Property-Based Testing of Abstract Machines an Experience Report

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Motivation

- While people fret about program verification in general, I care about the study of themeta-theory of programming languages
- This semantics engineering addresses *meta-correctness* of programming, e.g. (formal) verification of the trustworthiness of the *tools* with which we write programs:
  - from static analyzers to compilers, parsers, pretty-printers down to run time systems, see *CompCert*, *seL4*, *CakeML*, *VST* ...
- Considerable interest in frameworks supporting the "working" semanticist in designing such artifacts:
  - *Ott*, *Lem*, the *Language Workbench*, *K*, *PLT-Redex*...

Why bother?

- One shiny example: the definition of SML.

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- In the other corner (infamously) PHP:

> *"There was never any intent to write a programming language. I have absolutely no idea how to write a programming language, I just kept adding the next logical step on the way". (Rasmus Lerdorf, on designing PHP)*

- In the middle: lengthy prose documents (viz. the *Java Language Specification*), whose internal consistency is but a dream, see the recent *existential* crisis [SPLASH 16].

Meta-theory of PL

- Most of it based on common syntactic proofs:
  - type soundness
  - (strong) normalization
  - correctness of compiler transformations
  - non-interference ...
- Such proofs are quite standard, but notoriously fragile, boring, "write-only", and thus often PhD student-powered, when not left to the reader
- mechanized meta-theory verification: using **proof assistants** to ensure with maximal confidence that those theorems hold

Not quite there yet

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- unhelpful when the theorem I'm trying to prove is, well, wrong.

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- Formal verification is lots of hard work (especially if you're no Leroy/Appel)
- unhelpful when the theorem I'm trying to prove is, well, wrong. I mean, *almost right*:
  - statement is too strong/weak
  - there are minor mistakes in the spec I'm reasoning about
- We all know that a failed proof attempt is not the best way to debug those mistakes
- In a sense, verification only worthwhile if we already "know" the system is correct, not in the design phase!
- That's why I'm inclined to give *testing* a try (and I'm in good company!), in particular property-based testing.

PBT

- A light-weight validation approach merging two well known ideas:
  1. automatic generation of test data, against
  2. executable program specifications.
- Brought together in *QuickCheck* (Claessen & Hughes ICFP 00) for Haskell
- The programmer specifies properties that functions should satisfy inside in a very simple DSL, akin to Horn logic
- QuickCheck aims to falsify those properties by trying a large number of randomly generated cases.

QuickCheck's Hello World! (FsCheck, actually)

```
let rec rev ls =
    match ls with
    | [] -> []
    | x :: xs -> append (rev xs, [x])

let prop_revRevIsOrig (xs:int list) =
    rev (rev xs) = xs;;

do Check.Quick prop_revRevIsOrig ;;
>> Ok, passed 100 tests.

let prop_revIsOrig (xs:int list) =
    rev xs = xs
do Check.Quick prop_revIsOrig ;;

>>  Falsifiable, after 3 tests (5 shrinks) (StdGen (518275965,..
[1; 0]
```

Not so fast. . . 1/2

- Sparse pre-conditions:

  ```
  ordered xs ==> ordered (insert x xs)
  ```

- Random lists not likely to be ordered . . . Obvious issue of coverage. QC's answer: write your own generator
  - Writing generators may overwhelm SUT and become a research project in itself — IFC's generator consists 1500 lines of "tricky" Haskell [JFP15]
  - When the property in an invariant, you have to duplicate it as a generator and as a predicate and keep them in sync.
  - Do you trust your generators? In Coq's QC, you can *prove* your generators sound and even complete. Not exactly painless.
- We need to implement (and trust) shrinkers, the necessary evil of random generation, transforming large counterexamples into smaller ones that can be acted upon.

Not so fast... 2/2

Lots of current work on supporting coding or automatic derivation of (random) generators:

- Needed Narrowing: Classen [JFP15], Fetscher [ESOP15]
- General constraint solving: **Focaltest** [2010], **Target** [2015]
- A combination of the two in **Luck** [POPL17], a

Exhaustive data generation (small scope hypothesis): enumerate systematically all elements up to a certain bound:

- The granddaddy: **Alloy** [Jackson 06];
- **(Lazy)SmallCheck** [Runciman 08], **EasyCheck** [Fischer 07], α**Check**
- Most of the testing techniques in Isabelle/HOL

PBT for MMT

- PBT is a form of partial “model-checking”:
  - tries to refute specs of the SUT
  - produces helpful counterexamples for incorrect systems
  - unhelpfully diverges for correct systems
  - little expertise required
  - fully automatic, CPU-bound

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- **PBT** for MMT means:
  - Represent object system in a logical framework.
  - Specify properties it should have — you don't have to invent them, they're exactly what you want to prove anyway.
  - System searches (exhaustively/randomly) for counterexamples.
  - Meanwhile, user can try a direct proof.

