The Pip Protokernel

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Joint work with the Pip team

Pip Club Meeting 2018

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

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

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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)

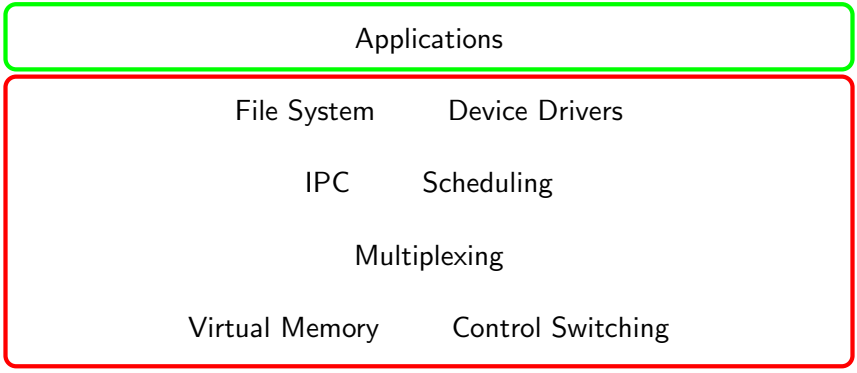
Correct? Ensured by a formal proof in Coq

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

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

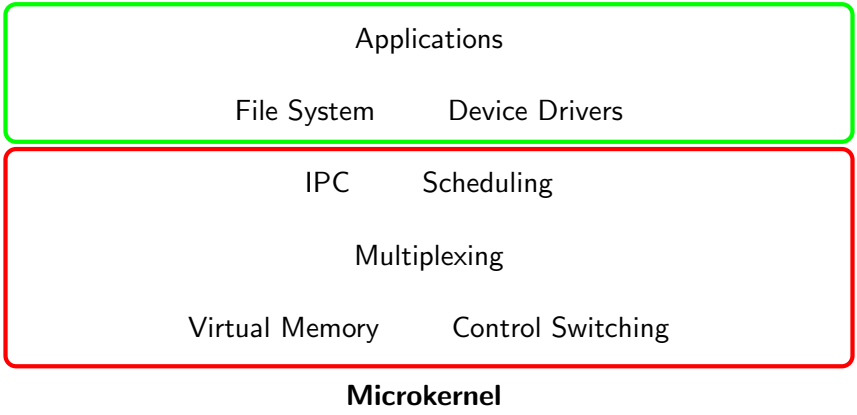
$$\text{simplifying the specification language} \Rightarrow \text{increasing feasibility of verified translation to C}$$

From monolithic kernel to the Pip protokernel



Monolithic Kernel

From monolithic kernel to the Pip protokernel



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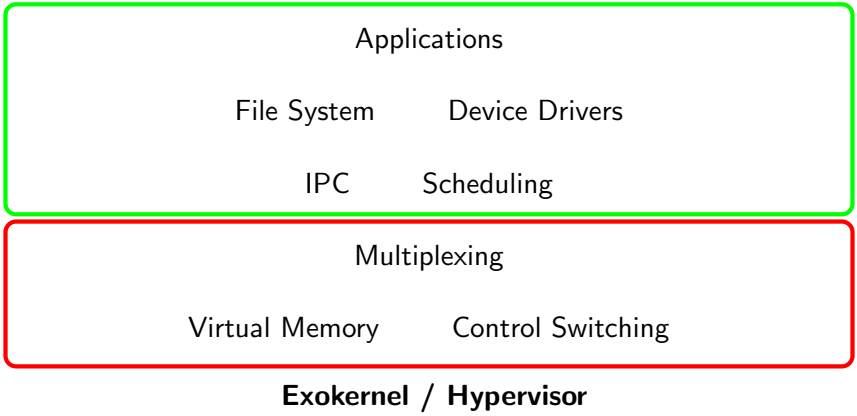
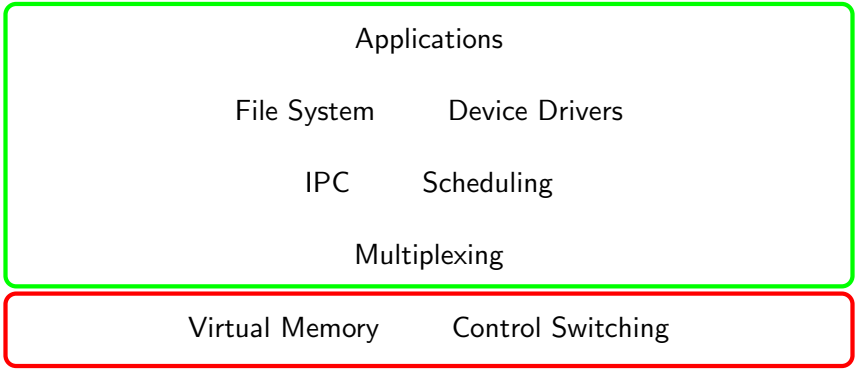


