Automatic Certification of Resource Consumption

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MRG: PCC infrastructure for resource-related properties

- MRG is a joint University of Edinburgh / LMU Munich project funded for 2002-2005 by the European Commission's pro-active initiative in Global Computing.
- The aim is to endow mobile code with independently verifiable certificates describing resource requirements, following the *proof-carrying code* paradigm.
- Applications with resource considerations: portable devices (phones, PDA's,. . .), Smartcards, embedded processors (car electronics,. . .), satellites, GRID services,. . .
- Example resources: memory (heap & stack), time, energy, network bandwidth, parameter values of system calls
- PCC: code consumer requires transmitted program to come with verifiable proof that his resource policy is fulfilled
- Approach (certifying compilation): translation from user language into machine language derives independently verifiable certificates

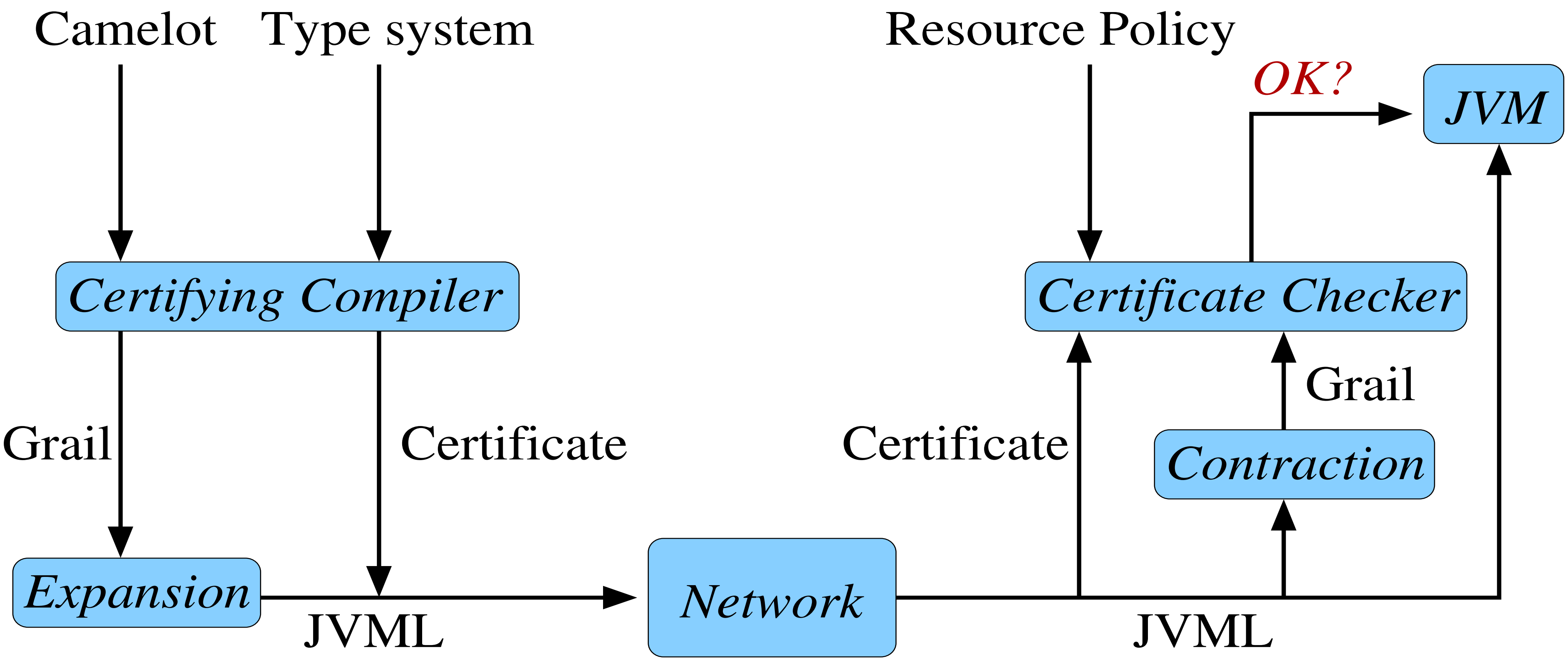
Outline

- Architecture of MRG
- Syntax and semantics of Grail
- Grail’s Program Logic
- Derived Assertions
- Web demo
- Conclusions

Components of MRG

- We write programs in a custom high-level language **Camelot**, a functional language with an OCaml-like syntax.
- Camelot is compiled into **Grail**, a functional intermediate code, which is isomorphic to a subset of JVML.
- We use an abstract **cost model** for the JVM which counts instructions and measures stack and heap sizes.
- Costs are calculated using a **annotated operational semantics** for Grail, reflecting the expansion into JVML.
- **Grail Logic** is a program logic which can express resource assertions about the operational semantics.
- Camelot has a **resource type inference system**, which is used to produce proofs in a **logic of derived assertions**.
- The annotated semantics, logics, and meta-theorems have all been formalised in **Isabelle**, and Isabelle proof scripts are used as our proof transmission format.

