lightweight formalism

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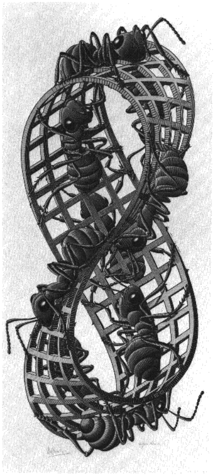
crisis of dependability

We have become dangerously dependent on large software systems whose behavior is not well understood
-- PITAC report, February 1999

software is
- unreliable
  fails in unpredictable ways
- inflexible
  changes make it worse
- expensive
  not much reuse of designs or code

traditional approaches



testing
- can't replicate real world
- tiny proportion of cases covered
- no help with incompleteness of spec

prototyping
- too costly for all but GUI
- temptation to build on prototype
- no guarantees for final product

process
- focus on human resources alone
- insensitive to nature of software
- can be major burden (hence XP, etc)

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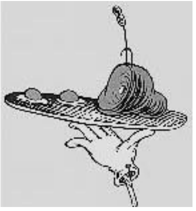
a new approach



models
- capture essence of spec & design
- much smaller than standard docs

patterns
- recognize recurring themes
- codify and reuse them

escaping from code
- not nimble enough for exploration
- poor communication medium
- our basic asset, but a huge liability

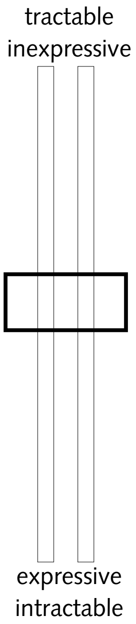
why formalism?

English + pictures
- ambiguous & imprecise
- not analyzable

formal notations
- based on mathematics
- offer simulation, calculation, analysis
  like conventional engineering

Praxis's CDIS system for UK air-traffic
- offered warranty to client
- formal specification: 8% of total cost
- low defect rate, overall cost saving

the alloy approach



automation
- simulation & checking of models
- tradeoff for full analyzability
- exploit Moore's law

process
- incremental and risk-driven
- apply in all phases of development
- at all levels from models to bytecode

origins
- Z formalism (Oxford)
- SAT solving technology (Bell Labs et al)
- semantic data models

applications of alloy

case studies
- Intentional Naming System
- Chord peer-to-peer nameservice
- rule-based access control
- COM interface rules

ongoing work
- models of conflict probe
- network topology protocols
- secure VPN
- object interaction in Java

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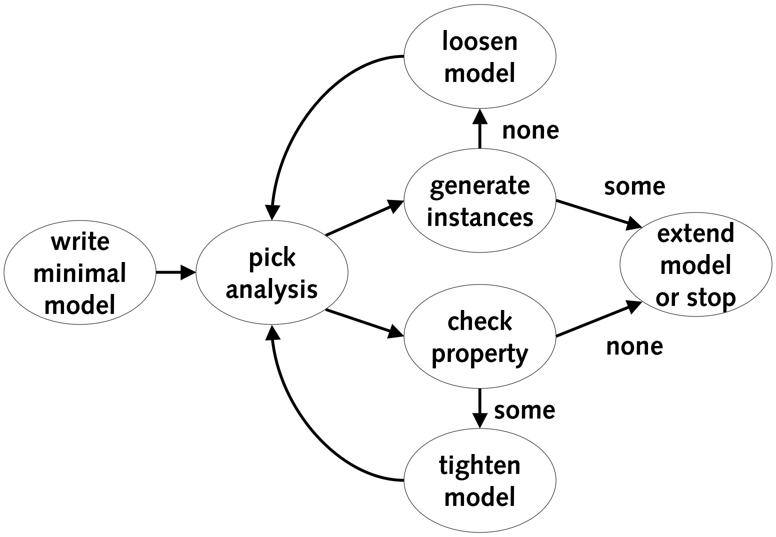
what I'll show you

a typical problem
- from a text-processing program
- express essence in Alloy
- apply automatic analysis

widely applicable
- based on common patterns (Command, Observer)
- same as our 1998 design of CTAS CM
- avoid failure with generic discipline

two levels: abstract design & code
- same notation, same analysis

how to use Alloy



the key to Alloy

partiality
- if my system has property P, will property Q follow?
- is environmental assumption A enough?

