Exploring Scenario Exploration

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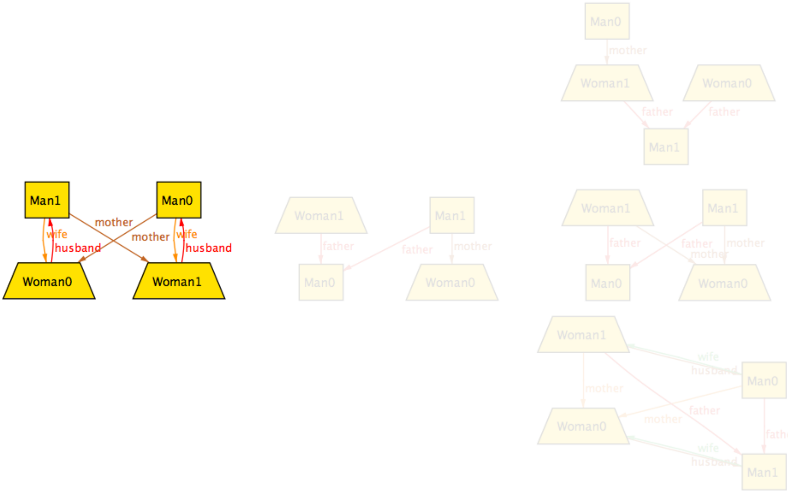
Introduction

- *Model finders* search for models that satisfy a given formula;
- Important at early MDE development stages to quickly generate *scenarios* and validate the specification;
- *Alloy*, and the underlying finder *Kodkod*, have proven suitable for this task;
- Limited usefulness: *no control* on how scenarios are generated:
  - Generate minimal / maximal scenarios;
  - Generate next closest / farthest scenarios;
  - Adapt to specification evolution;
  - ...

"I'm My Own Grandpa" in Alloy

```
abstract sig Person {
  father  : lone Man,
  mother  : lone Woman
}
sig Man extends Person {
  wife    : lone Woman
}
sig Woman extends Person {
  husband : lone Man
}
fact {
  no p:Person | p in p.^(mother+father)     // Biology
  wife = ~husband                           // Terminology
  no (wife+husband) & ^(mother+father)      // SocialConvention
  Person in                                 // NoSolitary
    Person.(mother+father+~mother+~father+wife+husband)
}
run {} for exactly 2 Man, exactly 2 Woman
```

"I'm My Own Grandpa" in Alloy



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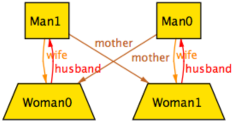

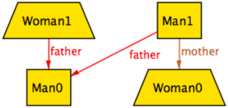

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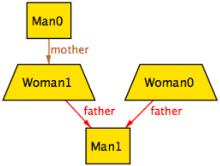

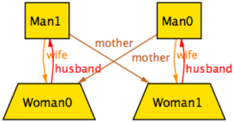

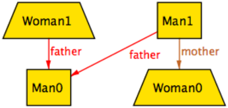

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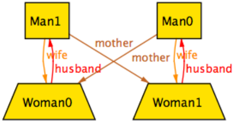

