Resource Typing in Guru

Aaron Stump[1] Evan Austin[2]

[1]Computer Science
The University of Iowa

[2]Computer Science
The University of Kansas

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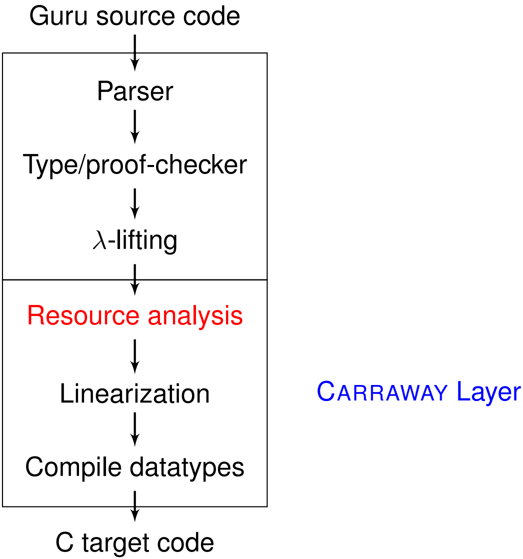
The GURU Verified-Programming Language

- Pure functional language + logical theory.
  - 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!]

The GURU Compiler



Functional Modeling for Imperative Abstractions

- I/O, mutable arrays, cyclic structures, etc.
- Do not fit well into pure FP.
- Approach: functional modeling. [1]
  - Define a pure functional model (e.g., `<list A n>` for arrays).
  - Model is faithful, but slow.
  - Use during reasoning.
  - Replace with imperative code during compilation.
  - Use *linear* types (alternatively, monads) to keep in synch.
- Combining dependent and linear typing is powerful.
  - Cf. "Safe Programming with Pointers through Stateful Views" [Zhu,Xi 2005].
  - Also, "End-to-end Verification of Security Enforcement is Fine" [Swamy,Chen,Chugh 2009].

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[1] Cf. "Beauty in the Beast" [Swierstra and Altenkirch 2007]

A Resource Typing Framework

- Idea: explore resource management with a framework.
- Framework implements concepts of resource, subresource.
- Different resource abstractions then defined:

reference-counted data   unique references

heap abstractions   read-only views

- On top of these, build data abstractions:
  - Mutable array abstractions.
  - Aliased data structures (e.g., FIFO queues).

A Framework for Resources

- Fundamental ideas:
  1. A resource can only be used by one entity at a time.
  2. A resource can be temporarily decomposed into subresources.
- Resource abstraction defined by *primitives*:
  - a trusted resource type,
  - a functional model in GURU,
  - trusted C code implementing the primitive.
- Resource analysis:
  - Check linearity conditions (used exactly once, affine).
  - Track subresource relationships.
  - Enforce *consumption annotations* on input variables:
    - (default) – consume exactly once/affine.
    - ˆ – consume but do not return.
    - **!** – do not consume.

Subresources

- “Deathly Hallows” as subresource of Harry Potter boxed set.
- Cannot use boxed set until all individual volumes returned.
- Sublist l′ as a subresource of (cons x l′).
- Subresource relationship based on type <R x>:
    - x:R – x has resource type R.
    - y:<R′ x> – y has resource type R’, and is a subresource of x.
- Cannot consume x until all subresources have been consumed.
- Need ˆ (“consume but do not return”) to consume y:<R′ x>.

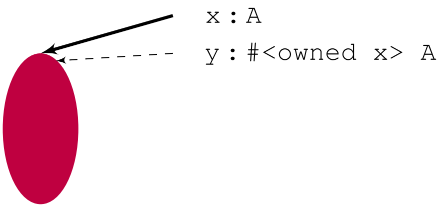
Resource Abstraction: Reference-Counted Data

```
ResourceType unowned [...].

Define primitive inc
 : Fun(spec A:type)(! #unowned y:A).#unowned A
 := fun(A:type)(y:A).y
«END
  inline void *ginc(void *y) { [...] }
END.

Define primitive dec
 : Fun(A:type)(^#unowned y:A).void
 := fun(A:type)(y:A).voidi
«END
  void gdec(int A, void *r) { [...] }
END.
```

- Inductive (tree-like) data are reference-counted.
- (Flat types like `bool` are `untracked`.)

Resource Abstraction: Owned References

```
ResourceType owned affine.

Define primitive inspect
 : Fun(spec A:type)(!#unowned x:A).#<owned x> A
 := fun(A:type)(x:A).x
«END
  #define ginspect(x) x
END.
```



- This y is *pinning* x.
- Cannot consume x while y is live.
  - No inc, dec required for y.
  - improved performance, still memory safe.

Mutable State and Readers/Writers

- For writing mutable state, require unique reference.
- Can implement readers/writers, using subresource idea.
  - Must check in the read-only views to get the read/write one.
  - For read/write, `x : #unique`.
  - For read-only, y : #<unique_owned x>.
- Use `unique/unique_owned` for arrays, queues, tries, etc.

Data Abstraction: Word-Indexed Mutable Arrays

- Type: `<warray A N L>`.
- Resource types: `unique`/`unique_owned`.
  - `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`.

Data Abstraction: FIFO Queues

- Mutable singly-linked list, with direct pointer to enqueue-end.
- **Aliasing.**
- Resource abstraction: *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).

Garbage Collection, Or Lack Thereof

- Garbage collection has led to great productivity gains...
- ... but can hurt performance.
- No continuum in mainstream: all GC (slow) or no GC (unsafe).
- GURU does not use GC.
  - Resource abstractions are memory safe.
  - But `heaplet` can leak memory for cyclic structures.
- A perfect world might provide:
  - GC'ed regions for productivity.
  - Heavier abstractions for safety without GC.
    - E.g., *compile-time* reference counting.
    - Significant verification burden.
  - Key: ability to choose which is more appropriate.

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	Time	Binary
HASKELL	1.18 s	581K
HASKELL (No GC)	0.49 s	
OCAML	0.61 s	131K
OCAML (No GC)	0.54 s	
GURU	0.42 s	37K

Queue Test		
Language	Time	Binary
HASKELL	1.08 s	614K
HASKELL (No GC)	0.53 s	
OCAML	0.66 s	132K
OCAML (No GC)	0.37 s	
GURU	0.60 s	37K

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`
Implementations: `Data.Sequence` (HASKELL), references (OCAML).

Future Directions

- Better abstractions for aliased structures.
- Realistic applications.
  - `versat`: verified modern SAT solver.
    - Complex code, uses mutable state.
    - Not too large.
    - Simple spec.: learned clauses derivable by resolution from input clauses.
- Meta-theoretic work on resources.
- To learn more:

  www.guru-lang.org

  "Verified Programming in Guru" book.

Extra Slides

Initializing Subdata in `match`-cases

- `Init`-function defined as part of resource abstraction.
- Suppose matching on `x:r`, subdatum `y:r'`.
- `Init`-function for `r-r'` initializes `y`.

```
Init ginit_unowned_unowned(#unowned x)(#unowned y).#unowned
«END
  inline void *ginit_unowned_unowned(int A,void *x,void *y) {
    ginc(y);
    return y;
  }
END.

Init ginit_owned_unowned(#owned x)(#unowned y).#<owned x> «END
  #define ginit_owned_unowned(A,x,y) y
END.
```

- Compressing chains of ownership:

```
t:<r y>   y:<r' z>
------------------
    @ t:<r z>
```