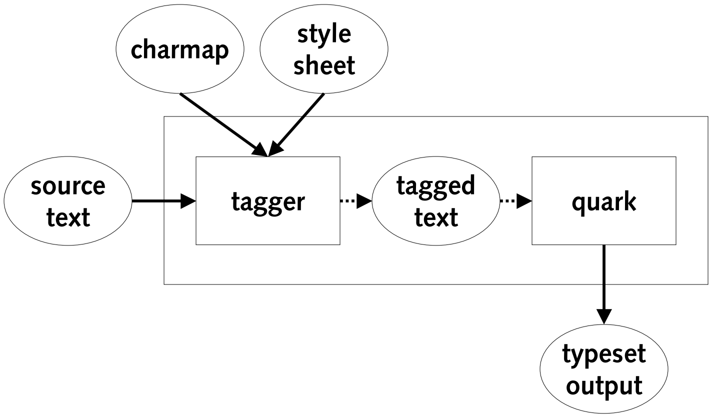
Alloy is a constraint language (ie, a logic)
- the less you say, the more can happen
- can express property
  without mechanism to achieve it

programming languages
- the less you say, the less can happen
- every property has to be achieved

example: tagger program

combine

- typographic quality & flexibility of Quark Xpress
- with convenience of textual input of TeX



charmap

style sheet

source text

tagger

tagged text

quark

typeset output

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sample translation

source

```
\point _A constraint solving technique_. We use a technology developed
previously [\cite{alloy-algorithm}] to analyze the skeleton
```

style sheet

```
<style:point><next:noindent><leader:\periodcentered>
```

charmap

```
<char:periodcentered><index:183>
```

tagged

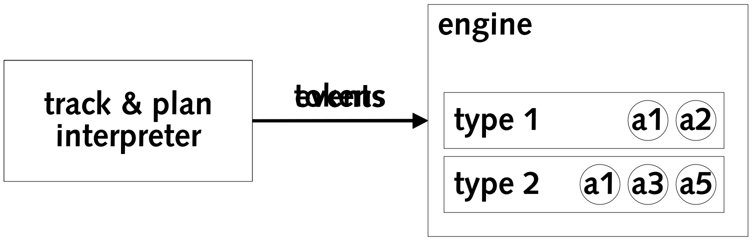
```
@point:<\#183><I>A constraint solving technique<I>. We use a technology
developed previously [6] to analyze the skeleton
```

output

· *A constraint solving technique.* We use a technology developed previously [6] to analyze the skeleton

abstract design

- source converted to stream of tokens
- each token consumed by engine
- engine executes all actions registered for token type
- actions may read & write files, register/deregister actions



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why are actions nice?

- flexible, context-sensitive behaviour
- without one huge, monolithic piece of code
- easy to turn behaviours on & off
- can have subengines: eg, for numbering strings

example: math mode

- $ starts and ends ‘math mode’: puts all letters in italics
- implemented as 2 actions
  for $ token: dollar_action
  for alphabetic string token: italicize_action
- dollar_action
  encapsulates mode
  registers/deregisters italicize_action

alloy basic concepts (ABC)

atom
- an indivisible, uninterpreted entity
  - a token, a token type, a person, a string, an aircraft

set
- an unordered collection of atoms
  - Token, Type, Person, String, Aircraft

relation
- a set of tuples of atoms
  - type: Token -> Type
  - myPhoneBk: Name -> Num
  - phoneBk: Name -> Name -> Num

