Formal Development of the Pip Protokernel

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Joint work with the Pip team

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The Pip protokernel: a brief system overview (*David Nowak*)

Pip design principles and security properties (*Narjes Jomaa*)

From the executable specification to C (*Paolo Torrini*)

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On-Demand Secure Isolation

- This research is part of the European project ODSI.
  - Led by Orange
  - 1 academic partner: The university of Lille
  - 8 industrial partners from France, Romania, and Spain
- In Lille: 3 PhD students and 1 postdoctoral researcher.
- The Pip protokernel is one of the foundations of this project.
- Security protocols are designed on top of Pip.
- Case studies by industrial partners: IoT, M2M, SCADA
- Common Criteria certification

Memory isolation between applications

Why? For safety and security

How? By software (OS kernel), and hardware (MMU, CPU kernel mode)

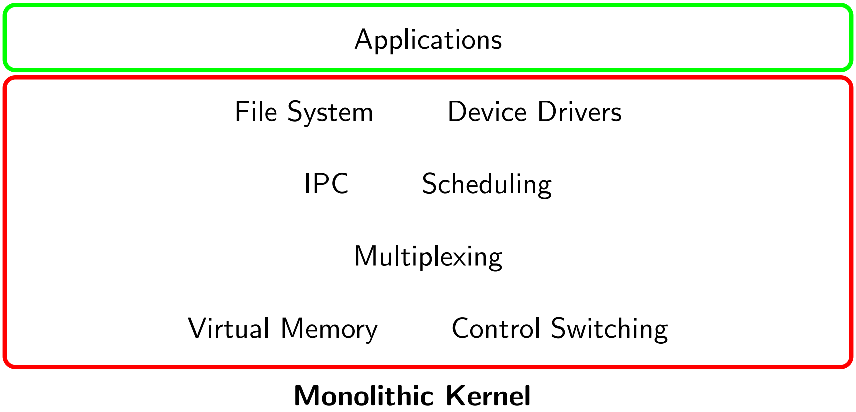
Correct? Ensured by a formal proof in Coq

Feasible? Yes, by reducing the trusted computing base to its bare bone

reducing the TCB $\Rightarrow$ increasing feasibility of a formal proof & reducing the attack surface

simplifying the specification language $\Rightarrow$ increasing feasibility of verified translation to C

From monolithic kernel to the Pip protokernel



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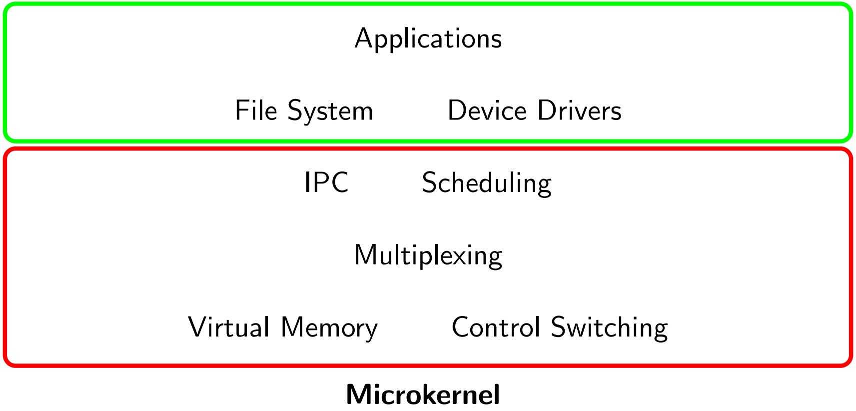
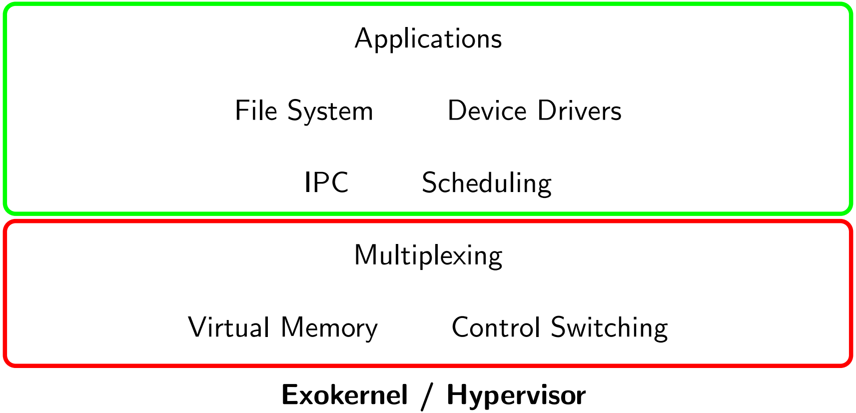
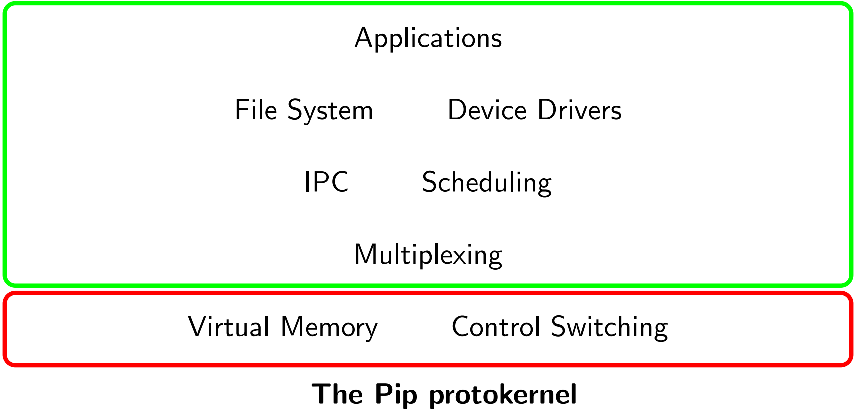


