Advancing Declarative Programming

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What is **Declarative** Programming?

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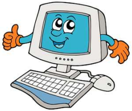
- say **what** , not how 
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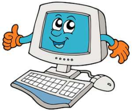
- say **what**  , not how 
  - describe what the program is intended to do in some terms that are both expressive and easy to use
- *"It would be very nice to input this description into some suitably programmed computer, and get the computer to translate it automatically into a subroutine"*

  \- C. A. R. Hoare ["An overview of some formal methods for program design", 1987]

Spectrum of The Declarative Programming Space

spec	formal logic		**spec**	DSL
engine	sophisticated search		**engine**	translation/compilation
apps	complex algorithms, constraint solving		**apps**	domain-specific uses

Spectrum of The Declarative Programming Space

(my previous work)

executable specs for java

program synthesis

Squander

Jennisys

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ALLOY* [ABZ'12,SCP'14,ICSE'15]

- more powerful constraint solver
- capable of solving a whole new category of formal specifications

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SUNNY [Onward'13]

- model-based web framework
- reactive, single-tier, policy-agnostic
- what instead of how

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• unified specification & implementation language

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ALLOY*: Higher-Order Constraint Solving

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typical uses of the alloy analyzer

• bounded software verification	→	but no software synthesis
• analyze safety properties of event traces	→	but no liveness properties
• find a safe full configuration	→	but not a safe partial conf
• find an instance satisfying a property	→	but no min/max instance

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higher-order

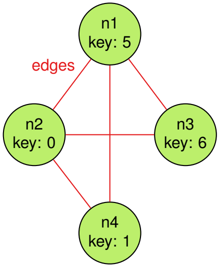
ALLOY*

- capable of automatically solving arbitrary higher-order formulas

First-Order Vs. Higher-Order: `clique`

first-order: finding a graph and a clique in it

- every two nodes in a clique must be connected



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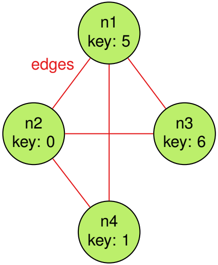


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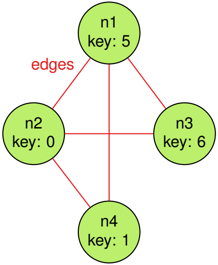


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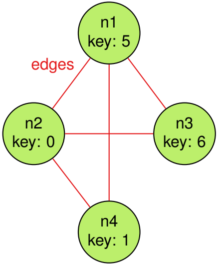


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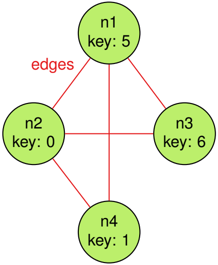


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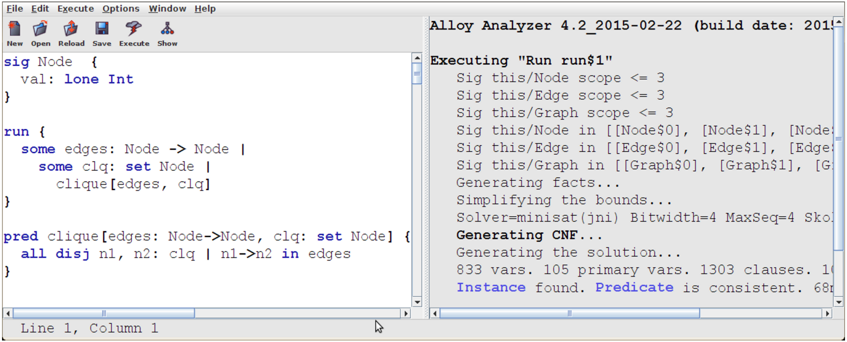

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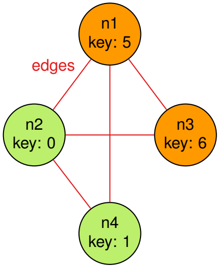


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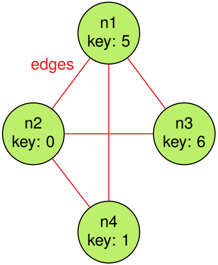
- there is no other clique with more nodes



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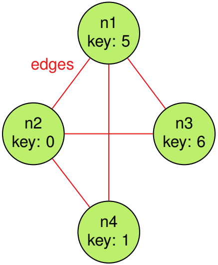


```
pred maxClique[edges: Node->Node,  clq: set Node] {
  clique[edges, clq]
  all ns: set Node |
    not (clique[edges, ns] and #ns > #clq)
}

run {
  some edges: Node -> Node |
    some clq: set Node |
      maxClique[edges, clq]
}
```

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expressible but <u>not solvable</u> in Alloy!