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alloy operators

set operators

s + t	union
s & t	intersection
s - t	difference

relation operators

s . r	image
p + q	union, etc

```
myPhoneBk: Name -> Num
  myFriends: set Name
  myFriends.myPhoneBk

phoneBk: Name -> Name -> Num
  me: Name
  me.phoneBk
  myFriends.phoneBk

mother: Name -> Name
  me.mother.phoneBk
  (me + me.mother).phoneBk
  me.phoneBk - me.mother.phoneBk
```

a design model of an action machine

```
sig Token {type: Type}
sig Type {}
sig Action {regs, deregs: Type -> Action}
sig Engine {table: Type -> Action}

fun execute (e, e′: Engine, t: Token) {
    doActions (e, e′, t.type.(e.table))
    }

fun doActions (e, e′: Engine, actions: set Action) {
    e′.table = e.table - actions.deregs + actions.regs
    }
```

simulation

```
Token       = to1, to2
Type        = ty1, ty2
Action      = a1, a2
Engine      = e1, e2

type        = to1 -> ty1,           to2 -> ty2
regs        = a1 -> ty1 -> a2,      a2 -> ty2 -> a1
deregs      = a1 -> ty1 -> a1,      a1 -> ty2 -> a1
table       = e1 -> ty1 -> a1,      e2 -> ty1 -> a2

e           = e1
e′          = e2
t           = to1
```

a design question

can implementation do actions in any order?

```
assert {
   all e, ei, e′, e″: Engine, t: Type,
      ax, ay: set t.(e.table) |
         doActions (e, ei, ax) && doActions (ei, e′, ay)
         && doActions (e, e″, ax+ay)
         => e′.table = e″.table
   }
```

counterexample

the scenario
- first doAction registers an action
- second doAction deregisters it
- but aggregate doAction collects deregisters upfront

design challenge

what strategy for order independence?

- must be simple and static

here’s one strategy

- group actions that reg/dereg each other
- say that ≤ 1 action of a group may register for type t
- rule out arbitrary initialization of engine

to check it

- write definition of grouping
- write registration and initialization rules
- recheck assertion

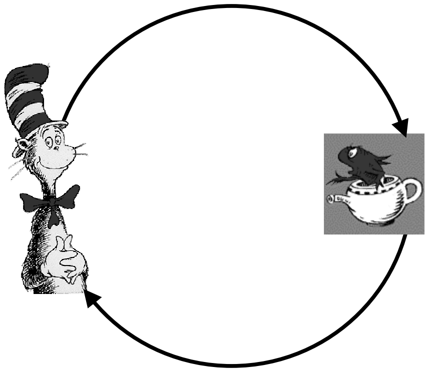
what the rest looked like …

```
sig GroupedAction extends Action {group: set Action}
fact {
    let depends = Action$regs + Action$deregs |
       Action$group = *(depends + ~depends)
    }
fact {Action = GroupedAction}

fact NoClashes () {
    all t: Type | no a: Action, a': a.group - a |
       a + a' in t.Action::regs
    }

fact NoArbitraryInits () {all e: Engine | e.table in Action.regs}
```

experience



- took me 2 hours to develop this strategy
- lots of false attempts on the way
  rapidly exposed by tool
- about 100 lines of Alloy written
- for 3 actions, 10^54 cases
  counterexample < 1 second
  exhausting space < 1 minute

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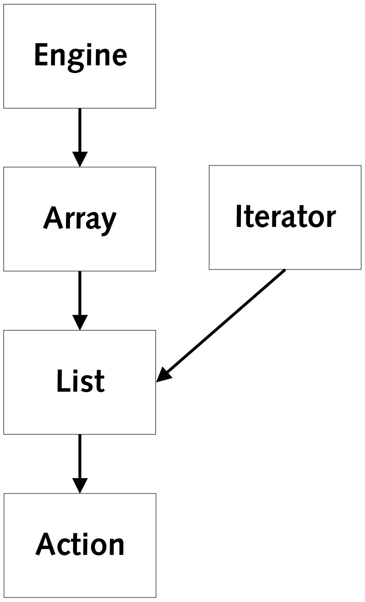
moving to code

Engine class
- holds action lists
- in array indexed on token type

consuming token
- creates iterator object
- yields each action in turn
  and performs it



code of engine

```
private LinkedList [] table;
…
public void register (Action action, int type) {
   actions[type].add (action);
   }

public void consume_token (Token token) {
   Iterator i = table[token.type].iterator ();
   while (i.hasNext ()) {
      Action a = (Action) i.next ();
      a.perform (token, i);
      }
   }
```