From monolithic kernel to the Pip protokernel



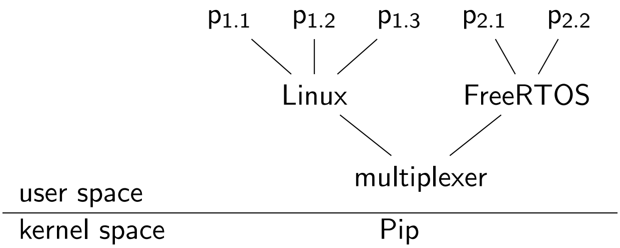
From monolithic kernel to the Pip protokernel



Partition tree

Pip organizes the memory into hierarchical partitions.

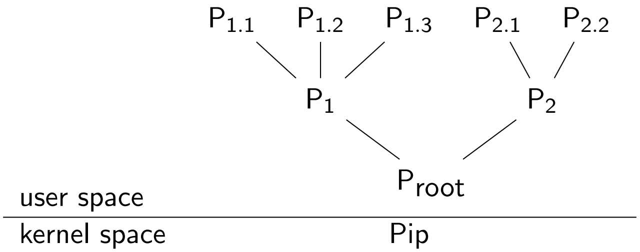
Example



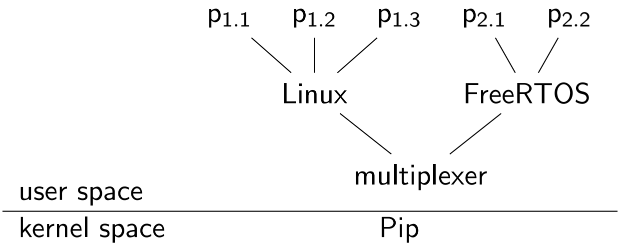
Partition tree: the point of view of Pip

The contents of each partition is not relevant for Pip.

- **Horizontal isolation**
  Partitions in different subtrees are isolated from each other,
  e.g. $P_{1.1}$ cannot access memory of $P_{1.2}$ or P_2.
- **Vertical sharing**
  A partition has access to the memory of its descendants.
- **Kernel isolation**
  Pip is isolated from all partitions.



Partition tree: dealing with interrupts



- **Software interrupts**
  - Pip deals with software interrupts to itself,
    e.g. FreeRTOS asks Pip to create a new partition.
  - Pip forwards other software interrupts to the caller's parent,
    e.g. $p_{1.2}$ make a system call to Linux.
- Pip forwards **hardware interrupts** to the root partition,
  e.g. a network packet has arrived.

