# Micro-Policies

## A Framework for Verified, Hardware-Assisted Security Monitors


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# Current collaborators on this project

- **Formal verification side**
  - Arthur Azevedo de Amorim (UPenn & INRIA Paris)
  - Maxime Dénès (UPenn)
  - Nick Giannarakis (INRIA Paris & NTU Athens)
  - Cătălin Hrițcu (INRIA Paris)
  - Benjamin Pierce (UPenn)
  - Antal Spector-Zabusky (UPenn)
  - Andrew Tolmach (Portland State)
- **Architecture side**
  - André DeHon, Udit Dhawan, Nikos Vasilakis, ... (UPenn)

# Computer systems are insecure

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- Today’s CPUs are mindless bureaucrats
  - “write past the end of this buffer” ... *yes boss!*
  - “jump to this untrusted integer” ... *right boss!*
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  - security-performance tradeoff

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  pervasive security enforcement impractical
  - security-performance tradeoff

  just write secure code ... all of it!
- Consequence: vulnerabilities in every system
  - violations of known safety and security policies


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- general dynamic enforcement mechanism for
  - critical invariants of **all** machine code
  - high-level abstractions and programming models

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  - “this word is an instruction, and this one is a pointer”
    “this word comes from the net, and this is private to A and B”

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  - tags and rules **defined by software** (miss handler; verified)
    **accelerated by hardware** (rule cache, near-0 overhead hits)

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  low overhead: <10% runtime, <50% energy, <12% power

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- monitor self-protection
- dynamic sealing
  compartmentalization
  memory safety
- control-flow integrity (CFI)
- hardware types (instr/ptr/...)
  taint tracking
- ...

# Micro-policies for ...

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recent draft

Verified
(in Coq)

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recent draft

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Evaluated (simulations)

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# Memory safety

- Prevent
  - **spatial violations**: reading/writing out of bounds
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# Memory safety

- Prevent
  - **spatial violations**: reading/writing out of bounds
  - **temporal violations**: use after free, invalid free
- Pointers become **unforgeable capabilities** 
  - can only obtain a valid pointer to a memory region

    by allocating that region or

    - by copying/offsetting an existing pointer to that region

# Memory safety micro-policy

| | |
|---|---|
| $T_v$ ::= $i$ \| $ptr(c)$ | tags on values |
| $T_m$ ::= $M(c,T_v)$ \| $F$ | tags on memory |

# Memory safety micro-policy

color of region

$T_v$ ::= i | ptr(c)    tags on values

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# Memory safety micro-policy

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tag of content

# Memory safety micro-policy

**p←malloc k**

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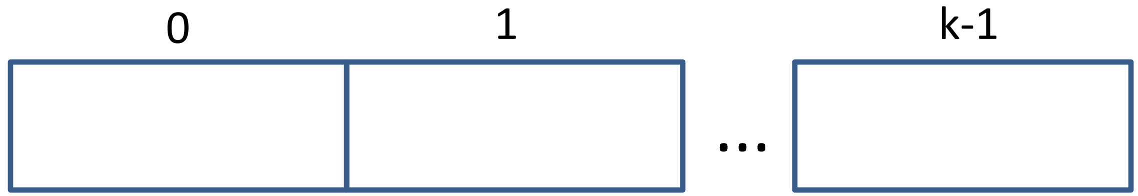


| | | |
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| $T_v$ | $::= i \mid ptr(c)$ | tags on values |
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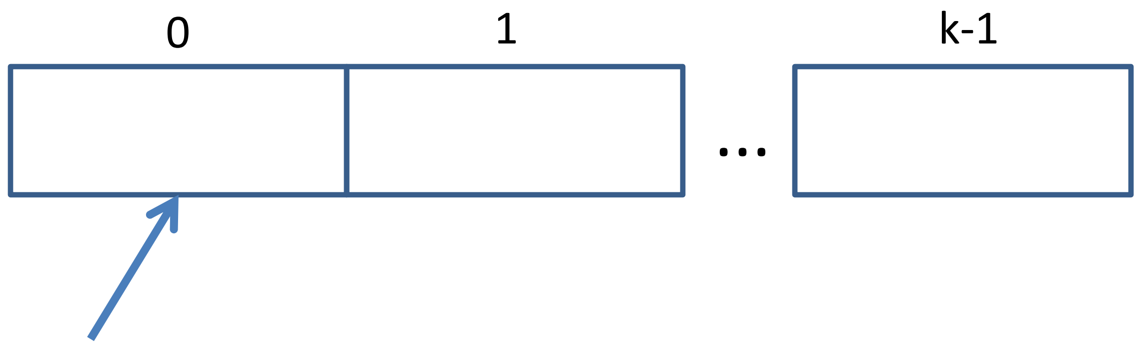


p = A8F0

| | |
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| $T_v$ ::= i \| ptr(c) | tags on values |
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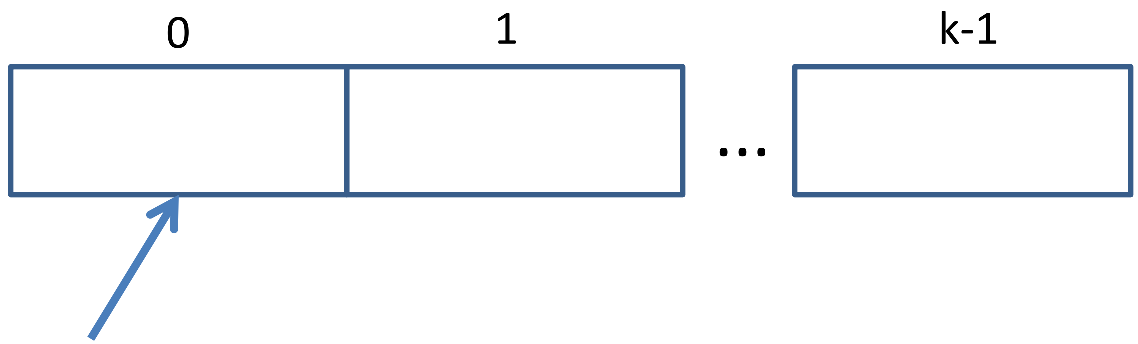
**p←malloc k**

fresh c

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$T_v$ ::= i | ptr(c)   tags on values