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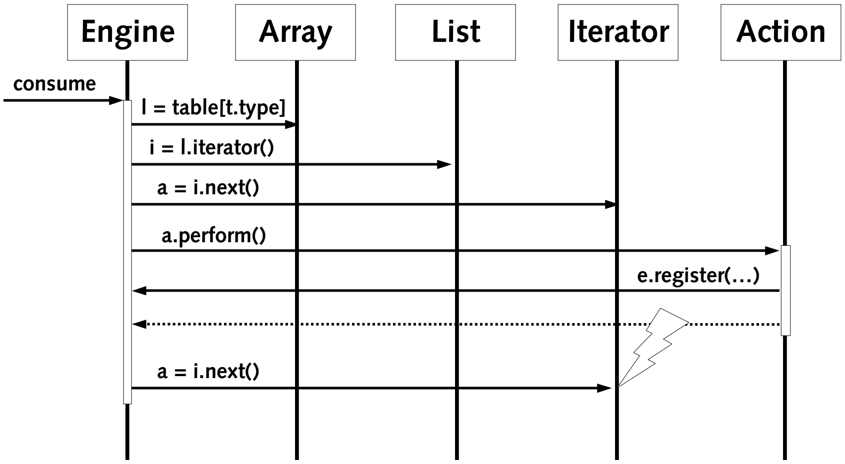
failure!



comodification

problem
- iterator shares state with list
- holds cursor into representation
- call to list's add may invalidate cursor

Java's solution
- iterator and list have version numbers
- list's iterator creates iterator with same version
- list's add/remove increments list version
- at start of iterator's next
    check versions match
    if not, throw exception

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approach

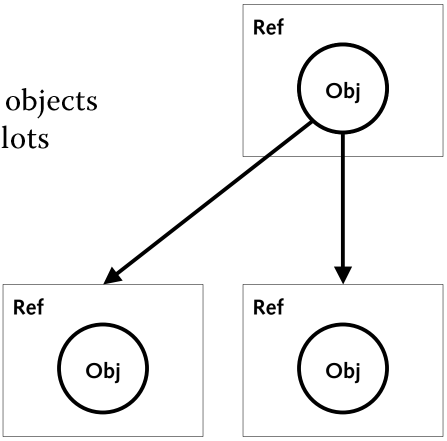
build minimal Alloy models
- of list and iterator
- of engine structure

translate engine method
- into Alloy assertion
- and analyze it

to fix problem
- develop general discipline
- add to model and reanalyze
- (check code against discipline)

modelling the heap

two kinds of Alloy atoms
- references: slots that hold objects
- objects: values that go in slots



```
sig Ref {}
sig Obj {}
sig State {
    refs: set Ref,
    obj: Ref ->? Obj
    }
```

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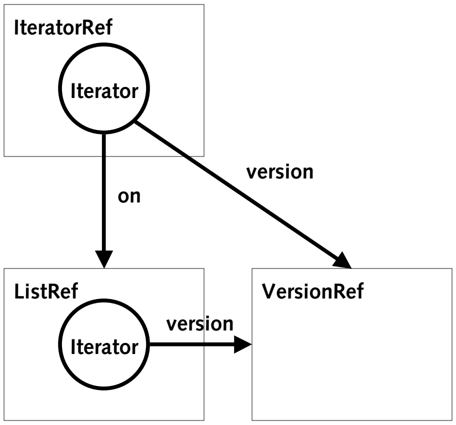
modelling iterators & lists



```
sig IteratorRef extends Ref{}
sig Iterator extends Obj {
    on: ListRef,
    left: set Ref
    version: VersionRef
    }

sig ListRef extends Ref{}
sig List extends Obj {
    elts: set Ref
    version: VersionRef
    }
```

modelling iterator methods

```
fun next (s, s′: State, this: IteratorRef, x: Ref) {
    x in this.(s.obj).left
    this.(s′.obj).left = this.(s.obj).left - x
    this.(s′.obj).version = this.(s.obj).version
    modifies (s, s′, this)
    }

fun next-pre (s, s′: State, this: IteratorRef) {
    this.(s.obj).version = this.(s.obj).on.(s.obj).version
    }

fun modifies (s, s′: State, rs: set Ref) {
    all x: s.refs - rs | x.(s′.obj) = x.(s.obj)
    }
```