MRG architecture



Works because of reversible expansion of Grail into JVML subset

Camelot

Camelot: ML-like first-order functional language (polymorphism, no references)

- Example program: insertion sort:

```
type iList = !Nil | Cons of int * iList
let ins a l =
  match l with Nil -> Cons(a,Nil)
             | Cons(x,t)@_ -> if a < x then Cons(a,Cons(x,t))
                                        else Cons(x, ins a t)
let sort l =  match l with Nil -> Nil | Cons(a,t)@_ -> ins a (sort t)
```

- Notation `@_` indicates destructive pattern match
- Whole program compilation where each Camelot function yields one JVM method
- Compilation includes an explicit memory manager (freelist)

Wish to certify memory consumption of compiled output.

Program analysis, certification & proof checking

```
let ins a l =
  match l with Nil -> Cons(a,Nil)
             | Cons(x,t)@_ -> if a < x then Cons(a,Cons(x,t))
                                       else Cons(x, ins a t)
let sort l =  match l with Nil -> Nil | Cons(a,t)@_ -> ins a (sort t)
```

- Memory consumption inferred from program annotations using a type system
- Result: `ins` consumes one memory cell, independent from actual input, `sort` does not consume any memory (in-place)
- In general: memory consumption expressed relative to size of input
- PCC-certificate: encoding of the result of the type inference in a program logic
- Certificate bundled with program for transmission
- JVM at consumer side uses modified class loader (security manager) that checks certificate in Isabelle before executing program

PCC: us and them

Existing approaches:

- Classic PCC: trusted special-purpose proof systems for proving light-weight properties of machine code (memory safety)
- Foundational PCC: operational model (processor) formalised in higher-order logic that is built on top of theorem prover Twelf, use Twelf proof terms as certificates

MRG:

- Formalise *instrumented* operational semantics of (virtual) machine language
- Use a general-purpose program logic (sound, complete & expressive, little automation)
- Derive special logics (interpreted type systems) in theorem prover

Grail: Characteristics

- Combine OO-aspects of bytecode (fields, methods) with (impure) low-level functional language
- Extends Appel-Kelsey-correspondence to machine level
- Functional view: first-order functions; no nesting; all free variables in parameters; applications only to values.
- Imperative view: easily convertible into various virtual machines formats
- registers = variables, jumps = tail-calls
- Coincidence between functional and imperative views makes conversion reversible
- Emitted bytecode is highly structured (Leroy’s conditions)

Syntax of Grail

- A Grail program is a list of *methods* each containing a list of tail-recursive *functions*.

$$
\begin{array}{rcl}
e \in \mathit{expr} & ::= & \mathtt{null} \mid i \mid x \mid \mathtt{prim}\, p\; x\; x \\
& \mid & \mathtt{new}\; c\; [\overline{t_i := x_i}] \\
& \mid & x.t \mid x.t{:=}x \\
& \mid & \mathtt{let}\; x = e\; \mathtt{in}\; e \mid e;e \\
& \mid & \mathtt{if}\; x\; \mathtt{then}\; e\; \mathtt{else}\; e \\
& \mid & \mathtt{call}\; f \mid c.m(\bar{a}) \\
a \in \mathit{args} & ::= & x \mid \mathrm{null} \mid i
\end{array}
$$

- Whole development formalized in Isabelle/HOL:
- named syntax,
- program encoded using global tables (functions and methods),
- op. semantics based on (finite) maps:

Grail: resource-instrumented operational semantics

- Based on (impure) big-step functional view:

  $$E \vdash h, e \Downarrow (h', v, p)$$

  where r is a *resource value* in some *resource algebra* $\mathcal{R}$.
- Moreover, the resources r are a purely “non-invasive” annotation on an ordinary operational semantics; evaluation of an expression is not affected by the resources consumed in subexpressions.
- The resource algebra has families of operations for each of the syntactic constructs of Grail. . .
- A resource algebra $\mathcal{R}$ has a carrier set R consisting of *resource values* $r \in R$, with:
  - For the atomic expressions, families of constants $\mathcal{R}^{\mathtt{null}} \in R$, etc.
  - For compound expressions, families of operations, e.g. $\mathcal{R}^{\mathtt{let}}_{x} \in R \times R \to R$.
- JVM case: R consists of quadruples:

  $$r = (\textit{clock}, \quad \textit{callc}, \quad \textit{invkc}, \quad \textit{invkdpth})$$

- Stack usage is approximated; heap usage calculated as the difference $\textit{size}(h') - \textit{size}(h)$.