Pip system calls

10 elementary system calls

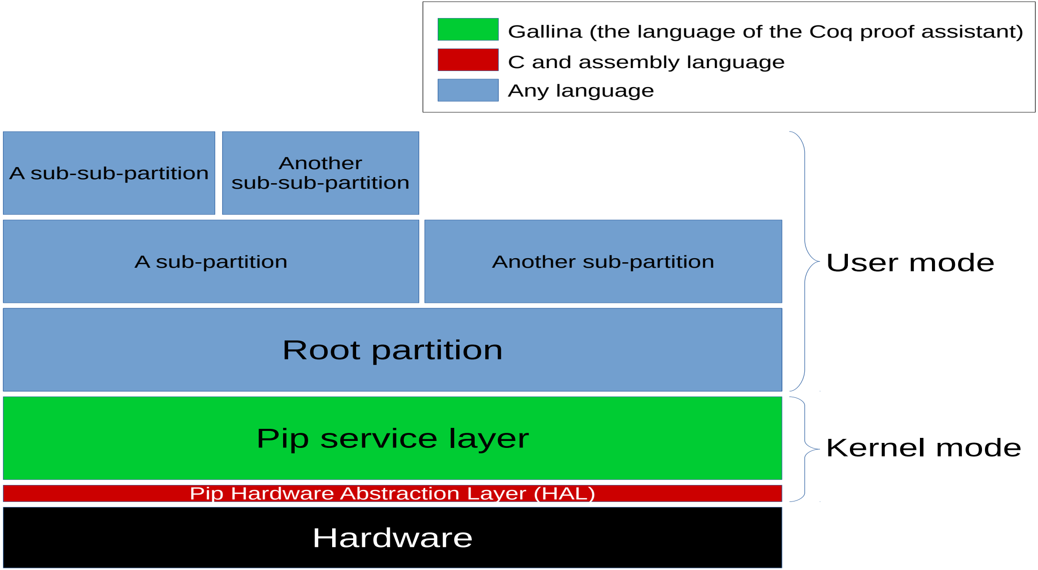
- **Memory management**

`createPartition`	creates a child partition
`removePartition`	deletes a child partition
`addVaddr`	lends a memory page to a child
`removeVaddr`	removes a memory page from a child
`pageCount`	the number of needed configuration pages
`prepare`	gives needed configuration pages
`collect`	takes back unused configuration pages
`mappedInChild`	returns the child using a given page

- **control switching**

`dispatch`	notifies a partition about an interrupt
`resume`	restores the context of a partition

Software layers



Applications

- The HAL of Pip has been ported to:
  - QEMU (x86)
  - x86
  - The Galileo board (Intel Pentium-compliant embedded board)
- Kernels ported on Pip
  - FreeRTOS: Tasks can be isolated in sibling partitions.
  - Linux 4.10.4: More involved because Linux configures MMU.
- Porting a kernel to Pip essentially consists of:
  - removing privileged instructions and operations, and
  - replacing them with system calls to Pip (paravirtualization).
- Drhystone benchmark: low overhead of 2,6% in terms of CPU cycles

Formal verification

- Formal verification of an executable specification of Pip

  Addressed by Narjes Jomaa in the next part of this presentation

- Verified translation of the executable specification into C

  Addressed by Paolo Torrini in the final part of this presentation

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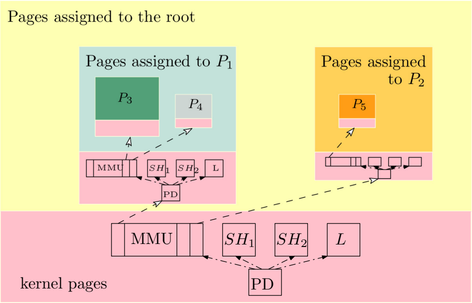
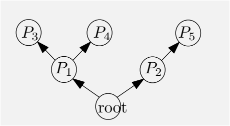
Partition tree management