File Edit Execute Options Window Help

New Open Reload Save Execute Show

```
sig Node { key: Int }

pred clique[edges: Node->Node, clq: set Node] {
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}

pred maxClique[edges: Node->Node, clq: set Node] {
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  all ns: set Node |
    not (clique[edges, ns] and #ns > #clq)
}

run { // find a maximal clique in a given graph
  let edges = Node -> Node |
  some clq: set Node | maxClique[edges, clq]
}
```

Line 10, Column 7

```
Alloy Analyzer 4.2_2015-02-22 (build date: 2015-02-2

Executing "Run run$1"
   Sig this/Node scope <= 3
   Sig this/Node in [[Node$0], [Node$1], [Node$2]]
   Generating facts...
   Simplifying the bounds...
   Solver=minisatprover(jni) Bitwidth=4 MaxSeq=4 Sko
   Generating CNF...
   Generating the solution...
A type error has occurred:  (see the stacktrace)
Analysis cannot be performed since it requires highe
quantification that could not be skolemized.
```

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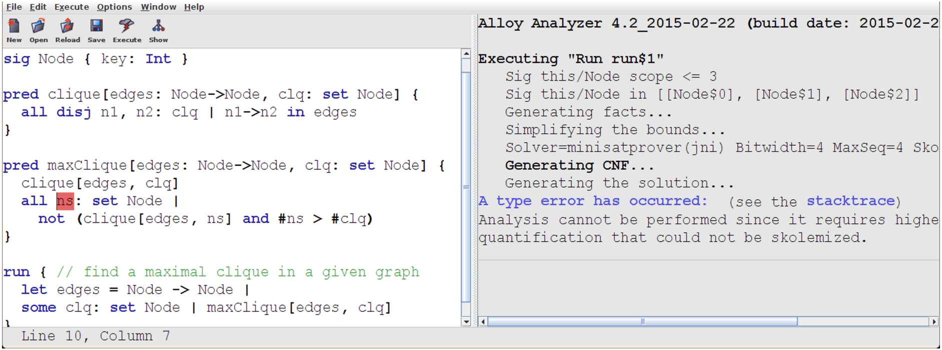

- **definition** of higher-order (as in Alloy):
  - quantification over all sets of atoms

Solving `maxClique` Vs. Program **Synthesis**

program synthesis	**maxClique**
find some program AST s.t., for all possible values of its inputs its specification holds	find some set of nodes s.t., it is a clique and for all possible other sets of nodes not one is a larger clique

program synthesis

```
some program: ASTNode |
  all env: Var -> Val |
    spec[program, env]
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some clq: set Node |
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similarities:

- the same **`some`**/**`all`** (∃∀) pattern
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how do existing program synthesizers work?

CEGIS: A Common Approach for Program Synthesis

original synthesis formulation

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run { some prog: ASTNode | all env: Var -> Val | spec[prog, env] }
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Counter-Example Guided Inductive Synthesis [Solar-Lezama, ASPLOS'06]

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1. search: find *some* program and *some* environment s.t. the spec holds, i.e.,

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2. verification: check if `$prog` holds for *all* possible environments:
   ```
   check { all env: Var -> Val | spec[$prog, env] }
   ```
   Done if verified; else, a concrete *counterexample* `$env` is returned as witness.

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3. induction: *incrementally* find a new program that *additionally* satisfies `$env`:
   ```
   run { some prog: ASTNode |
             some env: Var -> Val | spec[prog, env] and spec[prog, $env]}
   ```
   If UNSAT, return no solution; else, go to 2.

ALLOY* key insight

CEGIS can be applied to solve **arbitrary higher-order** formulas

ALLOY*

generality

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- key solver features for efficient implementation:
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wide applicability (in contrast to specialized synthesizers)

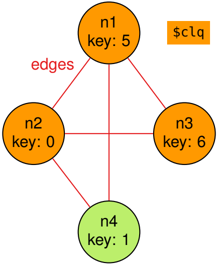
- program synthesis: `SyGuS` benchmarks
- security policy synthesis: `Margrave`
- solving graph problems: `max-cut`, `max-clique`, `min-vertex-cover`
- bounded verification: `Turán's` theorem

Generality: Nested Higher-Order Quantifiers