Testing and proofs: friends or foes?

- Isn't Dijkstra going to be very, very mad?

  > *"None of the program in this monograph,* **needless to say**, *has been tested on a machine" [Introduction to A Discipline of Programming, 1980]*

- Isn't testing the very thing theorem proving want to replace?
- Oh, no: test a conjecture before attempting to prove it and/or test a subgoal (a lemma) inside a proof
- In fact, PBT is nowadays present in most proof assistants (Coq, Isabelle/HOL):

The "run your research" game

- Following Robbie Findler and at.'s *Run Your Research* paper at POPL12 we want to see if we find faults in (published) PL models, but leaving the comfort of high-level object languages and addressing abstract machines and TALs.
- Comparing costs/be¡nefits of random vs exhaustive PBT
- We take on Appel et al.'s CIVmark: a benchmark for "machine-checked proofs about real compilers". No binders.
- A suicide mission for counterexample search:
  - The paper comes with two formalization, in Twelf and Coq
  - Data generation (well typed machine runs) more challenging than (singe) well-typed terms.

The plumbing of the list-machine

- The list-machine works operates over an abstraction of lists, where every value is either nil or the cons of two values

$$\text{value } a \;::=\; \text{nil} \mid \text{cons}(a_1,\ a_2)$$

- Instructions:

jump l	jump to label l
branch-if-nil $v\ l$	if $v = \text{nil}$ then jump to l
fetch-field $v\ 0\ v'$	fetch the head of v into v'
fetch-field $v\ 1\ v'$	fetch the tail of v into v'
cons $v_0\ v_1\ v'$	make a cons cell in v'
halt	stop executing
$\iota_1;\ \iota_2$	sequential composition

- Configurations:

$$\begin{array}{rcl} \text{program } p & ::= & \textbf{end} \mid p, l_n : \iota \\ \text{store } r & ::= & \{\ \} \mid r[v \mapsto a] \end{array}$$

Operational semantics

- $\boxed{(r,\ \iota) \overset{p}{\mapsto} (r',\ \iota')}$ for a fixed program p, in CPS-style. E.g.:

$$\frac{r(v) = \mathrm{cons}(a_0,\ a_1) \quad r[v' := a_0] = r'}{(r,\ (\textbf{fetch-field}\ v\ 0\ v';\ \iota)) \overset{p}{\mapsto} (r',\ \iota)}\ \text{step-fetch-field-0}$$

$$\frac{r(v) = \mathrm{cons}(a_0,\ a_1) \quad r[v' := a_1] = r'}{(r,\ (\textbf{fetch-field}\ v\ 1\ v';\ \iota)) \overset{p}{\mapsto} (r',\ \iota)}\ \text{step-fetch-field-1}$$

$$\frac{r(v_0) = a_0 \quad r(v_1) = a_1 \quad r[v' := \mathrm{cons}(a_0,\ a_1)] = r'}{(r,\ (\textbf{cons}\ v_0\ v_1\ v';\ \iota)) \overset{p}{\mapsto} (r',\ \iota)}\ \text{step-cons}$$

- Computations chained the Kleene closure of the small-step relation, with **halt** for the end of a program execution.
- A program p *runs* in the Kleene closure, starting from instruction at $p(l_0)$ with an initial store $v_0 \mapsto \mathrm{nil}$, until a **halt**

Static semantics

- Each variable has list type then refined to empty and nonempty lists

$$\text{type } \tau \ ::= \ \text{nil} \mid \text{list } \tau \mid \text{listcons } \tau$$

- The type system includes therefore the expected subtyping relation and a notion of *least common super-type*
- A *program typing* Π is a list of labeled environments representing the types of the variables when entering a block
- Type-checking follows the structure of a program as a labeled sequence of blocks.
- At the bottom, instruction typing $\boxed{\Pi \ \vdash_{\text{instr}} \Gamma\{\iota\}\Gamma'}$ where an instruction transforms a Γ into post-condition Γ' under the fixed the program typing Π.

$$\frac{\Gamma(v) = \text{listcons } \tau \quad \Gamma[v' := \tau] = \Gamma'}{\Pi \ \vdash_{\text{instr}} \Gamma\{\textbf{fetch-field } v \ 0 \ v'\}\Gamma'} \text{ check-instr-fetch-0}$$

$$\frac{\Gamma(v) = \text{listcons } \tau \quad \Gamma[v' := \text{list } \tau] = \Gamma}{\Pi \ \vdash_{\text{instr}} \Gamma\{\textbf{fetch-field } v \ 0 \ v'\}\Gamma'} \text{ check-instr-fetch-1}$$

Testing

Question What are the properties of interest?

