Dependently Typed Programming with Mutable State

Aaron Stump[1] Evan Austin[2]

[1]Computer Science
The University of Iowa

[2]Computer Science
The University of Kansas

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What Are Dependent Types?

- Indexed datatypes:

```
<list A n>               instead of     <list A>
<balanced_tree A d>                     <tree A>
<lam_t max_var>                         lam_t
```

- Dependent function types:

```
delete : Fun(x:nat)(l:<list nat (S n)>)
            (u:{(in x l) = tt}).
           <list nat n>
append : Fun(A:type)(n1 n2:nat)
            (l1:<list A n1>)(l2:<list A n2>).
          <list A (plus n1 n2)>
```

- Computing a type by recursion:

```
printf : Fun(s:format_string).(printf_t s)

(printf_t "%d"++s) => (int -> (printf_t s))
(printf_t "%x"++s) => (ptr -> (printf_t s))
(printf_t []) => unit
```

Why Dependent Types Matter [1]

Incrementality

[1] Title of invited talk at POPL 2006 by James McKenna.

Why Dependent Types Matter [1]

Incrementality   Intensionality

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Incrementality

- Adding verification usually is a big leap.
  - new specification language (at least first-order logic); and
  - new proof language(s), or
  - unpredictable, tricky tools (“you need an expert”).
- Not a big leap with dependent types.
  - From `<list A>` to `<list A n>` is easier.
  - Add verification judiciously, “pay as you go”.
- Goal: enable gradual increase in code quality.
  - Deep verification is at one limit.
  - Lightweight verification can improve code a lot.

Intensionality (Policies versus Properties)

- Properties expressing facts about code.
- Policies restrict how code can be used.
- Stating (proving) a property from a policy may be hard.
- Example policies:
  - Files may not be accessed after they are closed.
  - Uninitialized array locations may not be read.
  - Data computed from user's contact list cannot be auto-emailed. [2].

[2] See [Swamy, Chen, and Chugh 2009]

GURU at a High-Level

- Pure functional language + logical theory. [3].
  - Includes indexed datatypes, dependent function types.
  - Terms : Types.
  - Proofs : Formulas.

- Inspired by Coq/CIC, but with some improvements:
  - General recursion for terms.
    - Proofs are still sound.
    - Explicit casts instead of conversion => type equivalence still decidable.
  - Annotations dropped for type equivalence.
    - Including types, specificational ("ghost") data, and proofs.
    - Avoids problems with equality of proofs.
    - Like Implicit Calculus of Constructions (ICC).
  - Resource-tracking analysis [new!]

[3] See [Stump, Deters, Petcher, Schiller, Simpson 2009]

Functional Modeling for Imperative Abstractions

- I/O, mutable arrays, cyclic structures, etc.
- Do not fit well into pure FP.
- Approach: functional modeling.
  - Define a pure functional model (e.g., `<list A n>` for arrays). [4]
  - Model is faithful, but slow.
  - Use during reasoning.
  - Replace with imperative code during compilation.
  - Use *linear* (aka *unique*) types to keep in synch.

[4] Cf. [Swierstra and Altenkirch 2007]

Example: Word-Indexed Mutable Arrays

- Type: `<warray A N L>`.
  - `A` is type of elements.
  - `N` is length of array.
  - `L` is list of initialized locations.
- `(new_array A N) : <warray A N []>`.
- Writing to index `i`:
  - requires proof: `i < N`.
  - functional model: consume old array, produce updated one.
  - imperative implementation: just do the assignment.
  - array's type changes: `<warray A N i::L>`.
- Reading from index `i`:
  - does not consume array.
  - requires proof: `i` $\in$ `L`.

Example: FIFO Queues

- Mutable singly-linked list, with direct pointer to end.
- **Aliasing!**
- GURU approach: *heaplets* (part of heap).

Type	Functional Model	Imperative Implementation
`<heaplet A I>`	list of aliased values	nothing
`<alias I>`	index into heaplet `I`	reference-counted pointer

- Unverified queue:
  - Just memory safety
  - 138 lines total (6 lines proof).
- Verified queue:
  - Prove that `qin`-node has no next-pointer.
  - Requires reasoning about aliases.
  - 310 lines total (178 lines proof).

Resource-Tracking and Memory Management

- Memory deallocated explicitly.
- Resource-tracking analysis ensures safety.
- Different resource types available.
  - `unowned`: for reference-counted data.
  - `unique`: for mutable data structures.
  - `<owned x>`: for *pinning* references.

    ```
    x:unowned
    y:<owned x>
    ```

    Not allowed to consume `x` until `y` is consumed.

    Can safely omit inc/dec for `y`.

- GURU: no garbage collection!
- "Garbage Collection: Java Application Servers Achilles' Heel" [5]

[5] [Xian, Srisa-an, Jiang 08]

Empirical Comparison

Benchmark 1: In array storing $[0, 2^{20})$, do binary search for each element.

Benchmark 2: push all words in "War and Peace" through 2 queues.

Mutable Array Test	
Language	Avg Real Time
HASKELL	1.14 s
HASKELL (No GC)	0.45 s
OCAML	0.60 s
OCAML (No GC)	0.54 s
GURU	0.57 s

Queue Test	
Language	Avg Real Time
HASKELL	1.33 s
HASKELL (No GC)	0.60 s
OCAML	0.61 s
OCAML (No GC)	0.38 s
GURU	0.58 s

Compilers: `ghc 6.10.4, ocamlopt 3.11.1, gcc 4.3.3`
Machine: `2.67Ghz Intel Xeon, 8 GB mem, Linux 2.6.18`

Current Projects

- `versat`: verified modern SAT solver.
  - Complex code, uses mutable state.
  - Not too large.
  - Simple spec.: learned clauses derivable by resolution from input clauses.
  - With Duckki Oe, Derek Bruce.
- GOLFSOCK: verified LFSC proof checker.
  - LFSC = (Edinburgh) Logical Framework with Side Conditions.
  - My proposal for a meta-language for SMT proofs.
  - Fast C++ implementation (45% overhead for QF_IDL, difficulty 0-3). [6]
  - With Cesare Tinelli, Clark Barrett, Tianyi Liang, Yeting Ge, Andrew Reynolds.
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- "Eat your own dog food!"
- Let's eat what we grow.

[6] See [Oe, Stump, Reynolds 2009]

Future Goals

- More imperative abstractions:
  - Statically reference-counted heaplets.
  - Doubly-linked lists, hashmaps, etc.

- More automation:
  - Currently: `hypjoin t t' by p1 ... pn end`[7].
  - Extend to first-order formulas?
  - Goal: understandable, predictable tactics ("no expert needed").

- (For you) to learn more:
  - Version 1.0 is close to release:

    `www.guru-lang.org`

  - "Verified Programming in Guru" book.

[7] See [Petcher, Stump 2009].