From monolithic kernel to the Pip protokernel

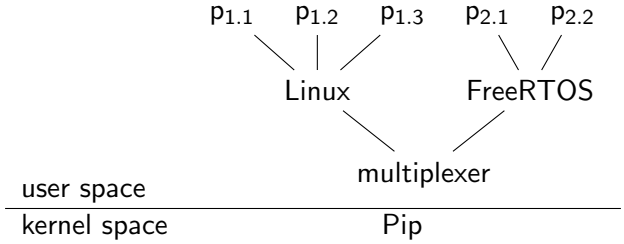


The Pip protokernel

Partition tree

Pip organizes the memory into hierarchical partitions.

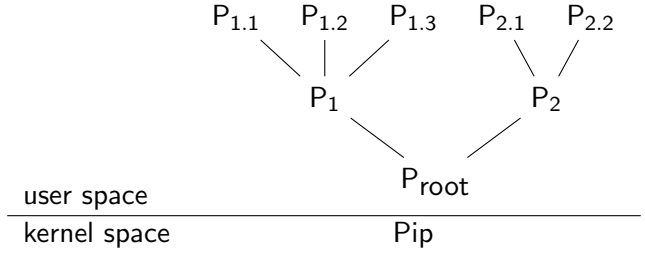
Example



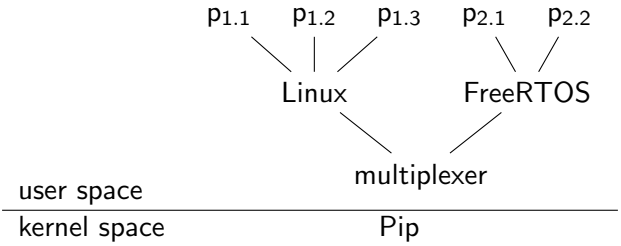
Partition tree: the point of view of Pip