Operational semantics

$$\frac{E\langle x\rangle = \mathit{Ref}\ l}{E \vdash h, x.t \Downarrow (h, h(l).t, \mathcal{R}^{\mathtt{getf}}(x,t))} \qquad (\textsc{getf})$$

$\mathcal{R}^{\mathtt{getf}}(x,t) = \langle 2\ 0\ 0\ 0\rangle$.

$$\frac{E \vdash h, e_1 \Downarrow (h_1, w, p) \quad w \neq \bot \quad E\langle x := w\rangle \vdash h_1, e_2 \Downarrow (h_2, v, q)}{E \vdash h, \mathtt{let}\ x = e_1\ \mathtt{in}\ e_2 \Downarrow (h_2, v, \mathcal{R}^{\mathtt{let}}(x, p, q))} \qquad (\textsc{let})$$

$\mathcal{R}^{\mathtt{let}}(r_1, r_2) = (1 + \mathit{max}(r_1, r_2))$

$$\frac{E \vdash h,\ f_{body}\ \Downarrow\ h',\ v,\ r}{E \vdash h,\ \mathtt{call}\ f\ \Downarrow\ h',\ v,\ \mathcal{R}_f^{\mathtt{call}}(r)}$$

$\mathcal{R}_f^{\mathtt{call}}(t, c, i, d) =\ (t+1,\ c+1,\ i,\ d)$

Other resource algebras (current work)

- Resource algebras usefully generalise the specific case to allow richer resource/security policies to be expressed. Examples include:
  - *parameter limit flags* set by parameter limit policies; here simply $R = \{\text{true}, \text{false}\}$.
  - *traces of method invocation sequences*, so e.g. $R = \{m^*\}$ where m ranges over method names.
  - *read-write effects on heap locations*, where $R = \{\langle \text{Rd}, \text{Or}, \text{RdWr} \rangle\}$ for $\text{Rd}, \text{Wr}, \text{RdWr} \subseteq$ *Locations*. Other e.g.s: live variables, complete traces of heaps during execution, . . .
- For some examples, additional indices/sorts are needed for the environment (stack) and heap, to extract or examine values.
- Further algebraic structure on $\mathcal{R}$ is perhaps useful and is currently under investigation. Current idea: a monoid with semi-lattice structure: composition of monoid + is composition of resources;

Program logic I

- Recent reappraisal of program (Hoare) logics: embeddings in theorem prover (Kleymann, Nipkow), Separation logics (Reynolds, O'Hearn), Java verification (Jacobs, de Boer, von Oheimb)
- Embedding a la Kleymann: deep embedding of language, shallow embedding of assertions, with soundness and (relative) completeness formally proven in theorem prover
- Pragmatic issue: meta-theoretic investigation vs program verification (automation). In MRG-PCC both issues are important!
- Judgements take the form $G \rhd e : P$
  - e is a Grail expression;
  - G is a set of assumptions context used for storing assumptions for recursive methods and functions;
  - P is an assertion, i.e. a predicate in the meta-logic
  - Assertions are simply predicates over semantic values:

    $$P[E, h, h', v, r]$$

    relating the environment, initial and final heaps, the result and the resource value.

Program logic II: proof rules

- No auxiliary variables (usage of pre-heap inspired by hooked variables in VDM)
- Judgements interpreted as partial "correctness" statements: validity $\models e : P$ defined as

$$\forall\, E\, h\, h'\, v\, p.\quad (E \vdash h, e \Downarrow (h', v, p) \longrightarrow P[E, h, h', v, r]$$

- Termination considered orthogonal

$$\frac{}{G \rhd x.t : \lambda\, E\, h\, h'\, v\, p.\, \exists\, l.\;\; E\langle x\rangle = \mathit{Ref}\ l \;\wedge\; h' = h \;\wedge\; v = h'(l).t \;\wedge\; p = \mathcal{R}^{\mathtt{getf}}(x, t)}\ (\text{VGETF})$$

$$\frac{G \rhd e_1 : P_1 \quad G \rhd e_2 : P_2}{G \rhd \mathtt{let}\, x = e_1\, \mathtt{in}\, e_2 : \lambda\, E\, h\, h'\, v\, p.\, \exists\, p_1\, p_2\, h_1\, w.\;\; P_1[E, h, h_1, w, p_1] \;\wedge\; w \neq \bot \;\wedge\; P_2[E\langle x := w\rangle, h_1, h', v, p_2] \wedge\; p = \mathcal{R}^{\mathtt{let}}(x, p, q)}\ (\text{VLET})$$

- Much simpler than Hoare-style logic (variable update in precondition)
- Structural and admissible rules: context lookup, rule of consequence, CUT.