modelling list methods

```
fun iterator (s, s′: State, this: ListRef, result: IteratorRef) {
    result.(s′.obj).on = this
    result.(s′.obj).version = this.(s.obj).version
    result.(s′.obj).left = this.(s.obj).elts
    modifies (s, s′, {})
    }

fun add (s, s′: State, this: ListRef, x: Ref) {
    this.(s′.obj).elts = this.(s.obj).elts + x
    modifies (s, s′, this)
    }
```

modelling the engine

```
sig Engine extends Obj {
   table: TypeRef ->! ListRef
   }

fun register (s,s': State, this: EngineRef, a: ActionRef, t: TypeRef){
   let l = t.(this.(s'.obj).table) {
      add (s, s', l, a)
      modifies (s, s', l)
      }
   }
```

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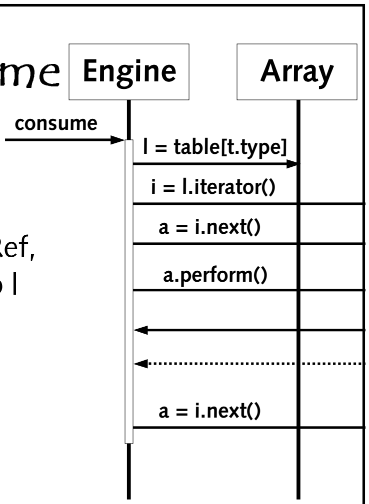
translating engine_consume



Engine

Array

consume

l = table[t.type]

i = l.iterator()

a = i.next()

a.perform()

a = i.next()

```
assert {
   all s0, s1, s2, s3: State,
      e, e': EngineRef, l: ListRef, i: IteratorRef,
      t: TokenRef, a: ActionRef, a': a.group l
         {
         l = t.(s0.obj).type.(e.(s0.obj).table)
         iterator (s0, s1, l, i)
         next (s1, s2, i, a)
         register (s2, s3, e', a')
         }
         => next-pre (s3, i)
   }
```

bug!

tool finds a counterexample
- what if one list for two types?
- fix multiplicity of table
- (and check code)

```
sig Engine extends Obj {
    table: TypeRef ?->! ListRef
    }
```

so what?

nimble modelling
- models are tiny
- analysis is fast
- feedback is motivating

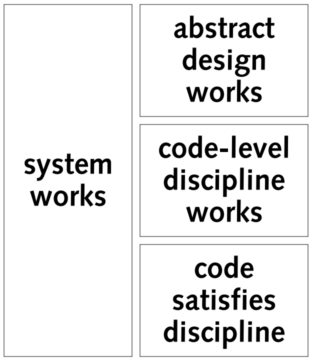
levels & phases
- abstract & code design
- early and late

systematic
- developed general rules
- discipline for future changes

context

design conformance

- NSF/ITR grant with Martin Rinard
- combines Alloy with Rinard's shape analysis



related research

verifying state machines

- Pathfinder: applies Spin to Java (Ames)
- Bandera: translates Java to finite state model (Kansas)
- SLAM: translates code to 'boolean programs' (Microsoft)
  for events not heap structure

lightweight code analysis

- LCLint (Maryland), PreFIX (Msft), ESC (Compaq)
  for simpler properties, eg null derefs
  uniform across code

acknowledgments

Alloy language and tool
- Ilya Shlyakhter
- Manu Sridharan
- Brian Lin

Alloy case studies
- Sarfraz Khrushid
- Mandana Vaziri
- Gregory Dennis
- Michal Mirvis
- Hoeteck Wee

Tagger example
- Alan Fekete

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links

http://sdg.lcs.mit.edu/~dnj/publications
  research papers
    alloy language
    alloy analysis technology
    object model extraction
    object models
  lecture notes
    software design with object models

http://sdg.lcs.mit.edu/alloy
  alloy analyzer
    new tool released mid-september