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

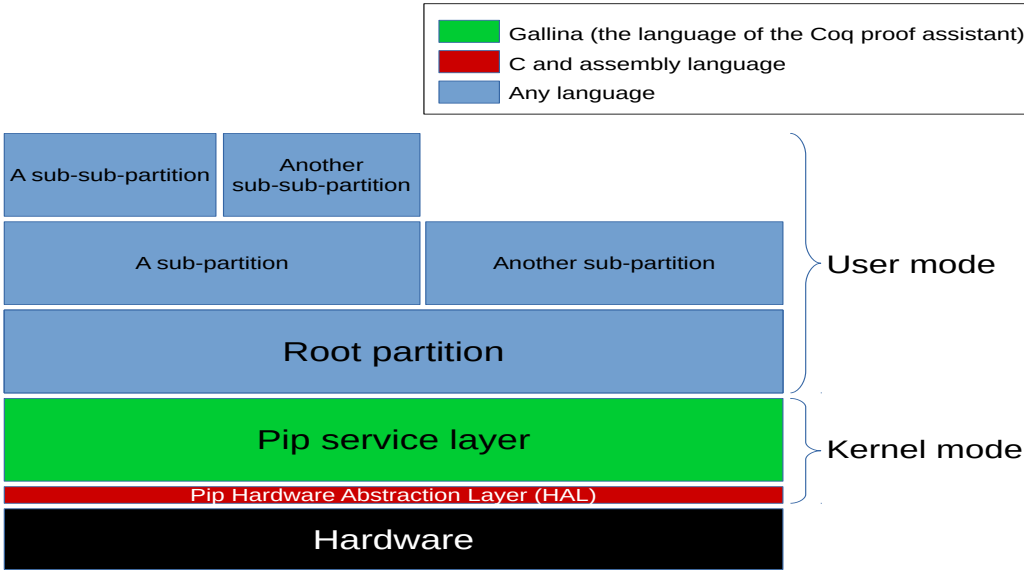
- **Memory management**

`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

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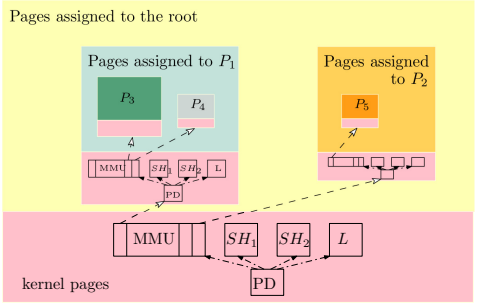
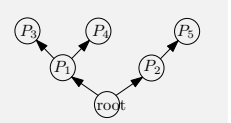
Partition tree management





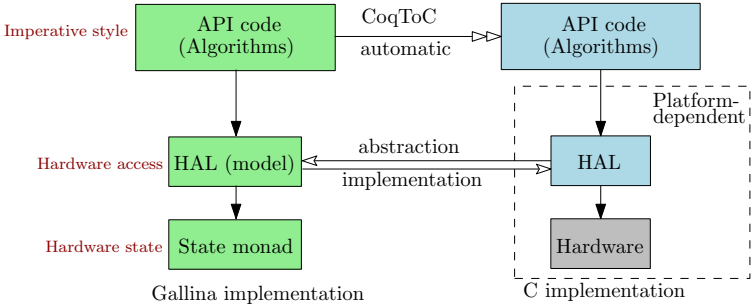
The configuration of a partition

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

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

Sample translation

– Low-level HAL primitives
– Higher-level monadic code

Pip monadic code in Coq

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

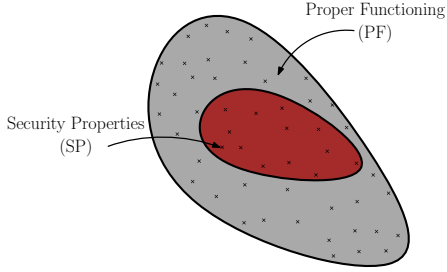
Its generated translation to C

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

Security properties

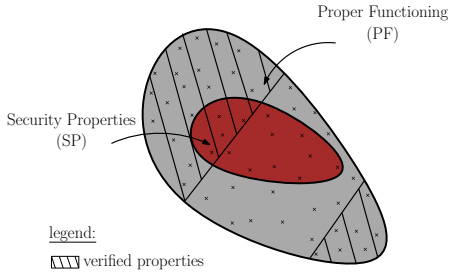
Classification of properties

Proper functioning : a property related to a one or more service of the system
Security : a property that should be preserved by all the services of the system



- Prove all SP $\not\Rightarrow$ Prove all PF
- Prove all PF $\Rightarrow$ Prove all SP;

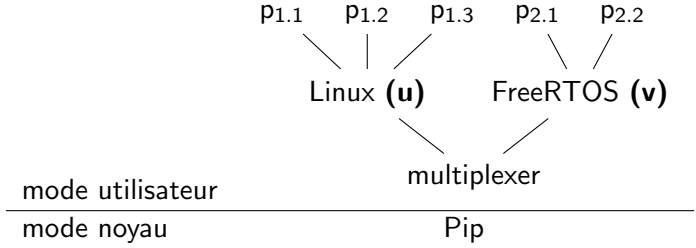
Reduce the number of properties to prove



- identify security properties;
- identify the subset of correctness properties that shoud be verified to ensure security properties

✓ Non interference property[1]

"a security domain **u** *is noninterfering with domain* **v** *if no action performed by* **u** *can influence subsequent outputs seen by v."*

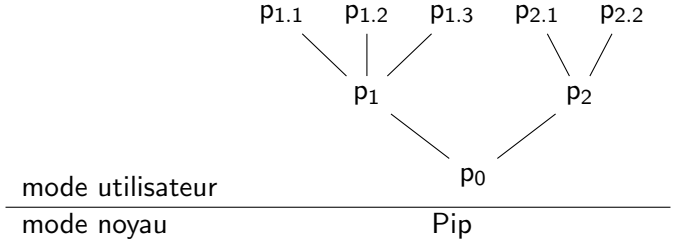


[1] John Rushby. *Noninterference, transitivity, and channel-control security policies*. SRI International, Computer Science Laboratory, 1992.