The configuration of a partition

- Partition descriptor (*PD*)
- MMU tables
- Shadow 1 (*SH1*) and Shadow 2 (*SH2*)
- Linked list (*L*)

MMU briefly

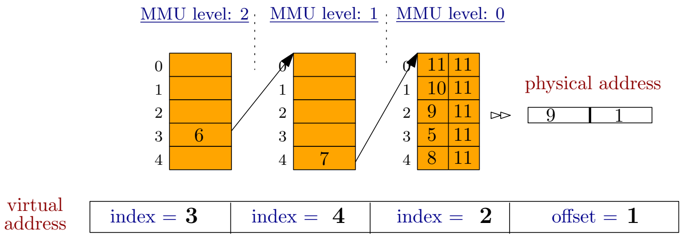
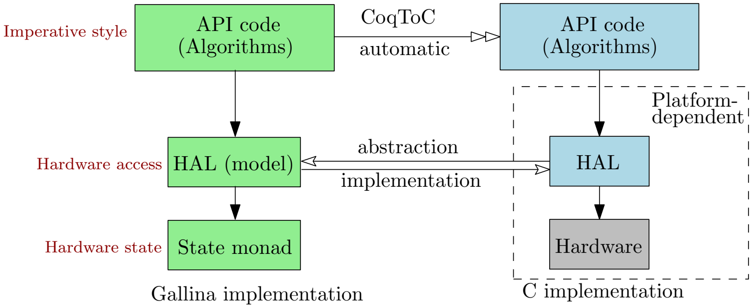


Figure: MMU with 3 levels of indirection

Data structure of partitions

- MMU structure: Define assigned pages and access control
- Mirror the MMU structure
  - Shadow 1: Find out which pages are assigned to children and which pages are used as a partition descriptor identifier *(security)*
  - Shadow 2: Ease getting back the ownership of assigned pages *(efficiency)*
- List (L): Ease getting back the ownership of pages lent to the kernel *(efficiency)*

Pip design principles

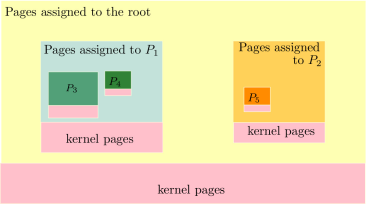


- Hardware state: the part that is relevant to model the partition tree
  - the partition that is currently active
  - the physical memory where Pip stores its own data
- Exclude the use of all objects that would require a GC: lists, trees → Encoding these structure in physical memory using the HAL

Security properties

The horizontal isolation property

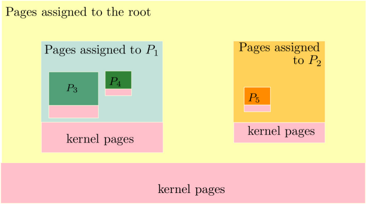
```
Definition HI s : Prop :=

∀ parent child1 child2 : page,

  parent ∈ (partitionTree s) →

  child1 ∈ (children parent s) →

  child2 ∈ (children parent s) →

  child1 ≠ child2 →

  (allocatedPages child1 s) ∩ (allocatedPages child2 s) = ∅.
```



- Sibling partitions cannot access each others memory.

Hierarchical TCB (vertical sharing)

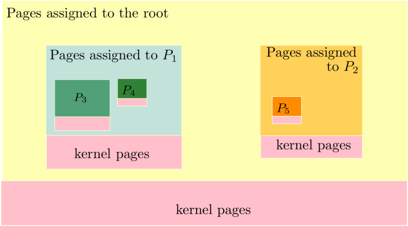
```
Definition VS s : Prop :=
∀ parent child : page,
 parent ∈ (partitionTree s) →
 child ∈ (children parent s) →
 (allocatedPages child s) ⊆ (assignedPages parent s).
```



- All the pages allocated for a partition are included in the pages assigned to its ancestors

The kernel isolation property

```
Definition KI s : Prop :=
∀ partition1 partition2 : page,
  partition1 ∈ (partitionTree s) →
  partition2 ∈ (partitionTree s) →
  (ownedPages partition1 s) ∩ (kernelPages partition2 s) = ∅.
```



- No partition can access to the pages owned by the kernel.