```
fun keysum[nodes: set Node]: Int {
  sum n: nodes | n.key
}

pred maxMaxClique[edges: Node->Node, clq: set Node] {
  maxClique[edges, clq]
  all ns: set Node |
    not (maxClique[edges,clq2] and
         keysum[ns] > keysum[clq])
}

run maxMaxClique for 5
```




```
Executing "Run maxMaxClique for 5"
   Solver=minisat(jni) Bitwidth=5 MaxSeq=5 SkolemDepth=3 Symmetry=20
   13302 vars. 831 primary vars. 47221 clauses. 66ms.
   Solving...
   [Some4All] started (formula, bounds)
   [Some4All]  candidate found (candidate)
   [Some4All]   verifying candidate (condition, pi) counterexample
                |- [OR] solving splits (formula)
                |- [OR]   trying choice (formula, bounds) unsat
                |- [OR]   trying choice (formula, bounds) instance
                |-   [Some4All] started (formula, bounds)
                |-   [Some4All]  candidate found (candidate)
                |-   [Some4All]   verifying candidate (condition, pi) success (#cand = 1)
   [Some4All]   searching for next candidate  (increment)
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   [Some4All]   verifying candidate (condition, pi) success (#cand = 3)
                |- [OR] solving splits (formula)
                |- [OR]   trying choice (formula, bounds) unsat
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                |-   [Some4All] started (formula, bounds)
   Instance found. Predicate is consistent. 490ms.
```

Semantics: General Idea

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     - → `FOL` : first-order formula
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     - → `FOL` : first-order formula
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  3. solve using the following decision procedure
     - → `FOL` : solve directly with Kodkod (first-order relational solver)
     - → `OR` : solve each disjunct separately
     - → `∃∀` : apply CEGIS

ALLOY* Implementation **Caveats**

```
some prog: Node |
  acyclic[prog]
  all eval: Node -> (Int+Bool) |
    semantics[eval] implies spec[prog, eval]
```

$\rightarrow$

$\exists\forall($*conj*: `$prog in Node and acyclic[$prog],`
eQuant: `some eval ...,`
aQuant: `all eval ...)`

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- `solve` $\neg aQuant$ against the `$cand` *partial instance*

$\rightarrow$ *counterexample* `$cex`: value of the $eQuant.var$ relation

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- partial solution known upfront
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- use *incremental solving* to add

  replace $eQuant.var$ **with** `$cex` **in** $eQuant.body$

  to previous search condition

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- `solve` *conj* $\wedge$ *eQuant*

→ *candidate instance* `$cand`: values of all relations except *eQuant*.*var*

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- `solve` $\neg$*aQuant* against the `$cand` *partial instance*

→ *counterexample* `$cex`: value of the *eQuant*.*var* relation

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- use *incremental solving* to add
  `replace` *eQuant*.*var* **`with`** `$cex` **`in`** *eQuant*.*body*
  to previous search condition

incremental solving
- continue from prev solver instance
- the solver reuses learned clauses

ALLOY* Implementation **Caveats**

```
some prog: Node |
  acyclic[prog]
  all eval: Node -> (Int+Bool) |
    semantics[eval] implies spec[prog, eval]
```

$\rightarrow$

$\exists\forall($*conj*: `$prog in Node and acyclic[$prog],`
eQuant: `some eval ...,`
aQuant: `all eval ...`$)$

1. candidate search

- `solve` *conj* $\wedge$ *eQuant*

$\rightarrow$ *candidate instance* `$cand`: values of all relations except *eQuant.var*

2. verification

- `solve` $\neg$*aQuant* against the `$cand` *partial instance*

$\rightarrow$ *counterexample* `$cex`: value of the *eQuant.var* relation

partial instance
- partial solution known upfront
- enforced using *bounds*

3. induction

- use *incremental solving* to add
  replace *eQuant.var* **with** `$cex` **in** *eQuant.body*
  to previous search condition

incremental solving
- continue from prev solver instance
- the solver reuses learned clauses

? *what if the increment formula is not first-order*

– optimization 1: use its weaker "first-order version"

ALLOY* **Optimization**

2. domain constraints

"for all possible `eval`, if the semantics hold then the spec must hold"

vs.

"for all `eval` that satisfy the semantics, the spec must hold"

ALLOY* **Optimization**

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pred synth[prog: Node] {
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↓
candidate search

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a valid candidate doesn't have to satisfy the `semantics` predicate!

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```
pred synth[prog: Node] {
  all eval: Node -> (Int+Bool) when semantics[eval]
    spec[prog, eval]
}
```