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# Memory safety micro-policy

**p←malloc k**

fresh c

| 0 | 1 | | k-1 |
|---|---|---|---|
| 0@M(c,i) | 0@M(c,i) | … | 0@M(c,i) |

p = A8F0

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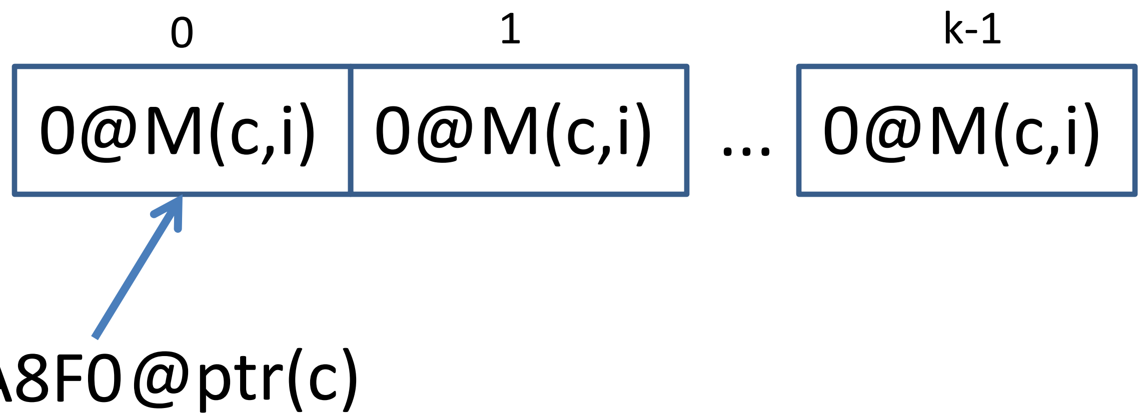


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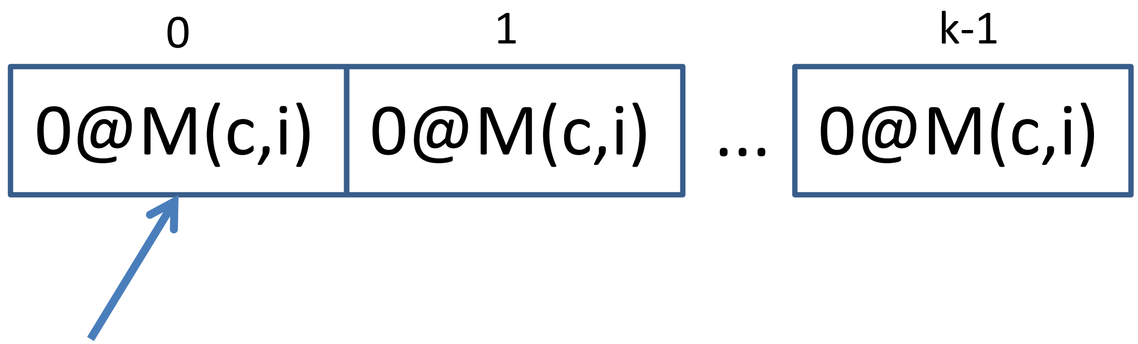


p = A8F0@ptr(c)

**q ← p + 1**

| | | |
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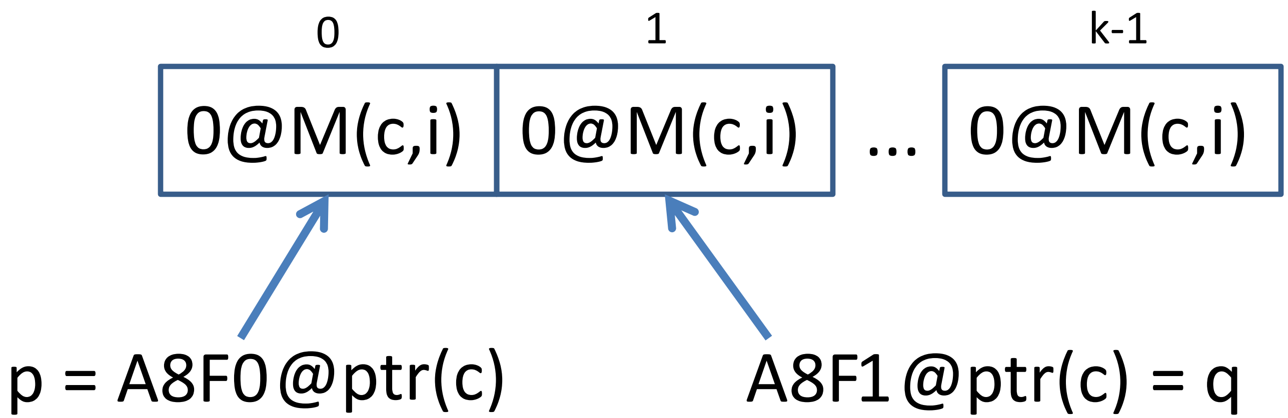