Information flow property

- As a corollary to VS and HI:
  Non-influence property for isolated partition was proved
- Abstract information flow model
- Assumption about hardware side effects

Verification approach

Verification approach

Hoare logic on top of the LLI (Low Level Interface) monad

{{Precondition}} Program {{Postcondition}}

- Program: a monadic function (of type `LLI A`)
- Precondition: a unary predicate on the starting state
- Postcondition: binary predicate on the returned value and on the ending state

```
Definition hoareTriple {A : Type}
(P : state → Prop) (m : LLI A)
(Q : A → state → Prop) : Prop :=
∀ s, P s → match m s with
  | val (a, s') ⇒ Q a s'
  | undef _ _ ⇒ False
  end.
```

{{ P }} m {{ Q }}

States that if the precondition holds then

- the postcondition holds; and
- there is no undefined behavior

The need of consistency properties

- We cannot prove the following invariant

  {{HI & VS & KI}} API_service {{HI & VS & KI}}

- Properties about the Pip's data structure are missing
  - The precondition should be strengthened with consistency properties
  - The consistency properties must also be preserved

  {{HI & VS & KI & C}} API_service {{HI & VS & KI & C}}

- consistency $\approx$ well-formedness of Pip's data structures

Example: createPartition invariant

{{HI & VS & KI & C}} createPartition v1 v2 v3 v4 v5 {{HI & VS & KI & C}}

Proceed forward using transitivity (1/2)

```
{{HI & VS & KI & C}}

  perform currentPart := getCurPartition in
  perform ptv1FromPD := getTableAddr currentPart v1 nbL in
          ...
  if negb accessv1 then ret false else
  writeAccessible ptv1FromPD idxv1 false ;;
  ...
{{HI & VS & KI & C}}
```

Proceed forward using transitivity (2/2)

First sub-goal:

{{HI & VS & KI & C}}

getCurPartition

{{HI & VS & KI & C & P currentPart }}

Second sub-goal:

{{HI & VS & KI & C & P currentPart}}

```
perform ptv1FromPD := getTableAddr currentPart v1 nbL in
        ...
if negb accessv1 then ret false else
writeAccessible ptv1FromPD idxv1 false ;;
        ...
```

{{HI & VS & KI & C}}

Verification overview

Invariants (`Qed`)	**line of proof**
createPartition (300 loc)	$\approx$ 60000
createPartition + addVaddr (50 loc)	$\approx$ 78000
createPartition + addVaddr + mappedInChild(20 loc)	$\approx$ 78250

Table: Overview of the proof

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Translating to C

Coq executable model and extracted OCaml code:

- needs big runtime environment
- not efficient enough

We need a translation to low level languages:

- HAL: manual implementation in assembly and C
- Service Layer: C code automatically generated from Gallina
- currently compiled by GCC

Translating to C

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We need a translation to low level languages:

- HAL: manual implementation in assembly and C
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However: we want a verified translation to CompCert C

- certified compilation
- tail-recursive optimisation

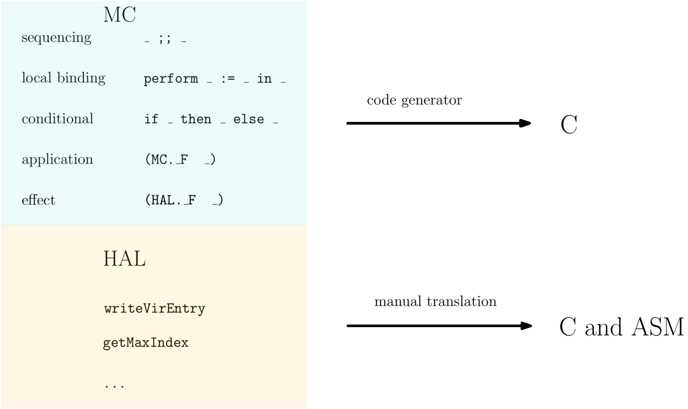
Pip monadic code (MC)

- Low-level HAL primitives
- Higher-level monadic code (MC)

```
Fixpoint initVTable timeout shadow1 idx :=
  match timeout with
  | 0 ⇒ ret tt
  | S timeout1 ⇒
    perform max := getMaxIndex in
    perform res := Index.ltb idx max in
    if (res)
    then
      perform daddr := getDefaultVAddr in
      writeVirEntry shadow1 idx daddr ;;
      perform nidx :=  Index.succ idx in
      initVTable timeout1 shadow1 nidx
    else ...
  end.
```

Translation to C

We use a Haskell-implemented translator (*digger*) to translate from the Gallina AST of MC to C.



