\ d: Dir \mid \neg\ (d \subseteq d.\hat{}contents)$

$\forall\ f: File \mid one\ contents.f$

$\forall\ d: Dir \mid one\ contents.d$



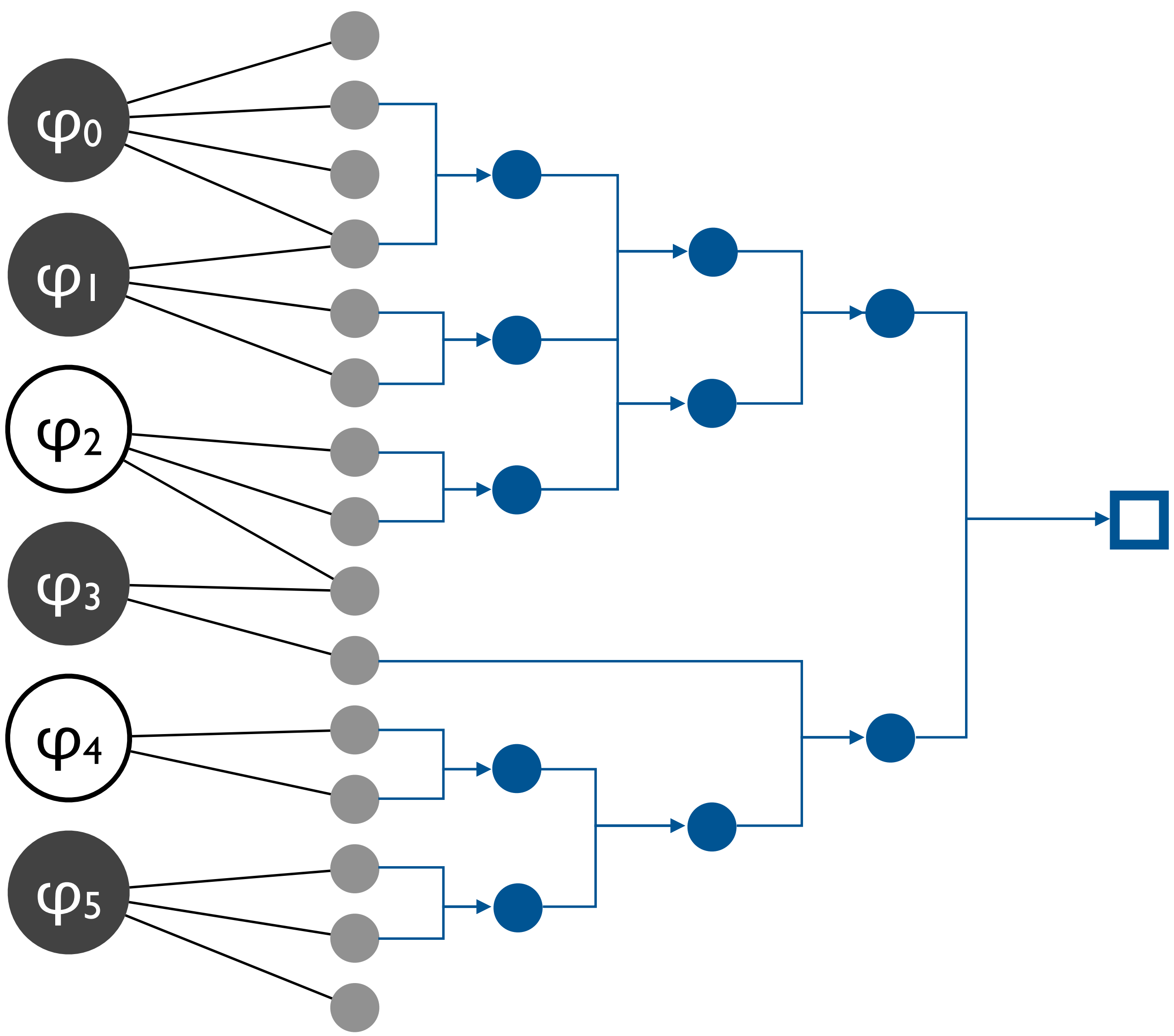
High-level minimal cores from low-level proofs



How to use the proof at the SAT level to find a minimal core at the specification level when

- SAT proof is not minimal
- minimal SAT core may map to a large specification core?

Recycling core extraction



Key idea: minimize core by removing constraints at the specification level but re-use valid resolvents from the previous step so that the solver doesn't have to re-derive them.

Summary

Today

- Finite model finding for first-order logic with quantifiers, relations, and transitive closures

Next lecture

- Reasoning about program correctness