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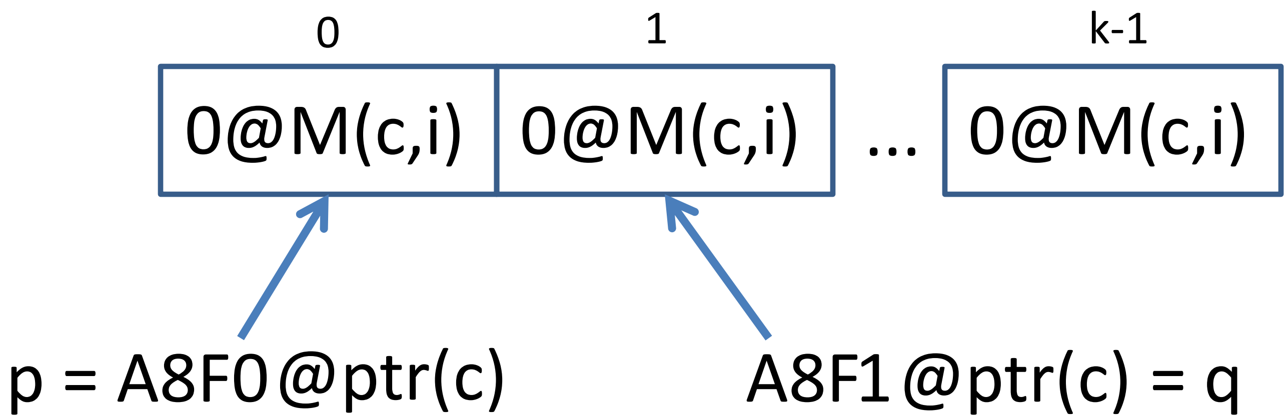


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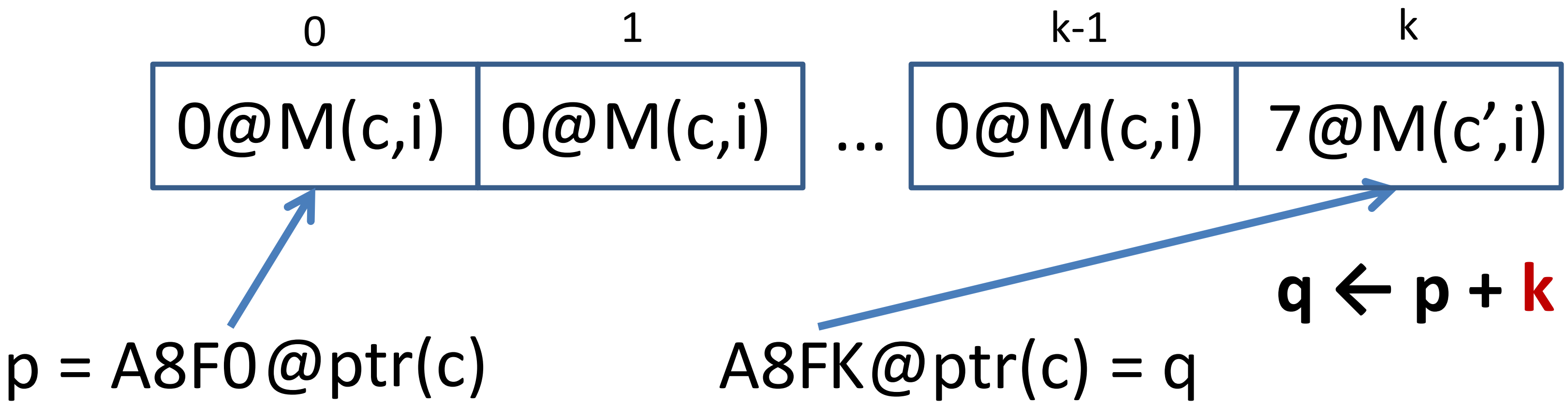


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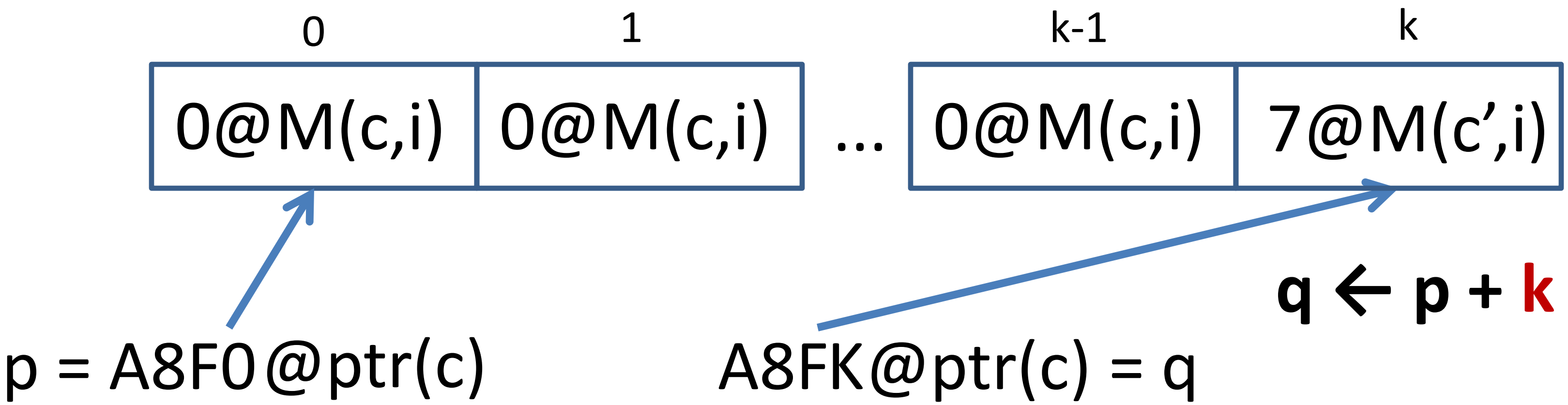


