analyzable models for software design

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why analyzable models?

why models?
› figure out what problem you’re solving
› explore invented concepts
› communicate with collaborators

why analyzable?
› not just finding errors early
› analysis breathes life into models!

software based on simple, strong models tends to have cleaner interfaces, fewer bugs, and is easier to use and to maintain.
an inspiration (POPL, 1980)

Formal Specification As a Design Tool

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ABSTRACT: The formulation and analysis of a design specification is almost always of more utility than the verification of the consistency of a program with its specification. Good specification tools can assist in this process, but have generally not been proposed and evaluated in this light. In this paper we outline a specification language combining algebraic axioms and predicate transformers, present part of a non-trivial example (the specification of a high-level interface to a display), and finally discuss the analysis of this specification.
desiderata

language must be
› small and simple
› expressive, esp. for structure
› declarative (for partiality)

analysis must be
› fully automatic
› semantically deep
alloy: a structural, analyzable logic

a notation inspired by Z
› just (sets and) relations
› everything’s a formula
› but not easily analyzed

an analysis inspired by SMV
› billions of cases in second
› counterexamples, not proof
› but not declarative
alloy’s origins

logical foundations
- ZF 1908
- Tarski 1941

relational databases
- Codd 1970
- Chen 1976

formal specification
- VDM 1973
- Larch 1983 1988
- Z 1988
- Alloy 1997
- OCL 1998

model checking
- SMV 1989
- BMC 1999

object-oriented methods
- OMT 1991
- UML 1995

planning
- Kautz 1992
- Ernst 1997

SAT solvers
- DP 1962
- Zhang 1994
- RelSAT 1997
- Chaff 2001
- Berkmin 2002
demo
ideas behind alloy

language
› every value’s a relation
› everything else is a constraint
› no hard-wired idioms

analysis
› it’s all constraint solving
› bounding the scope
› exploiting SAT
every value’s a relation
**signatures: making structure first order**

*problem: how to get composite structures, but stay first order*

**traditional viewpoint**
- member of set Book is a record
- addr component is a (binary) relation

**alloy’s viewpoint**
- member of set Book is an atom
- addr component is a ternary relation

```
sig Book { addr: Name -> Addr}
addr: Book -> Name -> Addr
```
relational operators

all values are represented as relations
\{(a),(b)\} for a set
\{(a)\} for a scalar
\{(a,b)\} for a tuple

operators
\[ p + q, p \ - q, p \ & q, \sim p, \ * p, \ ^ p, \ p \ \text{in} \ q \]
\[ p \cdot q = \{(p_1, \ldots, p_{n-1}, q_2, \ldots, q_m) \mid (p_1, \ldots, p_n) \in p \land (p_n, q_2, \ldots, q_m) \in q\} \]
\[ p \rightarrow q = \{(p_1, \ldots, p_n, q_1, \ldots, q_m) \mid (p_1, \ldots, p_n) \in p \land (q_1, \ldots, q_m) \in q\} \]

example
\[ b'.addr = b.addr + n->a \]
\[ b = \{(B0)\}, \ b' = \{(B1)\}, \ n = \{(N0)\}, \ a = \{(A0)\}, \ addr = \{(B1,N0,A0)\} \]
why relations are nice

easy to understand
  › binary relation is a graph
  › ternary relation is a graph/atom

easy to implement
  › first order, so tractable
  › relational kernel like compiler’s IL

uniformity

set of addresses associated with name n in set of books B

Alloy:  n.(B.addr)
Z:  \( \cup \{ b: B \mid b.addr (| \{n\} |) \} \)
OCL:  B.addr[n]->asSet()
everything else is a constraint

predicates
› invariants
  pred Init (s: State) {...}
› operations
  pred Op (s, s’: State) {...}
› traces
  pred Traces () {
    Init (first ()) and all s: State - last () | Op (s, next(s)) }

assertions
› invariants are preserved
  assert Safe {all s,s’: State | Safe(s) and Op(s,s’) => Safe(s’)}
› undo works
  assert UndoOK {all s,s’,s”: State | Op(s,s’) and Undo(s’,s”) => s”= s}
no hard-wired idioms

what’s hard-wired?
› relational structure
› facts/predicates/functions/assertions
› subtypes and parametric polymorphism
› ... but not: state machines, traces, attributes/associations, etc

idioms of Alloy usage
› refinement of Z-style operations (security, Bolton)
› asynchronous processes (key management, Taghdiri)
› transitions based on history (Rendezvous, Jazayeri)
› global synchronized events (Firewire, Jackson)
› recursive lookup function (Intentional Naming, Khurshid)
› object-oriented heap (Java views, Waingold)
› flat data model (access control, Zao)
› ...
sample idioms: change of state