↓

candidate search

```
some prog: Node |
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a valid candidate must satisfy the `semantics` predicate!

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   - ? does ALLOY* scale beyond “toy-sized” graphs

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   - ? power: how many SyGuS benchmarks can be solved with ALLOY*
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Alloy* Evaluation

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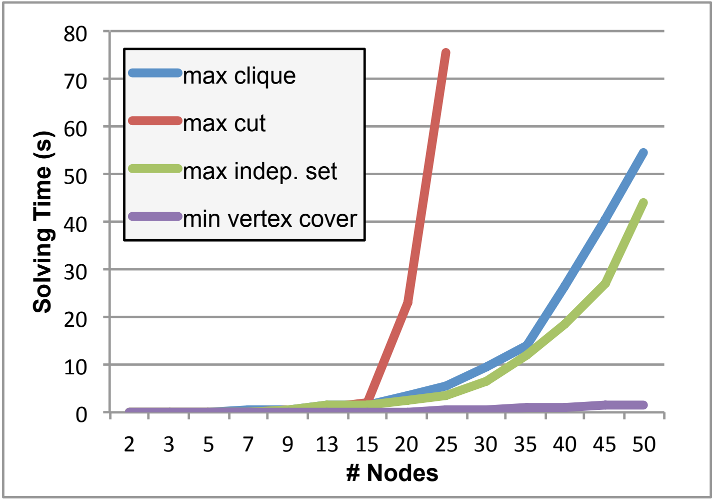
   - ? scalability: how does Alloy* compare to other synthesizers

3. benefits of the two optimizations
   - ? do Alloy* optimizations improve overall solving times

Evaluation: **Graph** Algorithms



Evaluation: Program **Synthesis**

expressiveness

- we extended Alloy to support bit vectors
- we encoded **123/173** benchmarks, i.e., all except "ICFP problems"
  - reason for skipping ICFP: 64-bit bit vectors (not supported by Kodkod)
  - (aside) not one of them was solved by any of the competition solvers

power

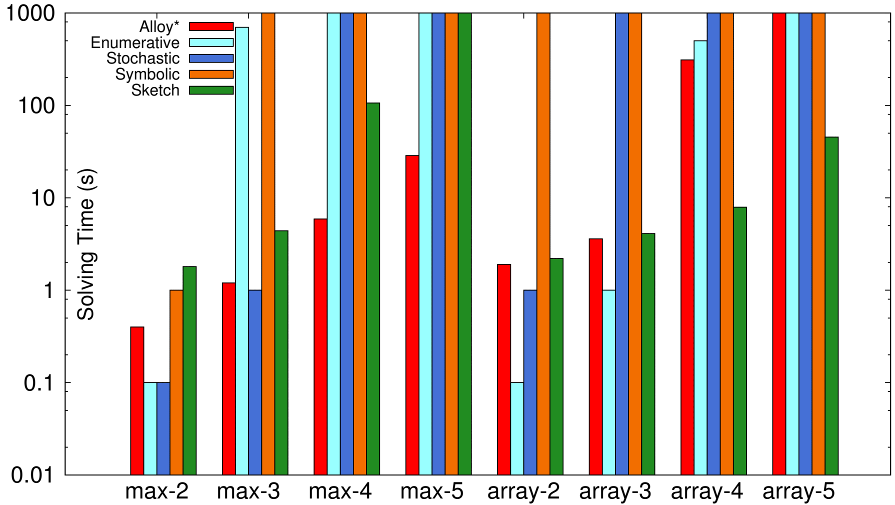
- ALLOY* was able to solve **all** different **categories** of benchmarks
  - integer benchmarks, bit vector benchmarks, let constructs, synthesizing multiple functions at once, multiple applications of the synthesized function

scalability

- many of the 123 benchmarks are either too easy or too difficult
  → not suitable for scalability comparison
- we primarily used the integer benchmarks
- we also picked a few bit vector benchmarks that were too hard for all solvers

Evaluation: Program **Synthesis**

scalability comparison (integer benchmarks)



Evaluation: Program **Synthesis**

scalability comparison (select bit vector benchmarks)

- benchmarks
  - `parity-AIG-d1`: full parity circuit using AND and NOT gates
  - `parity-NAND-d1`: full parity circuit using AND always followed by NOT

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`parity-AIG-d1`