**!p ← 7**

| | | |
|---|---|---|
| $T_v$ | ::= i \| ptr(c) | tags on values |
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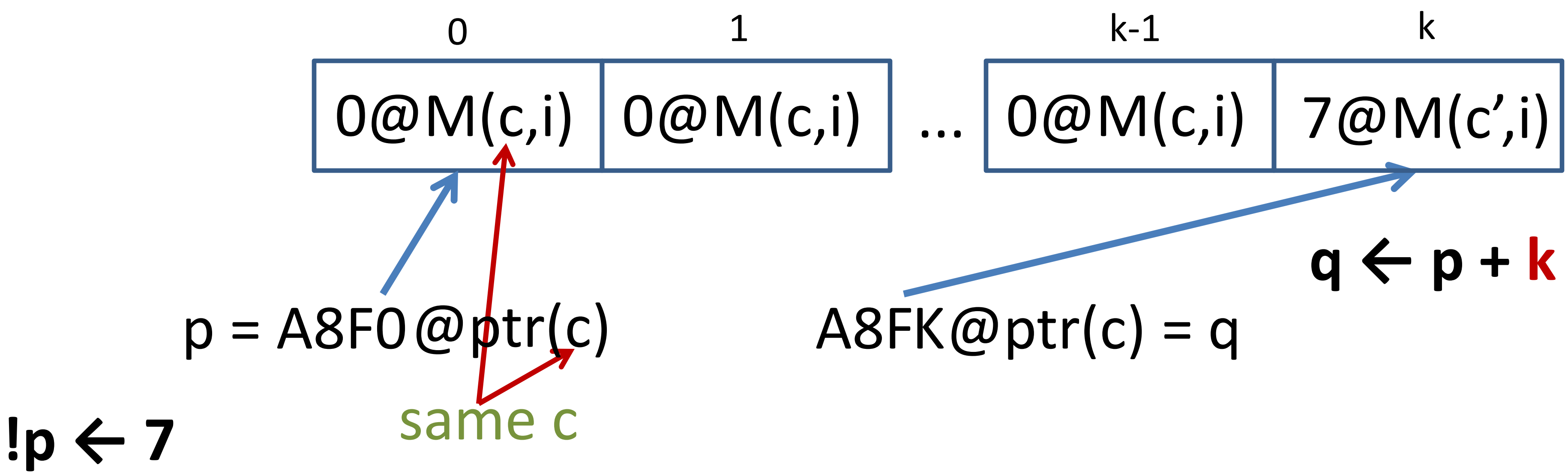
# Memory safety micro-policy

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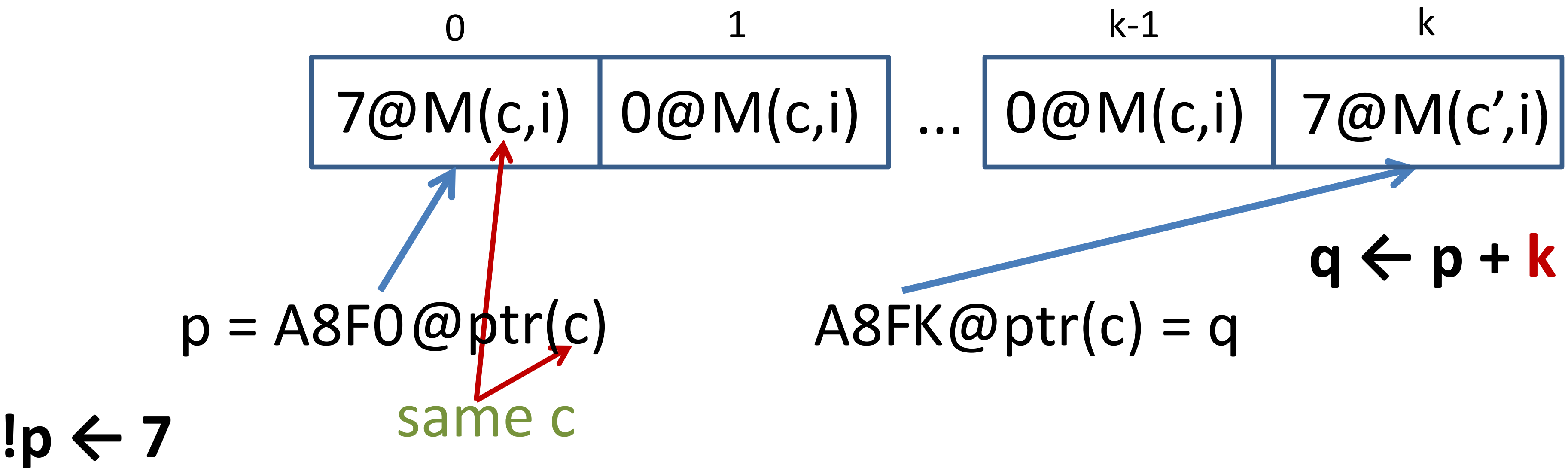


$T_v$ ::= i | ptr(c) — tags on values

$T_m$ ::= M(c,$T_v$) | F — tags on memory

# Memory safety micro-policy

| 0 | 1 | | k-1 | k |
|---|---|---|---|---|
| 7@M(c,i) | 0@M(c,i) | … | 0@M(c,i) | 7@M(c’,i) |

**q ← p + k**

p = A8F0@ptr(c)