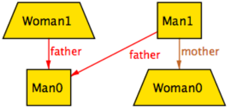

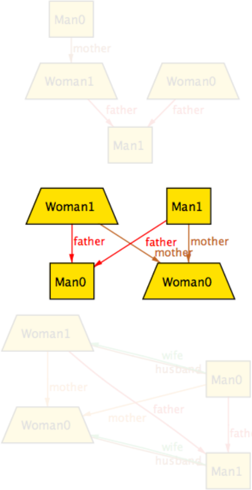

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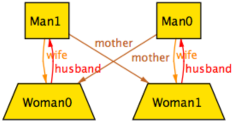
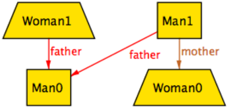
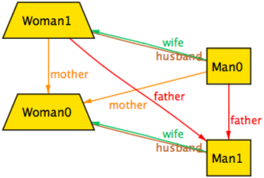
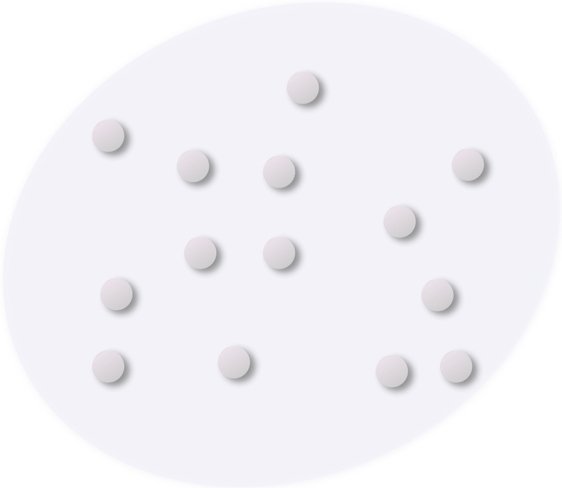






Motivation



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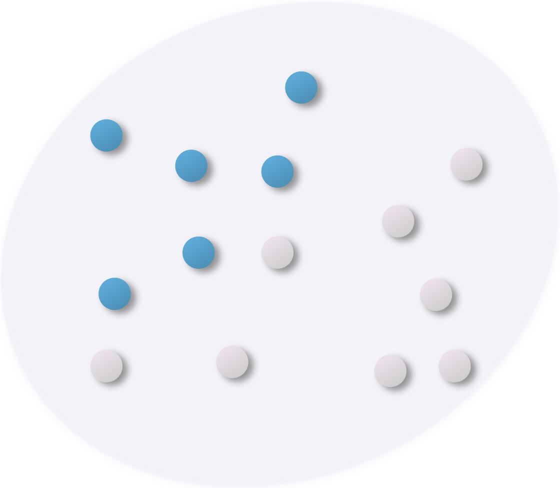

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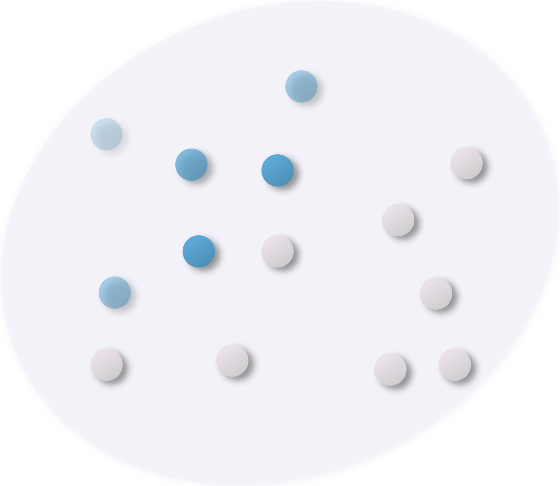

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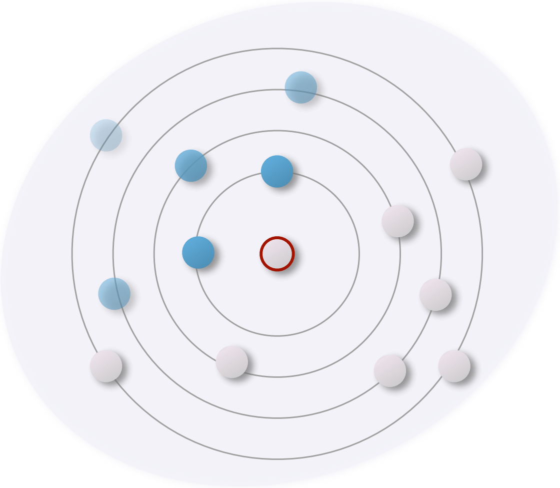