Shallow embedding

MC is a shallow embedding, i.e. a semantic representation of a language in Coq, based on a set of Gallina definitions.

```
Definition ret : A → LLI A := fun a s ⇒ val (a, s).

Definition bind : LLI A → (A → LLI B) → LLI B :=
 fun m f s ⇒ match m s with
 | val (a, s') ⇒ f a s'
 | undef a s' ⇒ undef a s' end.
```

```
perform x := m in e   for   bind m (fun x => e)

              m ;; e   for   bind m (fun _ => e)
```

Value types: `bool` and subtypes of `nat`

Sample translation

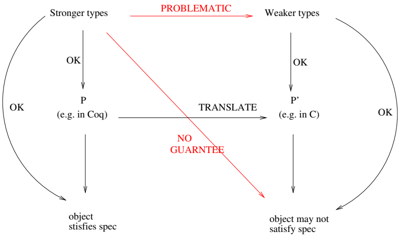
Example: a function defined in Coq, using the monadic code:

```
Definition getFstShadow (partition : page) : LLI page :=
  perform idx := getSh1idx in
  perform idxSucc := Index.succ idx in
  readPhysical partition idxSucc.
```

and its generated translation to C:

```
uintptr_t getFstShadow (const uintptr_t partition) {
  const uint32_t idx = getSh1idx ();
  const uint32_t idxSucc = succ (idx);
  return readPhysical (partition, idxSucc); }
```

Problem: generating verified code



General solution: define a semantic translation from weak to strong (w.r.t. types), and reverse it

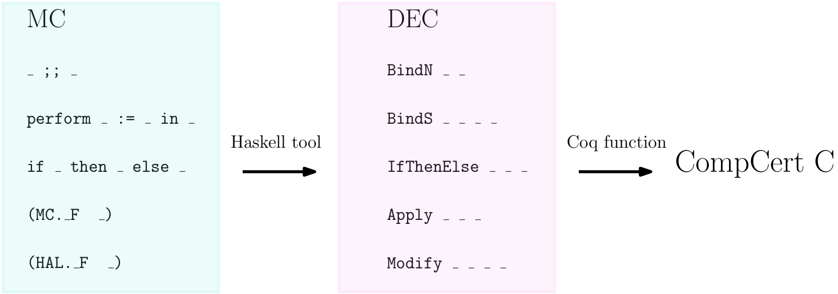
However: we do not want to define a semantics of C in Coq, we want to use an existing one which also provides compilation – CompCert C.

Verified translation: our approach

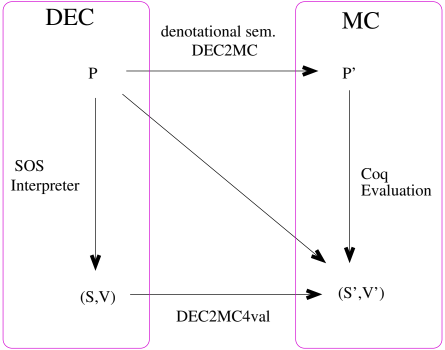
1. we build a Coq representation of MC as a deep embedding (DEC) and specify formally its semantics
   – operationally, implementing an SOS interpreter
   – denotationally, as interpretation of DEC into Gallina
2. use the denotational semantics to verify the translation of Pip into DEC
3. use the operational semantics to verify the translation to CompCert C

Translation through DEC

DEC is defined in terms of abstract datatypes: possible to manipulate it as an object in Coq – e.g. to define a formal translation from it



From DEC to MC (in Gallina) and back (in Haskell)