```
sig AIG extends BoolNode {
  left, right: one BoolNode
  invLhs, invRhs, invOut: one Bool
}
pred aig_semantics[eval: Node->(Int+Bool)] {
  all n: AIG |
    eval[n] = ((eval[n.left] ^ n.invLhs) &&
               (eval[n.right] ^ n.invRhs)
              ) ^ n.invOut}
run synth for 0 but -1..0 Int, exactly 15 AIG
```

`parity-NAND-d1`

```
sig NAND extends BoolNode {
  left, right: one BoolNode
}

pred nand_semantics[eval: Node->(Int+Bool)] {
  all n: NAND |
    eval[n] = !(eval[n.left] &&
                eval[n.right])
}
run synth for 0 but -1..0 Int, exactly 23 NAND
```

Evaluation: Program **Synthesis**

scalability comparison (select bit vector benchmarks)

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solving time w/ partial ordering: 20s
solving time w/o partial ordering: 80s

parity-NAND-d1

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    eval[n] = !(eval[n.left] &&
                eval[n.right])
}
run synth for 0 but -1..0 Int, exactly 23 NAND
```

solving time w/ partial ordering: 30s
solving time w/o partial ordering: ∞

Evaluation: Benefits of ALLOY* **Optimizations**

	base	**w/ optimizations**
`max2`	0.4s	0.3s
`max3`	7.6s	0.9s
`max4`	t/o	1.5s
`max5`	t/o	4.2s
`max6`	t/o	16.3s
`max7`	t/o	163.6s
`max8`	t/o	987.3s
`array-search2`	140.0s	1.6s
`array-search3`	t/o	4.0s
`array-search4`	t/o	16.1s
`array-search5`	t/o	485.6s

	base	**w/ optimizations**
`turan5`	3.5s	0.5s
`turan6`	12.8s	2.1s
`turan7`	235.0s	3.8s
`turan8`	t/o	15.0s
`turan9`	t/o	45.0s
`turan10`	t/o	168.0s

ALLOY* Conclusion

ALLOY* **is**

- general purpose constraint solver
- capable of efficiently solving arbitrary higher-order formulas
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- bit-blasting higher-order quantifiers: attempted, deemed intractable
- previously many ad hoc mods to alloy
  - aluminum, razor, staged execution, ...

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why is this important?

- accessible to wider audience, encourages new applications
- potential impact
  - abundance of tools that build on Alloy/Kodkod, for testing, program analysis, security, bounded verification, executable specifications, ...

SUNNY: Model-Based Reactive Web Framework

(my previous work)

executable specs for java

Squander

program synthesis

Jennisys

spec formal logic
engine sophisticated search
apps complex algorithms, constraint solving

ARbY [ABZ'14]

• unified specification & implementation language

spec DSL
engine translation/compilation
apps domain-specific uses

ALLOY* [ABZ'12,SCP'14,ICSE'15]

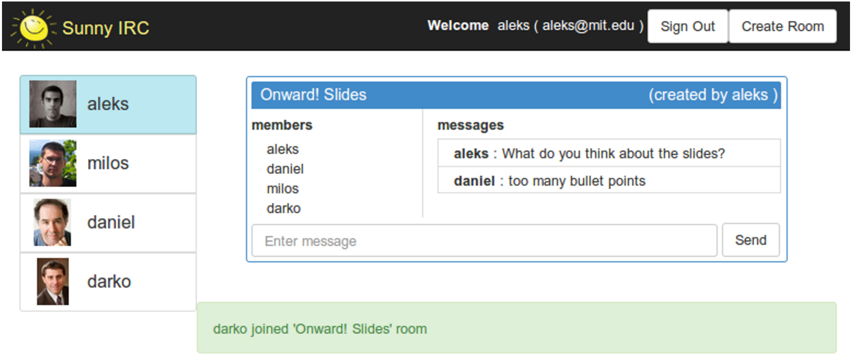
• more powerful constraint solver
• capable of solving a whole new category of formal specifications

SUNNY [Onward'13]

• model-based web framework
• reactive, single-tier, policy-agnostic
• what instead of how