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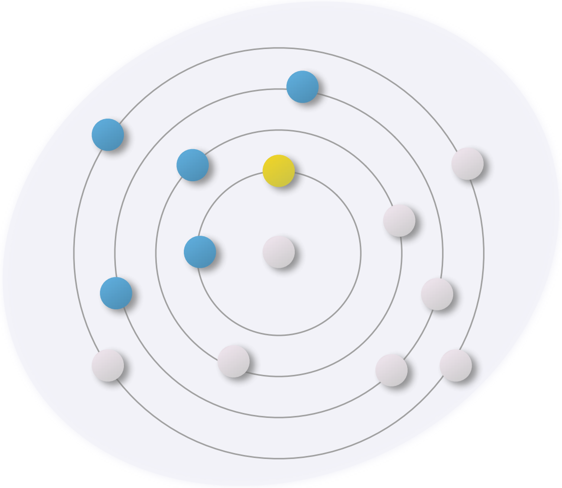

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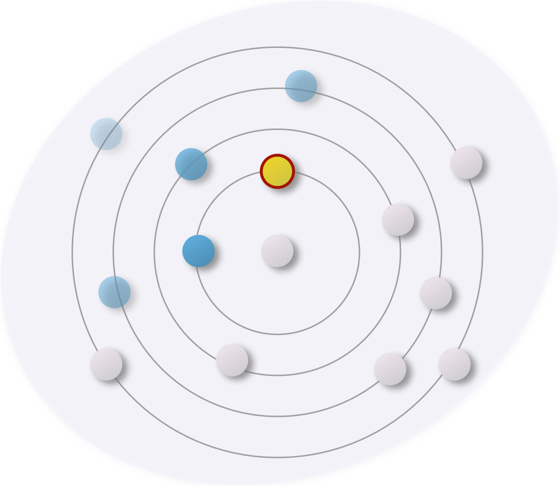

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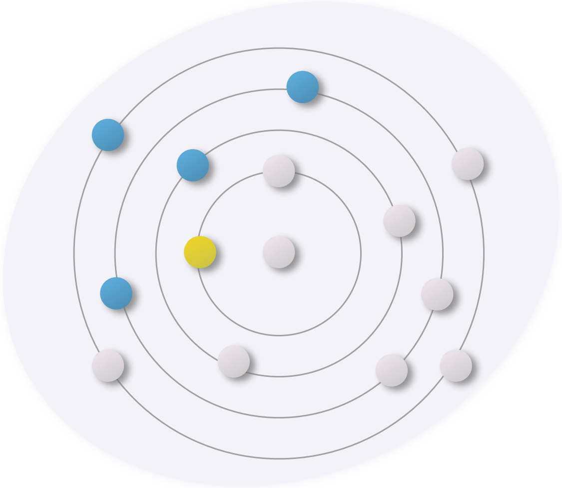


Overview

- We formalize the notion of *weighted target-oriented model finding*;
- Kodkod is extended to support such model finding problems;
- We explore a set of *scenario exploration operations* over them;
- The Alloy Analyzer is extended to support these scenario exploration operations.

Kodkod

- Kodkod = relational logic + partial instances;
- Relational logic:
  - High-level specification language;
  - Favors a navigational style similar to OO;
  - Includes closures to express reachability properties;
- Partial instances:
  - Capture a priori knowledge about the desired outcome;
  - Bound the set of admissible instances (by specifying which elements may or must be present).

Model Finding

- A *model finding problem* $\langle \mathcal{A}, L, U, \phi \rangle \in \mathcal{P}$ consists of:
  - a universe of atoms $\mathcal{A}$, from which tuple sets $\mathcal{T}$ are drawn;
  - lower- and upper-bounds $L, U : \mathcal{R} \to \mathcal{T}$ that define and bound the free relational variables $\mathcal{R}$;
  - a relational formula ϕ over $\mathcal{R}$ variables.
- Model finding returns (arbitrary) bindings $B : \mathcal{R} \to \mathcal{T}$ within L and U that satisfy ϕ.