A8FK@ptr(c) = q

**!q ← 42**

| | | |
|---|---|---|
| $T_v$ | ::= i \| ptr(c) | tags on values |
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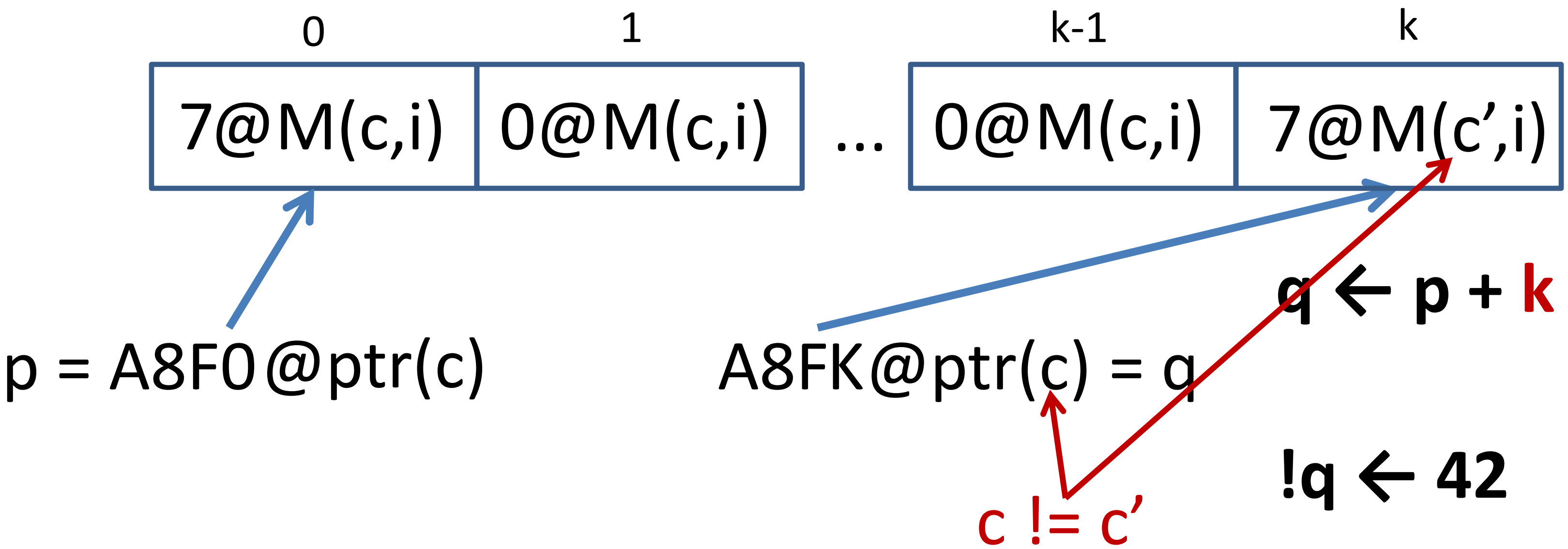
# Memory safety micro-policy

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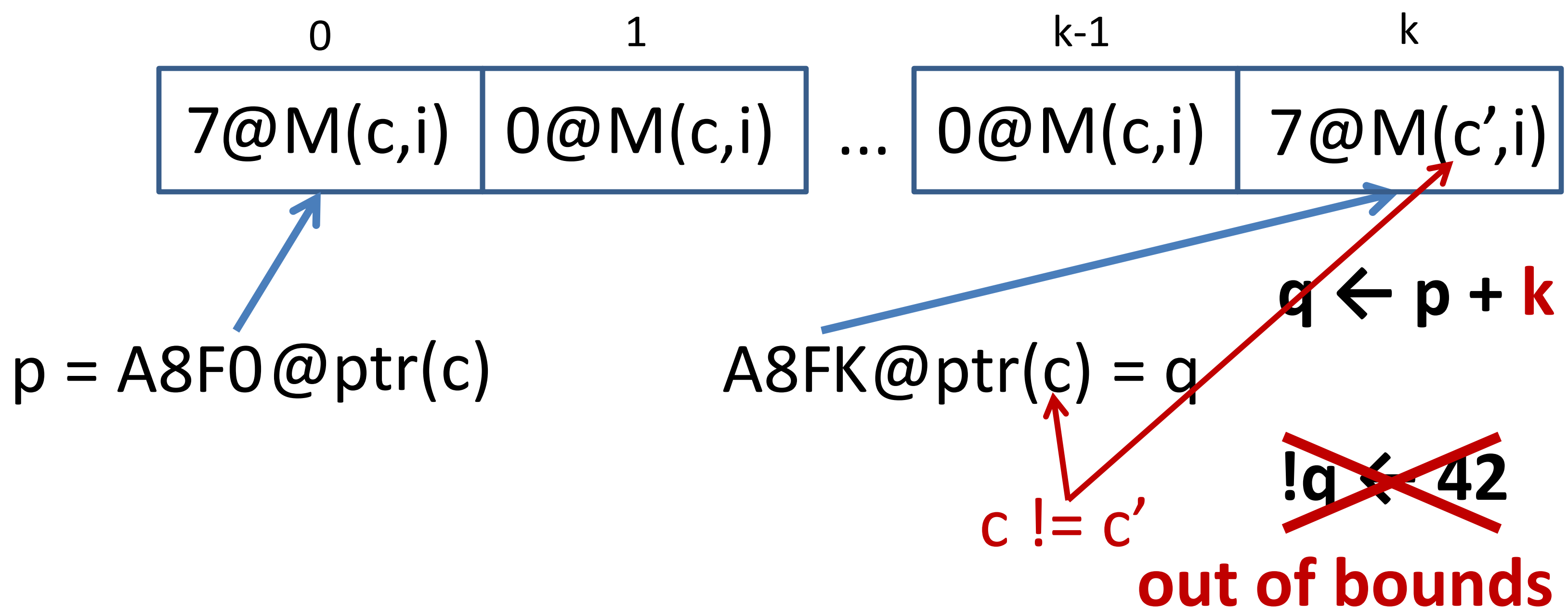