Answer The theorem the calculus satisfies:

$$\frac{p : \Pi \quad \Pi \vdash_{\text{instr}} \Gamma\{\iota\}\Gamma' \quad r : \Gamma}{\text{step-or-halt}(p,\ r,\ \iota)}\ \textit{progress}$$

$$\frac{p : \Pi \quad \vdash_{\text{env}} \Gamma \quad r : \Gamma \quad \Pi;\Gamma \vdash_{\text{block}} \iota \quad (r,\ \iota) \overset{p}{\mapsto} (r',\ \iota')}{\exists \Gamma'.\ \vdash_{\text{env}} \Gamma' \ \wedge\ r' : \Gamma' \ \wedge\ \Pi;\Gamma' \vdash_{\text{block}} \iota'}\ \textit{preservation}$$

More questions

- What about intermediate lemmas? Do they catch more bugs?
- What are the trade off between random and exhaustive generation on low-level code?

LP implementation: αCheck 1/2

- αCheck is a PBT tool on top of αProlog, a variant of Prolog with nominal abstract syntax.
- Equality coincides with $\equiv_\alpha$, $\#$ means "not free in", $\langle x \rangle M$ is an M with x bound, $\reflectbox{N}$ is the Pitts-Gabbay quantifier.
- Use nominal Horn formulas to write specs and checks
- A `check` $\reflectbox{N}\vec{a}\forall\vec{X}.A_1 \wedge \cdots \wedge A_n \supset A$ is a bounded query:
  $?\!-\ \reflectbox{N}\vec{a}.\ \exists\vec{X}.\ A_1 \wedge \cdots \wedge A_n \wedge gen(X_1) \wedge \cdots \wedge gen(X_n) \wedge not(A)$
  - Search via iterative-deepening for complete (up to the bound) proof trees of all hypotheses
  - Instantiate all remaining variables $X_1 \ldots X_n$ occurring in A with exhaustive generator predicates for all base types, automatically provided by the tool.
  - Then, see if conclusion fails using negation-as-failure.
- Can also use negation elimination (skip for today)

LP implementation: αCheck, 2/2

- The encoding is pure many-sorted Prolog: we not use the nominal machinery — not even for labels, as they have identity
- The check for *progress* is immediate: no set-up, the tool will add grounding generators for `P,R,I`:

```
#check "progress" 10:
   check_program(P, Pi),
   check_block(Pi, G, I),
   store_has_type(R, G) => step_or_halt(P, R, I).
```

- *Preservation* needs some work: the conclusion is existential $\exists \Gamma'.\ \vdash_{\mathsf{env}} \Gamma' \ \wedge\ \boxed{\ \mathsf{r':}\ \Gamma'\ }\ \wedge\ \Pi; \Gamma' \vdash_{\mathsf{block}} \iota'$ and we need custom made generator to ground Γ'

Functional implementation: FsCheck

- We ported the machine to **F#** (adapting the Coq code, easy) and checked with **FsCheck**, its porting of QuickCheck, with automatic derivation of generators from algebraic types.
- Those are (as expected) useless: top level checks had zero coverage: preconditions too hard for uniform distributions;
- We had to spend a lot of effort to produce well-typed programs, while having no type-inference whatsoever;
  - for progress , this means generate simultaneously a program `p`, a program typing `pi` that type-checks with `p`, a store `r` compatible with a type environment `g`, a label `l` that belongs to program `p` and the instruction `i` associated to label `l`.
- Wait, there is more: writing shrinkers here is non-trivial again , as we need to shrink modulo well-typing.