Program logic III: soundness & completeness

- Soundness proven as usual, by relativised validity and induction on height of derivations
- “Relative” completeness (Cook, Aczel): in rule of consequence, the implication only needs to *hold* rather than being *derivable*: incompleteness of HOL is inherited by program logic since language of assertions is not formalised
- Completeness proven by induction over program structure, by defining strongest specifications (most general triples)
- Both theorems have been proven in our mechanised formalization. For details, see our paper in TPHOLs ’04.
- A Grail program consists of a number of mutually methods/functions. To prove that each method and function satisfies a specification/invariant, we use a *specification table* SPEC which associates an assertion to each method/function.
- A context G is *table consistent* (“good”) for a program if it contains assumptions only of the form used in the procedure rules, and moreover the body of each procedure satisfies the claimed specification.

Program logic IV: example specification (insertion sort)

$$
\begin{aligned}
\textit{insSpec} \quad &\equiv \quad \textit{SPEC}\ \text{List ins}\ [a_1, a_2] = \\
&\qquad \lambda\, E\, h\, h'\, v\, p\, .\forall\, i\, r\, n\, X\, . \\
&\qquad\ (E\langle a_1\rangle = i \land E\langle a_2\rangle = \text{Ref}\, r \land h, r \models_X n \\
&\qquad\ \longrightarrow |\textit{dom}(h)| + 1 = |\textit{dom}(h')|\ \land\ p \leq \langle (An + B)\ (Cn + D)\ (En + F)\ (G \\
\textit{sortSpec} \quad &\equiv \quad \textit{SPEC}\ \text{List sort}\ [a] = \\
&\qquad \lambda\, E\, h\, h'\, v\, p\, .\forall\, i\, r\, n\, X\, . \\
&\qquad\ (\ E\langle a\rangle = \text{Ref}\, r \land h, r \models_X n\ \longrightarrow |\textit{dom}(h)| = |\textit{dom}(h')|\ \land\ p \leq \ldots)
\end{aligned}
$$

Lemma: *insSpec* $\land$ *sortSpec* $\longrightarrow\ \triangleright$ List.$sort([xs])$: *SPEC* List $sort\ [xs]$

- $h, r \models_X n$ defined inductively, introduces case-splits during verification
- Proof rules contain existentials over intermediate heaps and instrumentations
- $\leadsto$ automatic proof search impractical (and not desirable in MRG) even after applying all proof rules (VCG): automation by compiler difficult
- Certificate Generation: exploit program structure and compiler analysis by proving properties that are more closely related to the type system

Insertion sort: compiler output

```
method static public List ins(int a, D l) = ...D.make(a, null)...
method static public List sort(D l) =
        if l = null then null
                else  let h = l.HD in let t = l.TL in let _ = D.free(l) in
                      let l = List.sort(t) in List.ins(h, l)
```

. . . plus code for memory management and runtime environment methods

- **D.make**$(\ldots)$: takes object from freelist, or calls **new**
- **D.free**(x): inserts object into freelist
- **D.main**(l): constructs initial freelist, calls `List.sort`(**s2i**(l))

We wish to verify that

- any memory allocation throughout an invocation of **main** is performed during the initial construction of the freelist, and in particular that
- during the execution of `List.sort`(l), all invocations of **make** are executed on a non-empty freelist, i.e. no call to **new** is performed

Type-based analysis of Camelot programs

Type system by Hofmann and Jost (POPL 2003):

- Input: program containing a function **start**`: string list -> unit`

  Output: a *linear function* s such that **start**$(\mathtt{l})$ will not call **new** when evaluated in a heap h where

  - $\mathtt{l}$ points in h to a linear list of some length n
  - the freelist which forms a part of h is well-formed
  - the freelist does not overlap with $\mathtt{l}$
  - the freelist has length not less than $s(n)$
- How does this work?
  - Annotate types with freelist annotations for each constructor: $\mathbf{L}(k)$
  - Judgements $\Gamma, n \vdash e : T, m$ include information about *initial* and *final* size of freelist
  - Express final size of freelist as function of the size of the output
  - Complement this type system with some method for preventing deallocation of live cells (linear typing, usage aspects, layered sharing,. . .)