A simple web app: SUNNY IRC

custom-tailored internet chat relay app



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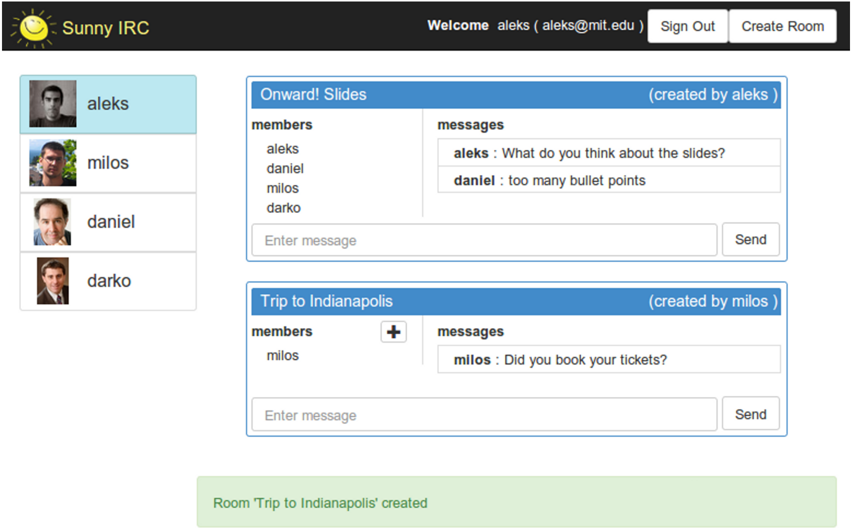

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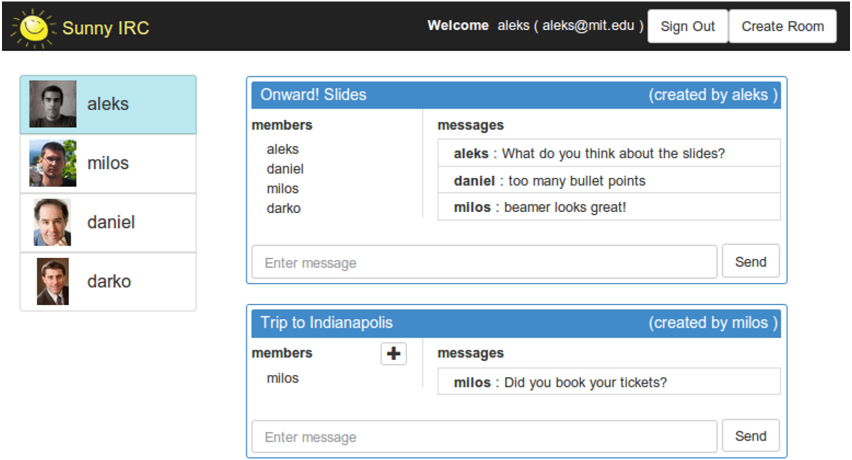

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  - low-level implementation level

exercise:

sketch out a model (design, spec)
for the Sunny IRC application

Sunny IRC: **data model**

```
user class User
# inherited: name, email: Text

 salute: ()-> "Hi #{this.name}"
```

```
record class Msg
 text: Text
 sender: User
 time: Val
```

```
record class ChatRoom
 name: Text
 members: set User
 messages: compose set Msg
```

- record: automatically persisted objects with typed fields
- user: special kind of record, assumes certain fields, auth, etc.
- set: denotes non-scalar (set) type
- compose: denotes ownership, deletion propagation, etc.

Sunny IRC: **machine model**

```
client class Client
  user: User
```

```
server class Server
  rooms: compose set ChatRoom
```

- client: special kind of record, used to represent client machines
- server: special kind of record, used to represent the server machine

Sunny IRC: **event model**

```
event class SendMsg
 from: client: Client
 to:   server: Server

 params:
  room: ChatRoom
  msgText: Text

 requires: () ->
  return "must log in!"    unless this.client?.user
  return "must join room!" unless this.room?.members.contains(this.client.user)

 ensures: () ->
  this.room.messages.push Msg.create(sender: this.client.user
                                     text: this.msgText
                                     time: Date.now())
```

- to, from: sender and receiver machines
- params: event parameters
- requires: event precondition
- ensures: event handler (postcondition)

challenge

how to make the most of this model?

challenge

how to make the most of this model?

goal

make the model executable as much as possible!