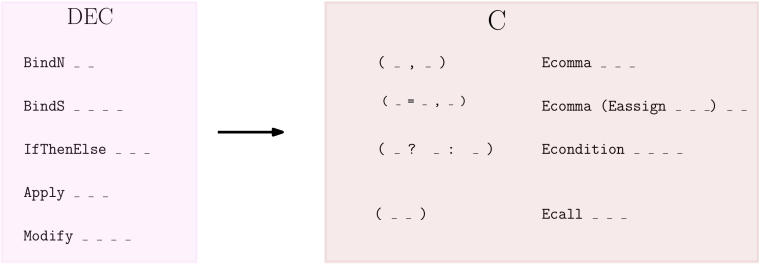


For the two semantics to agree:

for P a DEC program, DEC2MC4val (SOS_Int P) $=$ DEC2MC P

Pip $=$ DEC2MC (*Haskell_MC2DEC* Pip)

From DEC to C



Semantic soundness: need for a proof that behaviour is preserved.

Essentially – like adding a compilation step.

DEC expressions

```
Inductive Exp : Type :=
| Val (v: Value) | Var (x: Id)
| BindN (e1: Exp) (e2: Exp)
| BindS (x: Id) (t: option VTyp) (e1: Exp) (e2: Exp)
| IfThenElse (e1: Exp) (e2: Exp) (e3: Exp)
| Apply (f: Id) (prms: Prms) (fuel: Exp)
| Modify (t1 t2: VTyp) (xf: XFun t1 t2) (prm: Exp)
| BindMS (env: valEnv) (e: Exp)
| Call (f: Id) (prms: Prms)
with Prms : Type := PS (es: list Exp).
```

Recursive functions terminate (as in MC)

Modules, mutual recursion and side-effects

```
Parameter Id: Type.
Parameter State: Type.

Inductive Fun : Type :=
FC (formal_prms: list (Id * VTyp) (ret_type: VTyp)
   (default: Value) (body: Exp).

Record XFun (dt1 dt2: VTyp) : Type :=
{ x_modify : State → (mcTyp dt1) → State * (mcTyp dt2) }.
```

Operational semantics (small-step)

ϕ function environment

δ datavalue environement

Static:

$$\vdash \phi :: \Phi$$
$$\Phi; \Delta \vdash \mathit{exp} :: \mathit{vtyp}$$
$$\vdash \text{well\_typed } \phi$$

$$\vdash \delta :: \Delta$$
$$\Phi; \Delta \vdash \mathit{prms} :: \mathit{ptyp}$$

Dynamic:

$$\phi;\ \delta \Vdash (\mathit{state},\ \mathit{fuel},\ \mathit{exp}) \longrightarrow (\mathit{state}',\ \mathit{fuel}',\ \mathit{exp}')$$
$$\phi;\ \delta \Vdash (\mathit{state},\ \mathit{fuel},\ \mathit{prms}) \longrightarrow (\mathit{state}',\ \mathit{fuel}',\ \mathit{prms}')$$

Type soundness (SOS interpreter)

Type soundness for expressions (similarly for parameters):

$$
\begin{array}{ll}
\forall\ \Phi\ \Delta\ \mathit{exp}\ \mathit{vtyp}, & \Phi; \Delta \vdash \mathit{exp} :: \mathit{vtyp}\ \rightarrow \\
\forall\ \phi\ \delta\ \mathit{state}\ \mathit{fuel}, & \vdash \text{well\_typed}\ \phi\ \rightarrow \\
 & \vdash \phi :: \Phi\ \rightarrow \\
 & \vdash \delta :: \Delta\ \rightarrow \\
\multicolumn{2}{l}{\Sigma!\ \mathit{state}'\ \mathit{fuel}'\ v,} \\
\multicolumn{2}{l}{\quad \phi;\ \delta \Vdash (\mathit{state},\ \mathit{fuel},\ \mathit{exp}) \longrightarrow (\mathit{state}',\ \mathit{fuel}',\ \text{Val}\ v)}
\end{array}
$$

Proved in Coq, by double induction on fuel and the mutually defined typing relations.