"I'm My Own Grandpa" in Kodkod

```
{M0,M1,W0,W1}

Man     : ({M0,M1},{M0,M1})
Woman   : ({W0,W1},{W0,W1})
father  : ({},{(M0,M0),(M0,M1),(M1,M0),(M1,M1),
               (W0,M0),(W0,M1),(W1,M0),(W1,M1)})
mother  : ({},{(M0,W0),(M0,W1),(M1,W0),(M1,W1),
               (W0,W0),(W0,W1),(W1,W0),(W1,W1)})
wife    : ({},{(M0,W0),(M1,W0),(M0,W1),(M1,W1)})
husband : ({},{(W0,M0),(W1,M0),(W0,M1),(W1,M1)})

all p:Man | lone p.wife && all p:Woman | lone p.husband
all p:Man+Woman | lone p.father && lone p.mother
all p:Man+Woman | !(p in p.^(mother+father))
wife = ~husband
no ((wife+husband) & ^(mother+father))
Man+Woman in (Man+Woman).(father+mother+~father+~mother+wife+husband)
```

Target-oriented Model Finding

- A *weighted target-oriented model finding problem* $\langle \mathcal{A}, L, U, T, w, \phi \rangle \in \mathcal{P}$ consists of:
  - a regular model finding problem $\langle \mathcal{A}, L, U, \phi \rangle$;
  - targets $T : \mathcal{R} \to \mathcal{T}$ for some of the $\mathcal{R}$ variables within the bounds;
  - weights $w : \mathcal{R} \to \mathbb{N}_0$ for some of the $\mathcal{R}$ variables.
- Model finding returns bindings $B : \mathcal{R} \to \mathcal{T}$ that are solutions of $\langle \mathcal{A}, L, U, \phi \rangle$ and minimize the following distance:

$$\sum_{r \in \operatorname{dom} W} w(r)|B(r) \ominus T(r)| + \sum_{r \in \operatorname{dom} T \setminus \operatorname{dom} W} |B(r) \ominus T(r)|$$

"I'm My Own Grandpa" in Target-oriented Kodkod

```
{M0,M1,W0,W1}

Man     : ({M0,M1},{M0,M1},{M0,M1},3)
Woman   : ({W0,W1},{W0,W1},{W0,W1},3)
father  : ({},{(M1,M0),(W1,M0)},{(M0,M0),(M0,M1),(M1,M0),(M1,M1),
                                 (W0,M0),(W0,M1),(W1,M0),(W1,M1)},3)
mother  : ({},{(M1,W0)},{(M0,W0),(M0,W1),(M1,W0),(M1,W1),
                         (W0,W0),(W0,W1),(W1,W0),(W1,W1)},3)
wife    : ({},{},{(M0,W0),(M1,W0),(M0,W1),(M1,W1)},1)
husband : ({},{},{(W0,M0),(W1,M0),(W0,M1),(W1,M1)},1)

all p:Man | lone p.wife && all p:Woman | lone p.husband
all p:Man+Woman | lone p.father && lone p.mother
all p:Man+Woman | !(p in p.^(mother+father))
wife = ~husband
no ((wife+husband) & ^(mother+father))
Man+Woman in (Man+Woman).(father+mother+~father+~mother+wife+husband)
```

Scenario Exploration

- State transition system with model finding problems as states;
- Generates the first problem:

$$\text{init} : \mathcal{S} \rightarrow \mathcal{P}$$

- Given the previous solution, generates the succeeding problem:

$$\text{next} : \mathcal{P} \times (\mathcal{R} \rightarrow \mathcal{T}) \rightarrow \mathcal{P}$$

Embedding Specifications

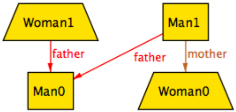
- A specification S is embedded in Kodkod as:

$$[\![\mathsf{S}]\!] = \langle \mathcal{A}_\mathsf{S}, L_\mathsf{S}, U_\mathsf{S}, \{\}, \underline{1}, \phi_\mathsf{S} \rangle$$

- Atoms are reified as relations:

$$\forall A \in \mathcal{A} | A \in \mathcal{R} \wedge L(A) = U(A) = \{A\}$$

- $[B]_=$ tests whether the value of the relations is that of B:

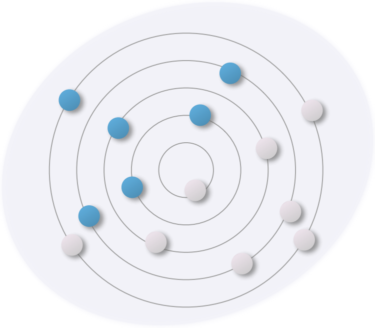


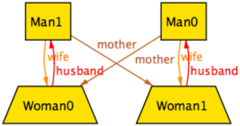

```
M0 + M1             = Man     and
W0 + W1             = Woman   and
M1->M0 + W1->M0     = father  and
M1->W0              = mother  and
none->none          = wife    and
none->none          = husband
```

Regular Generation

- Arbitrary scenarios.

$$\mathrm{init}(S) = \langle \mathcal{A}_S, L_S, U_S, \{\}, \underline{1}, \phi_S \rangle$$

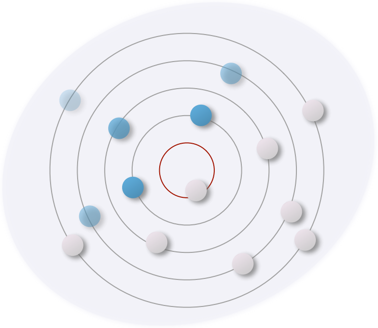




Minimal Generation

- Minimal scenarios.

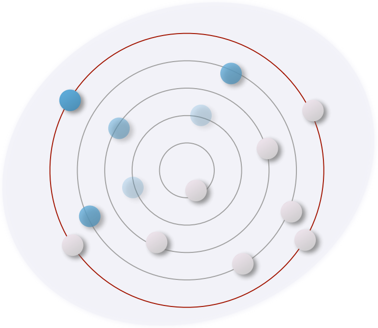
$$\mathsf{init}_{\perp}(\mathsf{S}) = \langle \mathcal{A}_{\mathsf{S}}, L_{\mathsf{S}}, U_{\mathsf{S}}, L_{\mathsf{S}}, \underline{1}, \phi_{\mathsf{S}} \rangle$$

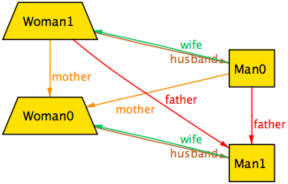


Maximal Scenarios

- Maximal scenarios (high complexity).

$$\text{init}_{\top}(\mathsf{S}) = \langle \mathcal{A}_{\mathsf{S}}, L_{\mathsf{S}}, U_{\mathsf{S}}, U_{\mathsf{S}}, \underline{1}, \phi_{\mathsf{S}} \rangle$$



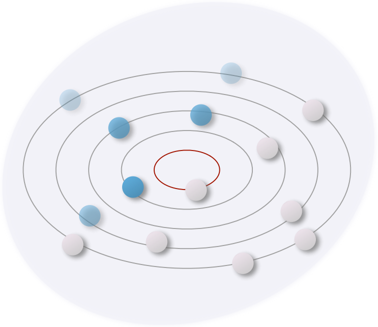


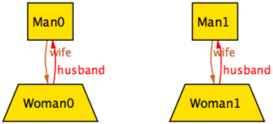
Weighted Generation

- Control the notion of 'minimal' and 'maximal' with w.

$$\mathrm{init}^{w}_{\perp}(\mathsf{S}) = \langle \mathcal{A}_{\mathsf{S}}, L_{\mathsf{S}}, U_{\mathsf{S}}, L_{\mathsf{S}}, w, \phi_{\mathsf{S}} \rangle$$

$$\mathrm{init}^{w}_{\top}(\mathsf{S}) = \langle \mathcal{A}_{\mathsf{S}}, L_{\mathsf{S}}, U_{\mathsf{S}}, U_{\mathsf{S}}, w, \phi_{\mathsf{S}} \rangle$$