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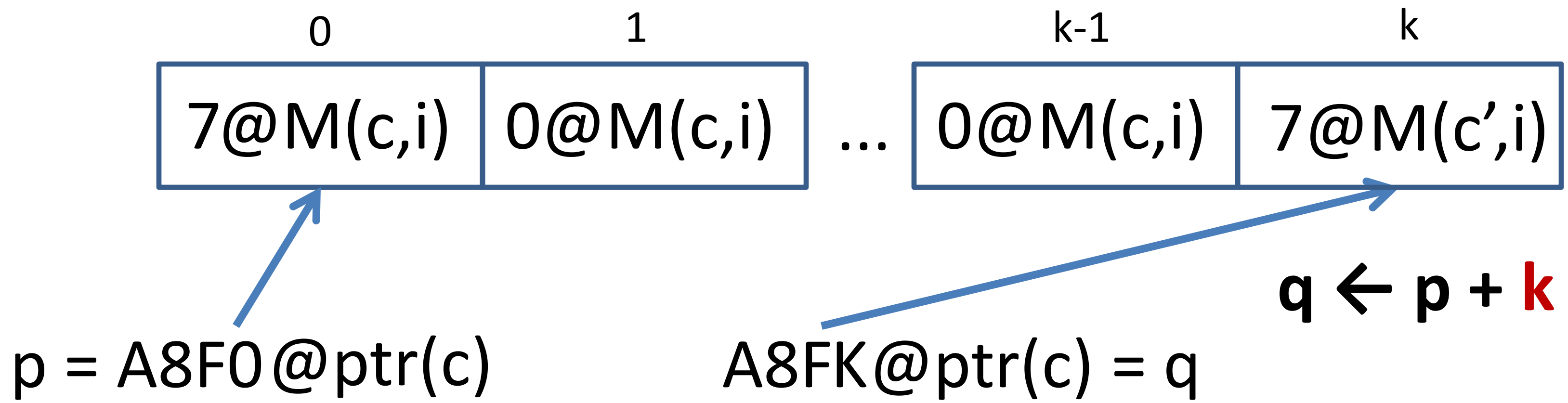


**q ← p + k**

**~~!q ← 42~~**

**out of bounds**

**free p**

| | | |
|---|---|---|
| $T_v$ | ::= i \| ptr(c) | tags on values |
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# Memory safety micro-policy

| 0 | 1 | | k-1 | k |
|---|---|---|---|---|
| 7@F | 0@F | … | 0@F | 7@M(c',i) |

p = A8F0@ptr(c)

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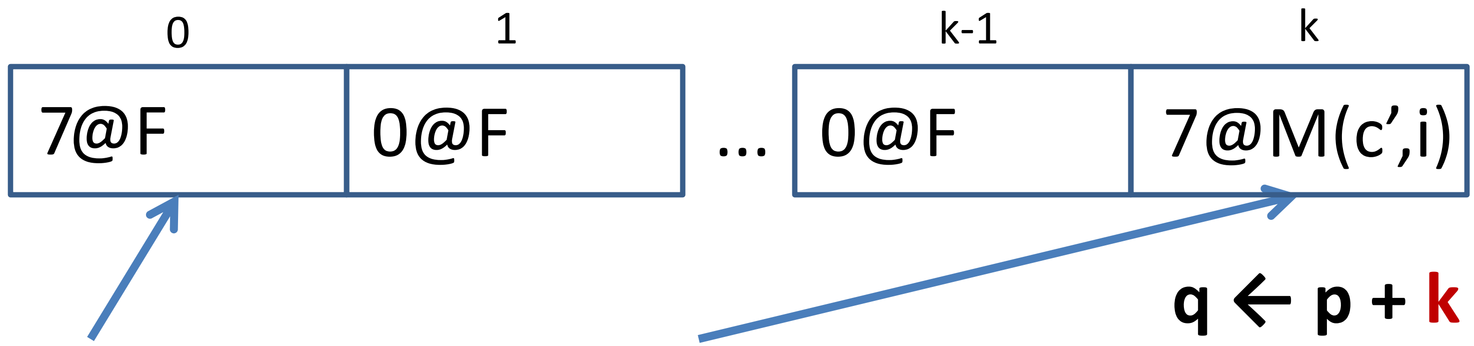


**q ← p + k**

p = A8F0@ptr(c)

A8FK@ptr(c) = q

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**out of bounds**

**free p**

**x ← !p**

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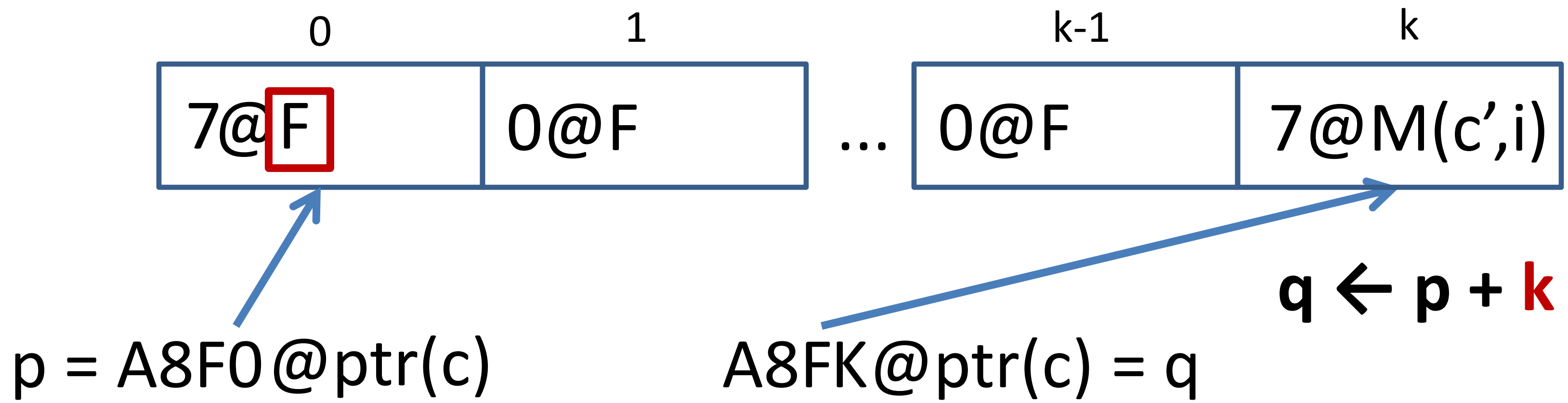