Operational semantics (Coq code)

```
Inductive ExpTyping :
  list (Id*FTyp) → list (Id*Value) → Exp → VTyp → Type
with PrmsTyping :
  list (Id*FTyp) → list (Id*Value) → Prms → PTyp → Type

Inductive FEnv_WT (fenv: list (Id*Fun)) : Type

Inductive AConfig (T: Type) : Type :=
                     Conf (state: W) (fuel: nat) (qq: T)

Inductive EStep (fenv: list (Id*Fun)) :
   list (Id*FCall) → list (Id*Value) →
                         AConfig Exp → AConfig Exp → Type
with PrmsStep (fenv: list (Id*Fun)) :
   list (Id*FCall) → list (Id*Value) →
                         AConfig Prms → AConfig Prms → Type
```

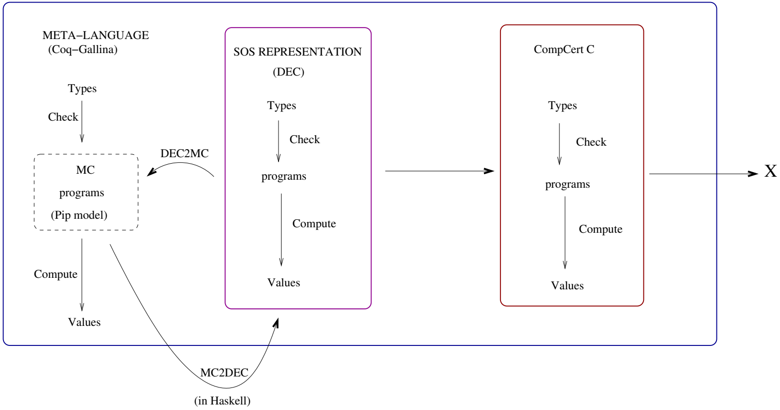
Denotational semantics

$$\Theta_e \;:\; \Theta_t\ \mathsf{funEnv} \to \Theta_t\ \mathsf{valEnv}\ \to \forall\ e : \mathsf{Exp},\ \mathsf{ILL\ State}\ (\Theta_t\ (\tau e))$$

$$
\begin{array}{ll}
\Theta_e\ \_\ \_\ (\mathsf{Val}\ v) & = \ \mathsf{ret}\ (\mathsf{ext}\ v) \\
\Theta_e\ \_\ VS\ (\mathsf{Var}\ x) & = \ \mathsf{ret}\ (\mathsf{find}\ x\ VS) \\
\ldots & \\
\Theta_e\ FS\ \ VS\ (\mathsf{BindS}\ x\ \_\ e_1\ e_2) & = \mathsf{let}\ t = \Theta_t\ (\tau e_1)\ \mathsf{in} \\
\qquad \mathsf{bind}\ \ (\Theta_e\ FS\ \ VS\ \ e_1) & (\Theta_e\ FS\ ((x, t) :: VS)\ e_2) \\
\ldots & \\
\Theta_e\ FS\ \ VS\ (\mathsf{Call}\ f\ \ prms) & = \\
\qquad \mathsf{bind}\ \ (\Theta_{es}\ FS\ \ VS\ prms) & (\mathsf{find}\ f\ \ FS) \\
\Theta_e\ FS\ \ VS\ (\mathsf{Modify}\ xf\ \ prm) & = \\
\qquad \mathsf{bind}\ \ (\Theta_e\ FS\ \ VS\ prm) & (\mathsf{x\_modify}\ xf)
\end{array}
$$

Provable in Coq: the two semantics (operational and denotational) agree

Summarising



Documentation

System:
Q. Bergougnoux, N. Jomaa, M. Yaker, J. Cartigny, G. Grimaud, S. Hym, D. Nowak, Proved Memory Isolation in Real-Time Embedded Systems through Virtualization, submitted

Formal modelling and verification of security properties:
N. Jomaa, P. Torrini, D. Nowak, G. Grimaud, Proof-oriented Design of a Separation Kernel with Minimal TCB, submitted

Translation:
P. Torrini, D. Nowak, DEC: Coq repository, https://github.com/2xs/dec.git
S. Hym, V. Oudjail, Digger: Haskell repository, https://github.com/2xs/digger

To find out more

`http://pip.univ-lille1.fr`

The Pip Development Team thanks you for your attention