› ‘established strategy’
  \[\text{sig Book } \{\text{addr: Name }\to \text{ Addr}\}\]
  \[\text{pred Clear } (b, b' : \text{Book}) \{\textbf{no} \ b'.\text{addr}\}\]

› object-oriented heap
  \[\text{sig State } \{\text{deref: Ref }\to \text{ Book}\}\]
  \[\text{pred Clear } (s, s' : \text{State}, b : \text{Ref}) \{\textbf{no} \ s'.\text{deref}[b]\}\]

› asynchronous processes
  \[\text{sig BookProcess } \{\text{addr: Name }\to \text{ Addr }\to \text{ Time}\}\]
  \[\text{pred Clear } (t, t' : \text{Time}, b : \text{BookProcess}) \{\textbf{no} \ b.\text{addr}.t'\}\]

› explicit events
  \[\text{sig Event } \{t : \text{Time}\}\]
  \[\text{sig ClearEvent } \textbf{extends} \text{ Event } \{b : \text{BookProcess}\}\]
  \[\text{pred trans } (e : \text{Event}) \{\text{e in ClearEvent }\Rightarrow \text{no e}.b.\text{addr}.t ,...\}\]
sample idioms: analysis

› refactoring
  pred lookup (b: Book, n: Name): set Target {...}
  pred lookup' (b: Book, n: Name): set Target {...}
  assert same {all b: Book, n: Name | lookup(b,n) = lookup'(b,n)}

› abstraction
  pred abs {c: Concrete, a: Abstract} {...}
  pred opC (c, c': Concrete) {...}
  pred opA (a, a': Abstract) {...}
  assert refines {all a, a': Abstract, c, c': Concrete |
    opC(c,c') and abs(c,a) and abs(c',a') => opA(a,a') }

› machine diameter
  pred noRepeats () {no disj b, b': Book | b.addr = b'.addr}
  -- when noRepeats is unsatisfiable, trace is long enough
all constraint solving

‘show me some relations satisfying these constraints’

simulation

sig Book { addr: Name -> Addr}
pred add (b, b’: Book, n: Name, a: Addr) {...}
run add
relations: b, b’, n, a, Book, Name, Addr, addr
constraint: decl constraints, facts, add

checking

assert lookupYields {all b: Book, n: b.names | some lookup(b,n)}
check lookupYields
relations: b, n, Book, Name, Addr, addr, ord/next
constraint: decl constraints, facts, axioms of next, not lookupYields
scope

language is undecidable
› so no sound & complete algorithm

“try all small tests”
› model proper is unbounded
› user defines scope in command
› scope bounds each basic type

small scope hypothesis
› many bugs have small counterexamples
› ... and models often have many bugs
small scope hypothesis

- smallest revealing scope
- cumulative invalid assertions
- 90%
- catch
- miss

consequences
- sound: no false alarms
- incomplete: can’t prove anything
engine: reduction to SAT

space is huge
› in scope of 5, each relation has $2^{25}$ possible values
› 10 relations gives $2^{250}$ possible assignments

will SAT help?
› SAT is hard (Cook, 1971)
› SAT is easy (Kautz, Selman et al, 1990’s)
› Chaff, Berkmin: thousands vars, millions clauses

translating to SAT
› view relation as a graph
› space of possible values: each edge is present or not
› label edge with boolean variable
› compositional translation
analyzer architecture