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**out of bounds**

**free p**

**x ← !p**

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# Memory safety micro-policy

| 0 | 1 | | k-1 | k |
|---|---|---|---|---|
| 7@$\boxed{\text{F}}$ | 0@F | … | 0@F | 7@M(c′,i) |

**q ← p + k**

p = A8F0@ptr(c)

A8FK@ptr(c) = q

~~**!q ← 42**~~

**out of bounds**

**free p**

~~**x ← !p**~~

**use after free**

| | | |
|---|---|---|
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# Memory safety micro-policy

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**1. Sets of tags**

$T_v$ ::= i | ptr(c)

$T_m$ ::= M(c,$T_v$) | F

$T_{pc}$ ::= $T_v$

# Memory safety micro-policy

**1. Sets of tags**

$T_v$ ::= i | ptr(c)

$T_m$ ::= M(c,$T_v$) | F

$T_{pc}$ ::= $T_v$

**2. Transfer function**

Record IVec := { op:opcode ; $t_{pc}$:$T_{pc}$ ; $t_i$:$T_m$ ; ts: ... }

Record OVec (op:opcode) := { $t_{rpc}$ : $T_{pc}$ ; $t_r$ : ... }

transfer : (iv:IVec) -> option (OVec (op iv))

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transfer : (iv:IVec) -> option (OVec (op iv))

Definition transfer iv :=

match iv with

| {op=Load; $t_{pc}$=ptr($c_{pc}$); $t_i$=M($c_{pc}$,i); ts=[ptr(c); M(c,$T_v$)]}

=> $_{\{t}$rpc=pt$_{r(}$cpc)$_{;}$ $t_r$=Tv}

# Memory safety micro-policy

**1. Sets of tags**

$T_v$ ::= i | ptr(c)

$T_m$ ::= $M(c,T_v)$ | F

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Record IVec := { op:opcode ; $t_{pc}$:$T_{pc}$ ; $t_i$:$T_m$ ; ts: ... }

Record OVec (op:opcode) := { $t_{rpc}$ : $T_{pc}$ ; $t_r$ : ... }

transfer : (iv:IVec) -> option (OVec (op iv))

Definition transfer iv :=

match iv with

| {op=Load; $t_{pc}$=ptr($c_{pc}$); $t_i$=M($c_{pc}$,i); ts=[ptr(c); M(c,$T_v$)]}

=> $\{t_{rpc}=ptr(c_{pc}); t_r=Tv\}$

| {op=Store; $t_{pc}$=ptr($c_{pc}$); $t_i$=M($c_{pc}$,i); ts=[ptr(c); $T_v$; M(c,$T_v$')]}

=> {$t_{rpc}$=ptr($c_{pc}$); $t_r$=M(c,$T_v$)}

...

# Memory safety micro-policy

**1. Sets of tags**

$T_v$ ::= i | ptr(c)

$T_m$ ::= M(c,$T_v$) | F

$T_{pc}$ ::= $T_v$

**2. Transfer function**

Record IVec := { op:opcode ; $t_{pc}$:$T_{pc}$ ; $t_i$:$T_m$ ; ts: ... }

Record OVec (op:opcode) := { $t_{rpc}$ : $T_{pc}$ ; $t_r$ : ... }

transfer : (iv:IVec) -> option (OVec (op iv))