Proof of the pudding: validating the list-machine

- The preservation property fails! Here's the offending program:

$$
\begin{array}{l}
(l_0 : \textbf{cons}(v_0, v_0, v_0); \text{jump } l_1); \\
(l_1 : \textbf{fetch-field}(v_0, 0, v_0);\ \textbf{jump } l_2); \\
(l_2; \textbf{halt})
\end{array}
$$

- There was a major mistake in the journal paper w.r.t. assigning *types* to values:

$$\frac{???}{\text{cons}(a_0,\ a_1) :\ \text{listcons } \tau}$$

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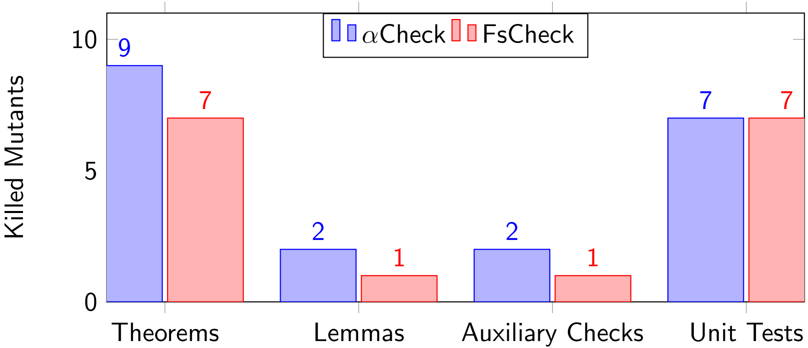
- Mutation Analysis:
  1. change a program inserting a single fault
  2. see if your testing method detects it (killing a mutant)
  3. it's as good at the killing *ratio*
- We adopted idea from mutation testing in Prolog to insert mutations such as:

$$\frac{\Gamma(v) = \text{listcons}\ \tau \quad \Gamma[v' := \boxed{\cancel{\text{list}}}\ \tau] = \Gamma'}{\Pi\ \vdash_{\text{instr}} \Gamma\{\mathbf{fetch\text{-}field}\ v\ 1\ v'\}\Gamma'}\ \text{check-instr-fetch*}$$

Mutation analysis: αCheck vs FsCheck



- # of mutants killed by each tool
- "Theorems" means type soundness, "lemmas" are intermediate (typically non-inductive) results, "auxiliary" are even lower checks coming from Twelf.
- "Unit tests" are just queries adapted from PLT-Redex

αCheck and top-level Theorems comes ahead, but we really need automatic mutation testing to be more confident.

Conclusions

- PBT is a great choice for meta-theory model checking. to spec'n'check on a regular basis
- Validating low-level languages is more challenging, but we can handle with the tools we have and some additional work.
- Checking specifications with αCheck is immediate
- Bare-to-the-bone QuickCheck is a lot of work to setup.
- W.r.t. costs/benefits, exhaustive generation, even in our naive way, comes ahead over the random approach ...
  - but we need automatic mutation testing to confirm this

Future work: other PBT tools

- We know very well that *FsCheck* and αCheck are the extremes of PBT tools and we really should run this benchmark with others that have *support* for custom generators
- Since the benchmark has no binders, the are many choices:
  - the new *QuickChick*, with automatically generated generators
  - *Luck* — but you still have to write gens and it's slow
  - Bulwhahn's *smart* generators in Isabelle/HOL, less likely *Nitpick*

Future work: αCheck

- αCheck works surprisingly well, given the naivete of its implementation: basically an iterative deepening modification of the original OCaml interpreter for αProlog
- But experiments with other abstract machines (IFC) reminds us of how naive we are w.r.t. the combinatorial explosion
- Change the hard-wired notion of bound ($\#$ of clauses used) and how it is distributed over subgoals:
  - Take ideas from **Tor**
- Bring in some random-ness by doing random backchaining: flip a coin instead of doing chronological backtracking
- Prune the search space by not generating terms that exercise "equivalent" part of the spec

Future work: going sub-structural

- It's folklore that linear logical framework are well suited to encode object logic with imperative features, e.g. Pfenning and Cervesato's encoding of MLR in **LLF**;
- Data structures for heaps, stores... are replaced by **linear, affine, etc** predicates
  - This seems promising for **exhaustive** PBT, where every constructor counts
  - Work in progress: linear version of the list-machine benchmark via the two level approach (in λ*Prolog*)
- Sub-structural PBT can bring some form of validation to frameworks such as **Celf**, whose meta-theory is not there yet
- Meta-interpreters not viable in the long run:
  - give the αCheck treatment to languages such as **LolliMon**
  - use program specialization to do amalgamation

Thanks for listening and have a good lunch!