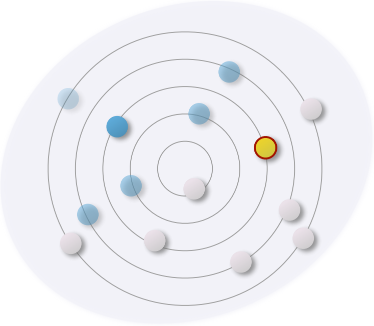


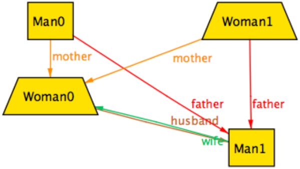


Generation from Instance

- Restart from a previously known instance B.

$$\mathrm{init}_B(\mathsf{S}) = \langle \mathcal{A}_\mathsf{S}, L_\mathsf{S}, U_\mathsf{S}, B, \underline{1}, \phi_\mathsf{S} \rangle$$

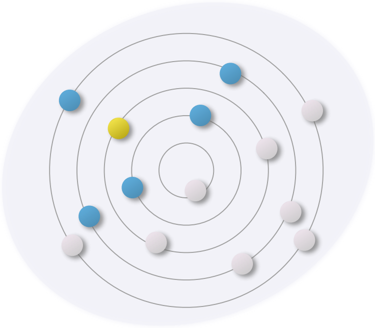


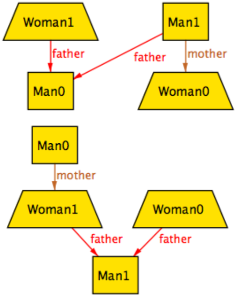


Regular Iteration

- Arbitrary solution.

$$\text{next}(\langle \mathcal{A}, L, U, \_, \_, \phi \rangle, B_0) = \langle \mathcal{A}, L, U, \{\}, \underline{1}, \phi \wedge \neg [B_0]_= \rangle$$





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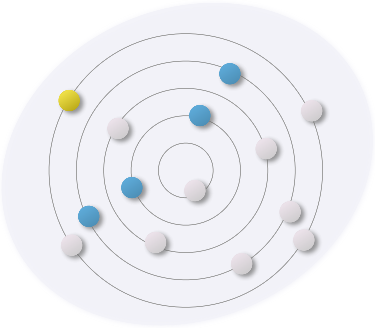
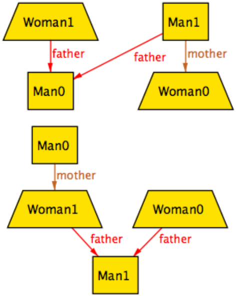
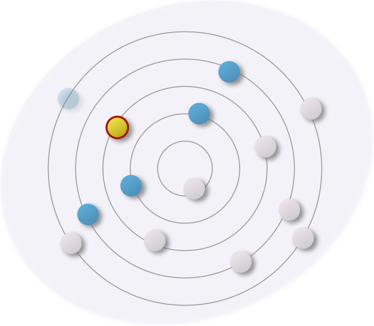


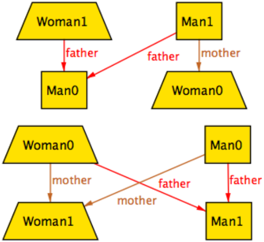


Least-change Iteration

- Generate solutions closest to the current one.

$$\text{next}_{\perp}(\langle \mathcal{A}, L, U, \_, \_, \phi \rangle, B_0) = \langle \mathcal{A}, L, U, B_0, \underline{1}, \phi \wedge \neg [B_0]_= \rangle$$