Reduce to elementary properties

✓ Non interference property

"a security domain **u** *is noninterfering with domain* **v** *if no action performed by* **u** *can influence subsequent outputs seen by v."*



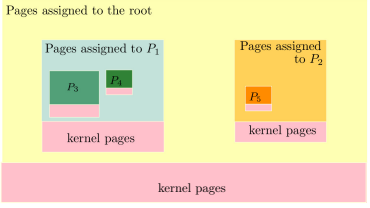
☞ isolation property ensured by Pip does not depend on actions performed by partitions

☞ reason about the memory of partitions

☞ isolation properties imply non interference property

The horizontal isolation property

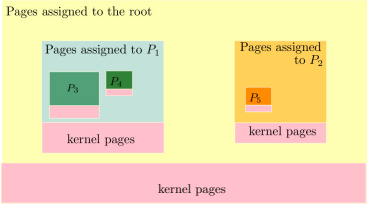
```
Definition HI s: Prop :=

∀ 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)

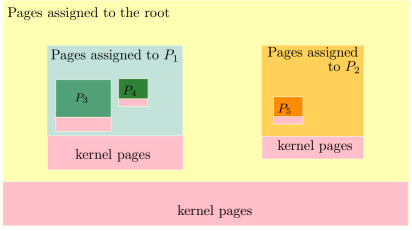
```
Definition VS s : Prop :=
∀ parent child : page,
 parent ∈ ( partitionTree s) →
 child ∈ (children parent s) →
 (allocatedPages child s) ⊆ (assignedPages parent s).
```



- 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.

Verification approach

Verification approach

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

```
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.
```

States that if the precondition holds then

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

```
{{P}} m {{Q}}
```

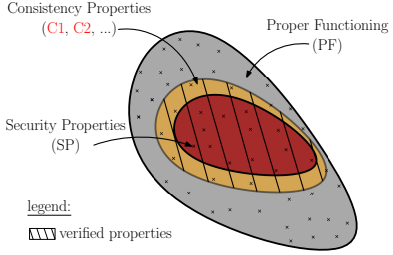
☞ `{{HI & VS & KI}} API_service {{HI & VS & KI}}`

The need of consistency properties

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

☞ consistency : C1, C2 ... ≈ well-formedness of Pip's data structures

{{HI & VS & KI & C1 & C2 & ..}} API_service {{HI & VS & KI & C1 & C2 & ..}}



- discovered incrementally during the proof
- must be preserved in order for isolation to be preserve

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

{{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)

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

First sub-goal:

{{HI & VS & KI & C}}

getCurPartition

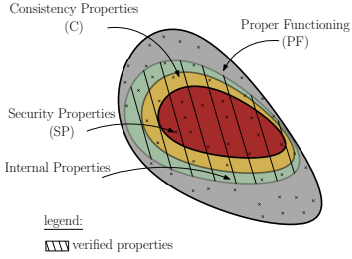
{{HI & VS & KI & C & P currentPart }}

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}}



☞ P currentPart : an internal property of createPartition

Verification overview

✓ one person year

Invariants	**lines of proof**
createPartition ($\approx 300 loc$)	$\approx$ 60000
createPartition + addVaddr ($\approx 110 loc$)	$\approx$ 78000
createPartition + addVaddr + mappedInChild ($\approx 40 loc$)	$\approx$ 78300
createPartition + addVaddr + mappedInChild + removeVaddr ($\approx 100 loc$)	$\approx$ 88300

Table: Size of the proof

Invariant	**duration**
createPartition	$\approx$ 10 months
addVaddr	$\approx$ 2 months
mappedInChild	$\approx$ 4 hours
removeVaddr	$\approx$ 2 weeks

Table: Duration of the verification

To find out more

http://pip.univ-lille1.fr