What is certificate generation?

- Verify the soundness of the type system w.r.t. the Camelot compilation by
  - interpreting the judgements in the program logic, using basic predicates about freelist representation and length, disjointness conditions of data-structures, *footprint* of program fragments
  - formally proving (in Isabelle/HOL) derived proof rules in the base logic
- Formulate the rules such that automated verification is possible
  - simple side conditions, no $\exists$-instantiations, syntax-directed;
  - provided that results of the compile-time analysis are communicated as method-level specifications (invariants)

$$\begin{aligned} \text{List.ins} &: \quad 1, \mathbf{I} \times \mathbf{L}(0) \longrightarrow \mathbf{L}(0), 0 \\ \text{List.sort} &: \quad 0, \mathbf{L}(0) \longrightarrow \mathbf{L}(0), 0 \end{aligned}$$

- Fixed assertion format $[\![U, n, [\Delta] \blacktriangleright T, m]\!]$

$$\begin{aligned} \text{List.ins} &: \quad [\![\{a, l\}, 1, [a : \mathbf{I}, l : \mathbf{L}(0)] \blacktriangleright \mathbf{L}(0), 0]\!] \\ \text{List.sort} &: \quad [\![\{l\}, 0, [l : \mathbf{L}(0)] \blacktriangleright \mathbf{L}(0), 0]\!] \end{aligned}$$

Proof rules

- LFD rule (Let):

$$\frac{\Gamma_1, n \vdash e_1 : A, k \qquad \Gamma_2, x : A, k \vdash e_2 : B, m}{\Gamma_1 \Gamma_2, n \vdash \texttt{let}\ x = e_1\ \texttt{in}\ e_2 : B, m}$$

- Note linearity condition for eliminating deallocation of live cells
- Certificate logic: linear context implemented in two components
- Proof rule (Let):

$$\frac{G \rhd e_1 : [\![U_1, n, [\Gamma] \blacktriangleright S, k]\!] \qquad G \rhd e_2 : [\![U_2, k, [\Gamma, x : S] \blacktriangleright T, m]\!]}{G \rhd \texttt{let}\ x = e_1\ \texttt{in}\ e_2 : [\![U_1 \cup (U_2 \setminus \{x\}), n, [\Gamma] \blacktriangleright T, m]\!]}\ U_1 \cap (U_2 \setminus \{x\}) = \emptyset$$

- Proof rules are expressed at a level where program variables occur (affinely) linear
- Atomic rules for (destructive and non-destructive) match-statements and for invocations of **make**
- Only the verification of the wrapper (uniform for all programs) needs to unfold the interpretation into the core logic

Certificates and automated verification

Producer-generated certificate:

- Content: method-level specifications in derived-assertions form
- Representation: Isabelle/HOL script that invokes a standard tactic **proveMe**

Consumer side:

- Tactic **proveMe** that
  - invokes derived proof rules (syntax-directed) and
  - discharges side conditions (set inclusions, arithmetic (in-)equalities).
  - Methods verified once, combination for mutual recursion via cut rule and parameter adaptation
  - Functions (basic blocks) verified once, via optimised treatment of merge points that combines imperative (dominator property) and functional (function parameters) viewpoints
  - Currently verified programs: functions over lists and trees (append, flatten, insertion sort & heap sort, . . .)
  - On-going generalization to algebraic data-type.

Discussion

Future work:

- Generalise existing system of derived assertions (sharing, usage-aspects, separation), and evaluate on bigger examples
- Extract stand-alone proof checker
- Derive specialised logics and certificate generation for other resources: frame stack, time, limits and separation conditions on method parameters

Conclusion:

- MRG-motto: certificate generation by interpreting type-systems in program logic
- Presented expressive program logic for low-level language
- Chain of abstractions: operational semantics $\longrightarrow$ general program logic $\longrightarrow$ derived specialised logics with automation
- Development backed up by implementation in Isabelle/HOL
- Sweet spot in debate “Classic vs. Foundational” PCC:
  $\leadsto$ Negotiation between proof size and TCB size

Credits

Numerous researchers and students have contributed to work on the MRG project, including:

- Don Sannella, Ian Stark, Stephen Gilmore, Martin Hofmann, David Aspinall;
- Kenneth MacKenzie, Lennart Beringer, Michal Konečný;
- Hans-Wolfgang Loidl, Olha Shkaravska;
- Matthew Prose, Nicholas Wolverson, Laura Korte;
- Robert Atkey, Steffen Jost;
- Robert Amadio.