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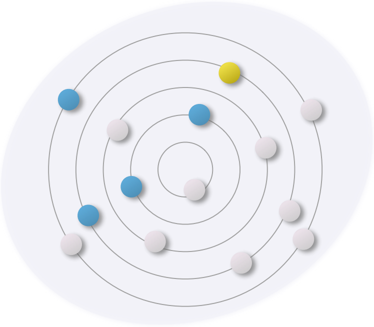
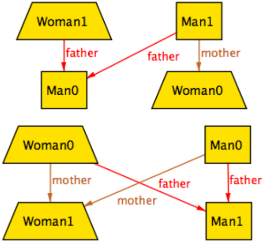
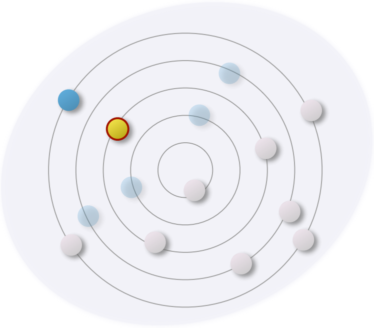


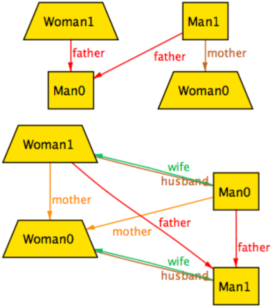


Most-change Iteration

- Generate solutions farthest from the current one.

$$\mathrm{next}_{\top}(\langle \mathcal{A}, L, U, \_, \_, \phi \rangle, B_0) = \langle \mathcal{A}, L, U, \overline{B_0}, \underline{1}, \phi \wedge \neg [B_0]_{=} \rangle$$





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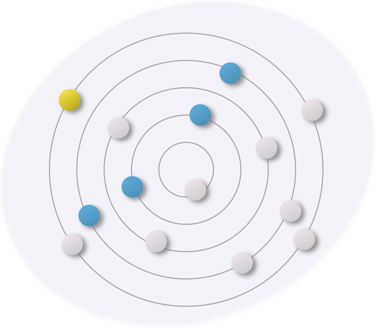

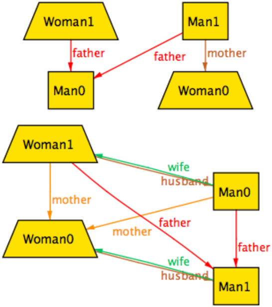

Other Iteration Operations

- *Weighted iteration*: control the notion of least- and most-change with w.

$$\mathsf{next}^{w}_{\perp}(\langle \mathcal{A}, L, U, \_, \_, \phi\rangle, B_0) = \langle \mathcal{A}, L, U, B_0, w, \phi \wedge \neg[B_0]_=\rangle$$

$$\mathsf{next}^{w}_{\top}(\langle \mathcal{A}, L, U, \_, \_, \phi\rangle, B_0) = \langle \mathcal{A}, L, U, \overline{B_0}, w, \phi \wedge \neg[B_0]_=\rangle$$

- *Circular iteration*: circulate a fixed preferred solution T.

$$\mathsf{next}_T(\langle \mathcal{A}, L, U, \_, \_, \phi\rangle, B_0) = \langle \mathcal{A}, L, U, T, \underline{1}, \phi \wedge \neg[B_0]_=\rangle$$

- *Extended iteration*: introduce a new constraint ψ.

$$\mathsf{next}_\psi(\langle \mathcal{A}, L, U, \_, \_, \phi\rangle, B_0) = \langle \mathcal{A}, L, U, B_0, \underline{1}, \phi \wedge \psi\rangle$$

Alloy Analyzer Extension

- Kodkod was extended to deploy PMax-SAT solvers with weights;
- The Alloy Analyzer was extended to support Kodkod with weighted target-oriented model finding;
- Implemented support for $\mathsf{init}_\perp$, $\mathsf{init}_\top$, $\mathsf{next}^w_\perp$ and $\mathsf{next}^w_\top$ as proof of concept;
- Seamless integration to the regular Alloy user;
  - Weights are stored in the theme.

Conclusions

- Scenario exploration operations formalized over weighted target-oriented problems;
- New functionalities improve the usefulness of the Alloy Analyzer in scenario exploration;
- Subsumes previously proposed scenario exploration techniques;

- *Extension*: Implement the additional operations in the Analyzer;
- *Usability*: Infer weights from user feedback;
- *Evaluation*: Empirical study on the effectiveness of new scenario exploration operations.