- Alloy formula
- Alloy instance
- Translate formula
- Mapping
- Translate model
- Boolean formula
- SAT solver
- Boolean instance
- Customized visualization
- Scope
- Symmetry breaking, template detection, optimizations
what I haven’t told you about…

scalability: dancing around the intractability tarpit
  › implemented: symmetry, sharing, atomization
  › prototyped: circuit minimization

overconstraint: the dark side of declarative models
  › unsat core prototype
  › highlights contradicting formulas

new type system: real subtypes
  › makes semantics fully untyped
  › still no casts, down or up
  › catches more errors, more flexible, better performance
experience: design analyses

case studies
  › about 30 completed
  › serious flaws in published designs found

distinguishing features
  › complex data structures (eg, file synchronization)
  › network protocol over all topologies (eg, firewire, chord)
  › partial model; only some operations (eg, intentional naming)
  › not state machine (eg, ideal address translation)

typically
  › a few hundred lines of Alloy
  › longest analysis time: 10 mins to 1 hour
sample application: intentional naming

› a resource discovery scheme
› database and queries are attribute/value trees

*Balakrishnan et al, SOSP99*
sample application: intentional naming

what we did
› built Alloy model from SOSP description
› checked paper’s claims: none held
› checked code fixes: they didn’t work either
› formulated and checked more basic claims
  \textbf{assert} Monotone { 
    \textbf{all} db: DB, q: Query, r: Rec | lookup(db,q) \textbf{in} lookup(add(db,r),q)
  }
› developed notion of conformance
› fixed algorithm & code

900 lines of testing code vs. 100 lines of Alloy
Khurshid & Jackson, ASE 2000
sample application: beam scheduler

Northeast Proton Therapy Center
› 4 treatment rooms, multiplexed beam
› beam requests from treatment control rooms
› allocated by master control room
› beam scheduler automates de/allocation

what we did
› translated developer’s OCL model into Alloy
› analyzed for small flaws (simulation, invariants, etc)
› checked commutativity for all operation pairs
   Request ; Alloc = Alloc ; Request
› found many non-commuting pairs, strange behaviours

Dennis, Jackson, Rayside, Seater
experience: education

helps teach modelling
  › abstract descriptions, concrete cases
  › closest useable modelling language to logic?

where’s it’s been used
  › taught in about 20 courses worldwide
  › mostly masters courses on modelling

how long to learn?
  › undergraduate, no formal methods background
  › can build and analyze small models in 2 weeks
applications: code analysis

- procedure specification
- procedure source code
- unroll loops, bound heap
- alloy formula instance is execution trace
- NOT
- AND
- alloy formula instance is counter trace

applied to small, complex algorithms
› Schorr-Waite garbage collection
› red-black trees

*Mandana Vaziri’s doctoral thesis*
applications: test case generation

why?
› easier to write invariant than test cases
› all test cases within scope give better coverage
› symmetry breaking gives good quality quite

applied to Galileo, a NASA fault tree tool
› generated about 50,000 input trees, each less than 5 nodes
› found unknown subtle flaws

Sarfracz Khurshid’s doctoral thesis
new views on old questions

mathematical or informal models?
› not about Greek symbols (but removing them helps)
› mathematical means simple & analyzable
› real challenge for novices is abstraction

executable or abstract?
› alloy: you can have your cake and eat it (slowly)
› compromise higher order, not declarative features

simulation or verification?
› really the same: show me a good (bad) state
› it’s not about subtle bugs
tool impact

developing a tool
› sanity check on language design
› complexity is intolerable
› good for implementation = good for users?
› visualization is crucial

using a tool
› amazing how many errors are exposed
› raises the bar, gives sense of confidence
› simulation is under-rated: it works!
some research based on alloy

› automatic analysis of action diagrams
  -- R. Venkatesh, TCS India
› discovery of refinements
  -- Christie Bolton, Oxford
› Ag: Alloy with dynamic logic
  -- Marcelo Frias (U. Buenos Aires)
› justifying object model transforms
  -- Paulo Borba (Pernambuco, Brazil)
› web ontology analysis
  -- Jin Sing Dong (Singapore)
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alloy.mit.edu

- downloads for OS X, windows, linux
- courses, talks, case studies, papers, tutorial
- book in preparation: *Analyzeable Models of Software*
- coming soon: Alloy 3.0