Traditional **MVC** Approach

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- boilerplate:
  - write a matching DB schema
  - turn each record into a resource (model class)
  - turn each event into a controller and implement the CRUD operations
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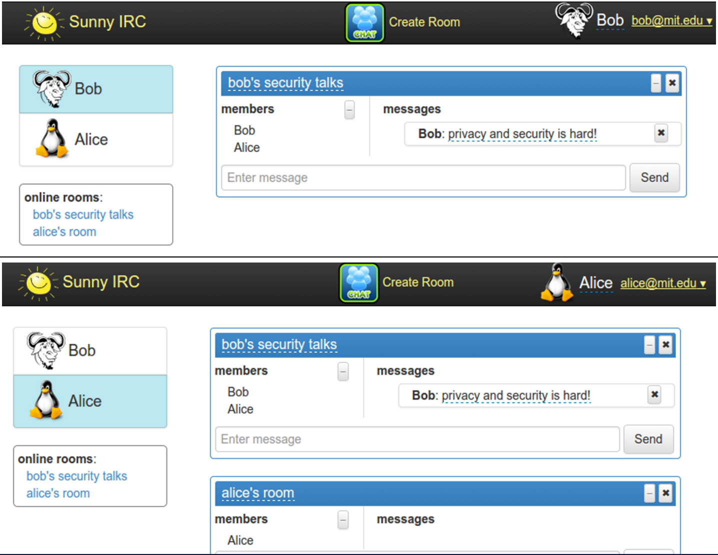
SUNNY demo

demo: responsive GUI without messing with javascript



GUIs in SUNNY: **dynamic templates**

- like standard templating engine with data bindings
- automatically re-rendered when the model changes

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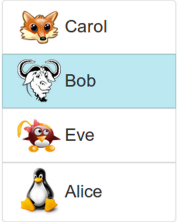
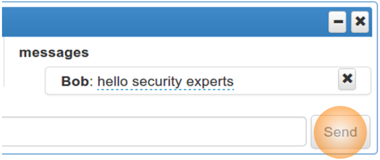
online_users.html

```
<div>
  {{#each Server.onlineClients.user}}
    {{> user_tpl user=this}}
  {{/each}}
</div>
```



GUIs in SUNNY: **binding to events**



GUIs in SUNNY: binding to events

room_tpl.html

```
<div {{SendMsg room=this.room}} >
  <div>
    <input type="text" name="text"
       placeholder="Enter message"
       {{SendMsg_msgText}}
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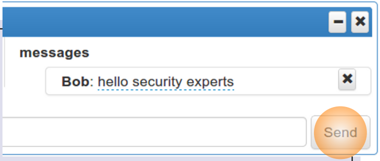
  </div>
  <button {{sunny_trigger}}>Send</button>
</div>
```



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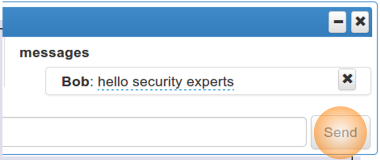

- html5 `data` attributes specify event type and parameters
- dynamically discovered and triggered asynchronously
- no need for any Ajax requests/responses
  - the data-binding mechanism will automatically kick in

Adding New Features: **adding a field**

implement user status messages

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- all it takes:

```
user class User
  status: Text
```

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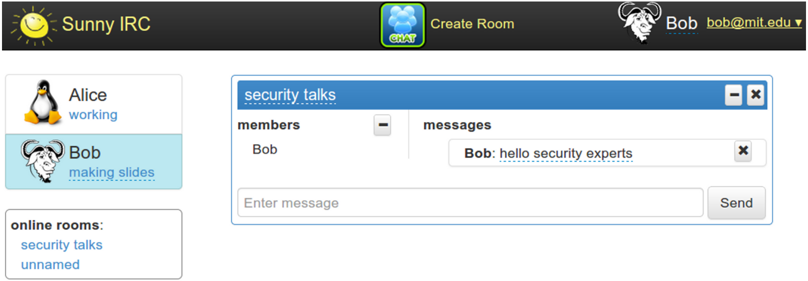

Security/Privacy: **write** policies

forbid changing other people's data

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- declarative and independent from the rest of the system
- automatically checked by the system at each field access

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hide avatars unless the two users share a room

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policy User,
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- **read denied** → empty value returned instead of raising exception

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```

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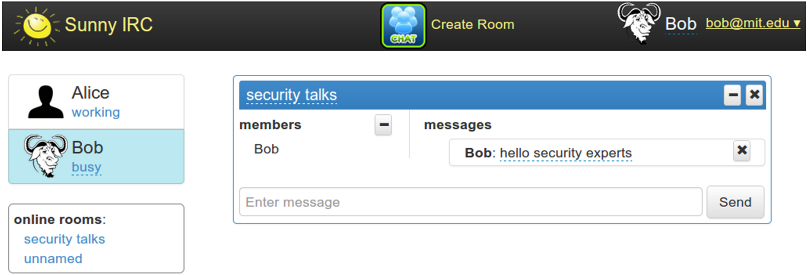
invisible users: hide users whose status is “busy”

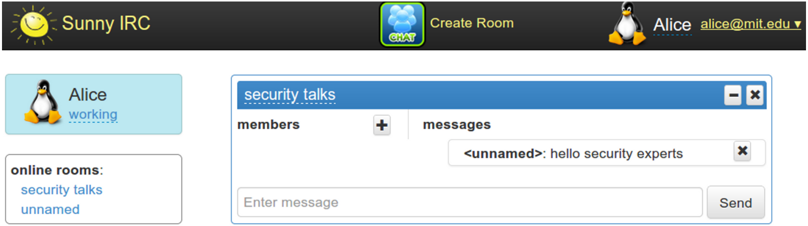
```
policy User,
 find: (users) -> clntUser = this.client?.user
                  return this.allow(filter users, (u) -> u.equals(clntUser) ||
                                                         u.status != "busy")
```

- **find policies** → objects entirely removed from the client-view of the data

Demo: defining **access policies** independently

no GUI templates need to change!





Policy Checking in SUNNY

access control style

- policies attached to fields
- implicit principal: client which issued current request
- evaluate against the dynamic state of the program
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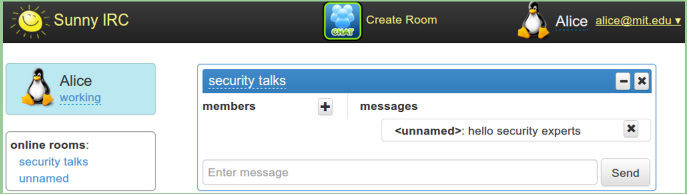
- evaluate against the dynamic state of the program
- policy code executes in the current client context
  - circular dependencies resolved by allowing recursive operations
- policy execution creates reactive server-side dependencies



  - Alice's client doesn't contain Bob's status field at all
  - nevertheless, it automatically reacts when Bob changes his status!

Related Work: Reactive + Policies

	checking policies	enforcing policies	reactive

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Reactive Web (Ur/Web, Elm, Flapjax, Meteor, ...)	✔	✗	✔

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Traditional IF (Resin, Jiff, Dytan, ...)	✔	✗	✗
Reactive Web (Ur/Web, Elm, Flapjax, Meteor, ...)	✔	✗	✔
Enforcing Policies (Jeeves, Hails/LIO, ...)	✔	✔	✗

Related Work: Reactive + Policies

	checking policies	enforcing policies	reactive
UI Frameworks (.NET, XAML, Backbone.js, AngularJS, ...)	✗	✗	✔
Traditional IF (Resin, Jiff, Dytan, ...)	✔	✗	✗
Reactive Web (Ur/Web, Elm, Flapjax, Meteor, ...)	✔	✗	✔
Enforcing Policies (Jeeves, Hails/LIO, ...)	✔	✔	✗
Sunny	✔	✔	✔

Example SUNNY **Apps**

gallery of applications

- internet relay chat
  - implement invisible users with policies
- party planner
  - intricate and interdependent policies for hiding sensitive data
- social network
  - highly customizable privacy settings
- photo sharing
  - similar to “social network”, but in the context of file sharing
- mvc todo
  - from single- to multi-user with policies

SUNNY: the big picture

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declarative nature of SUNNY

- centralized unified model
- single-tier
- uncluttered focus on essentials: **what** the app should do

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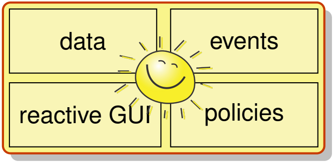

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going forward:

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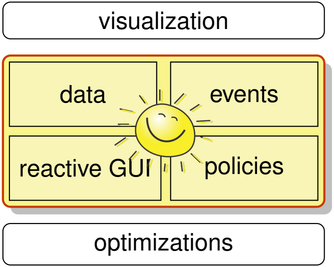
  - scalable/parallelizable back ends
  - clever data partitioning
  - declarative model-based cloud apps
- visualization
  - flexible model-based GUI builder
  - generic & reusable widgets



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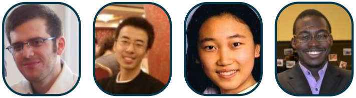

co-authors/ collaborators

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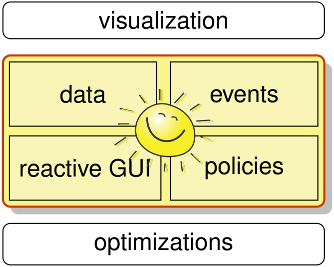

Thank You!

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