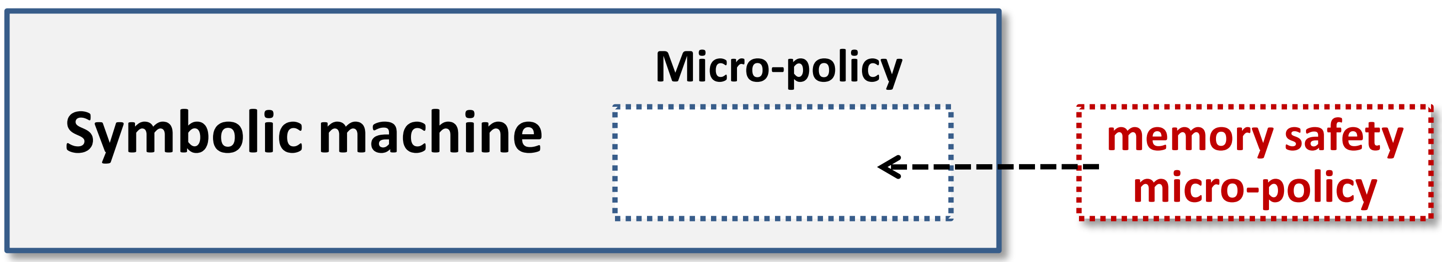
**3. Monitor services**

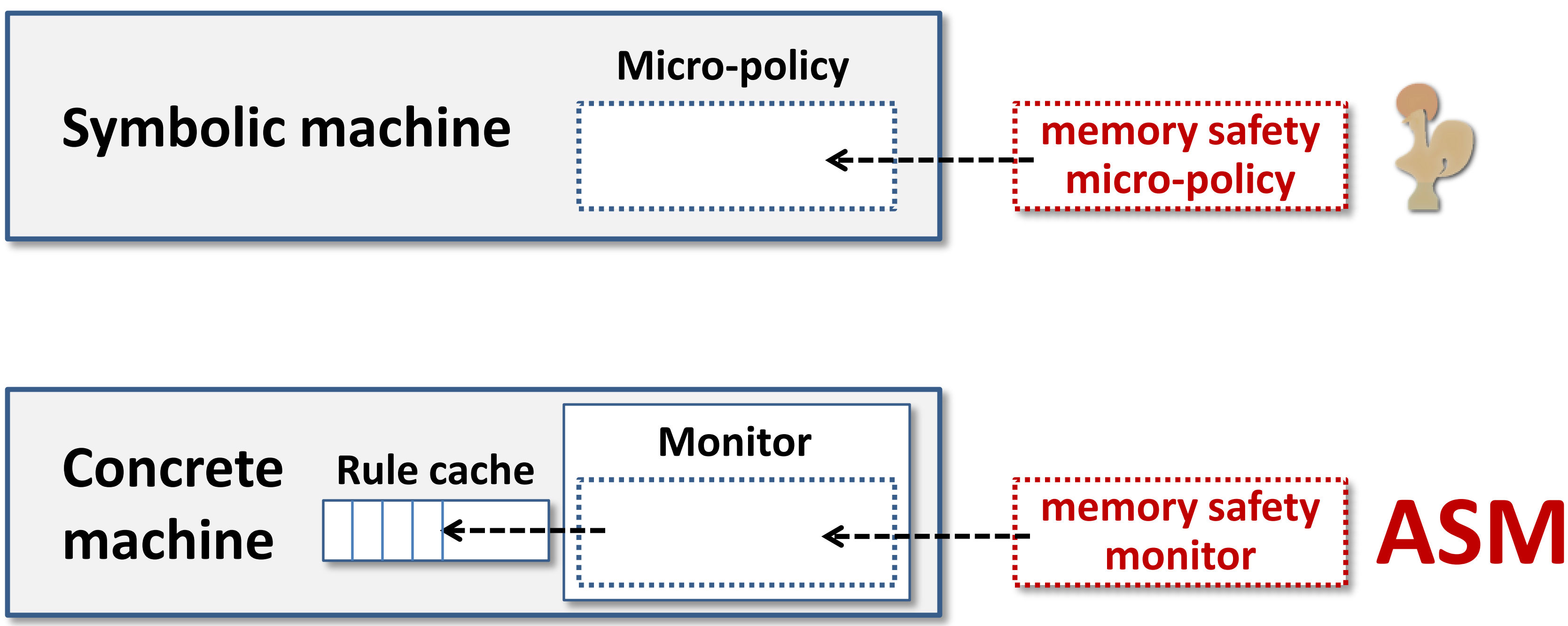
Record service := { addr : word; sem : state -> option state; ... }

Definition mem_safety_services : list service :=

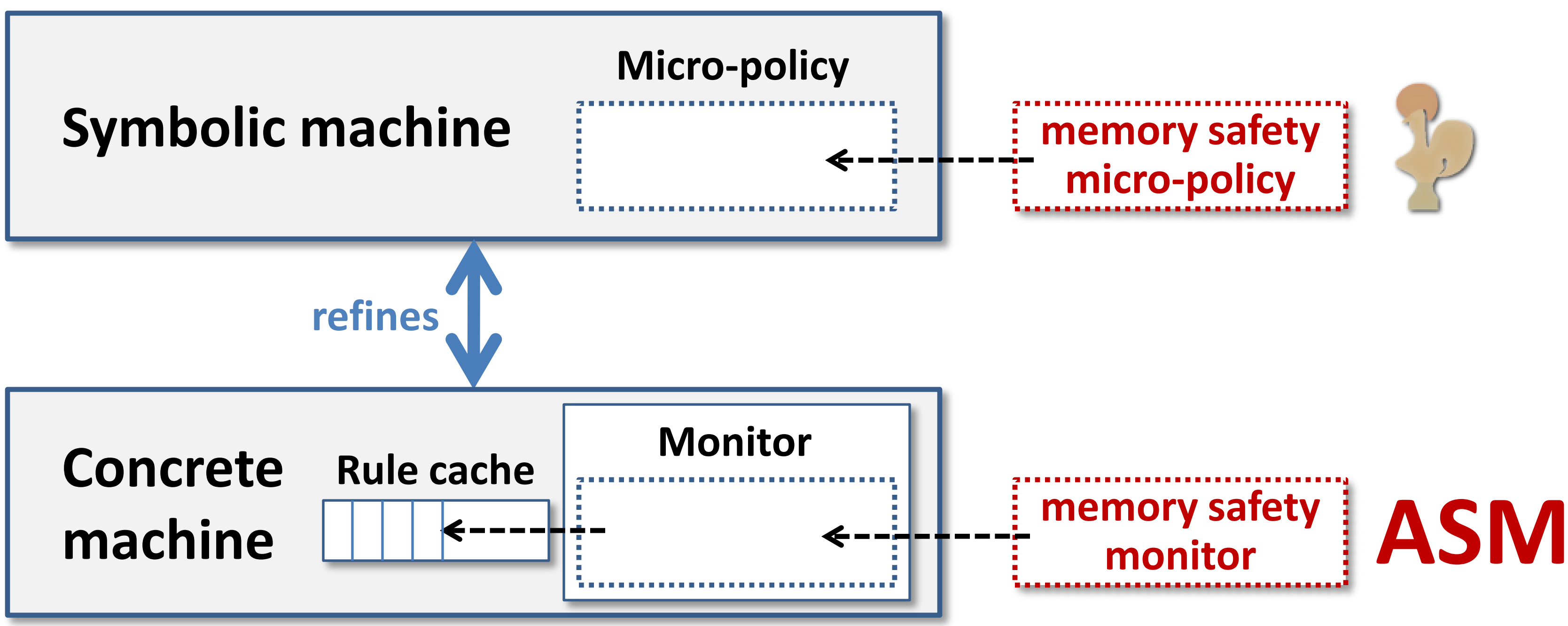
[malloc; free; size; base; eq].

**memory safety micro-policy**


Symbolic machine
Micro-policy
memory safety
micro-policy


Symbolic machine
Micro-policy
memory safety
micro-policy
Concrete
machine
Rule cache
Monitor
memory safety
monitor
ASM

# Verification



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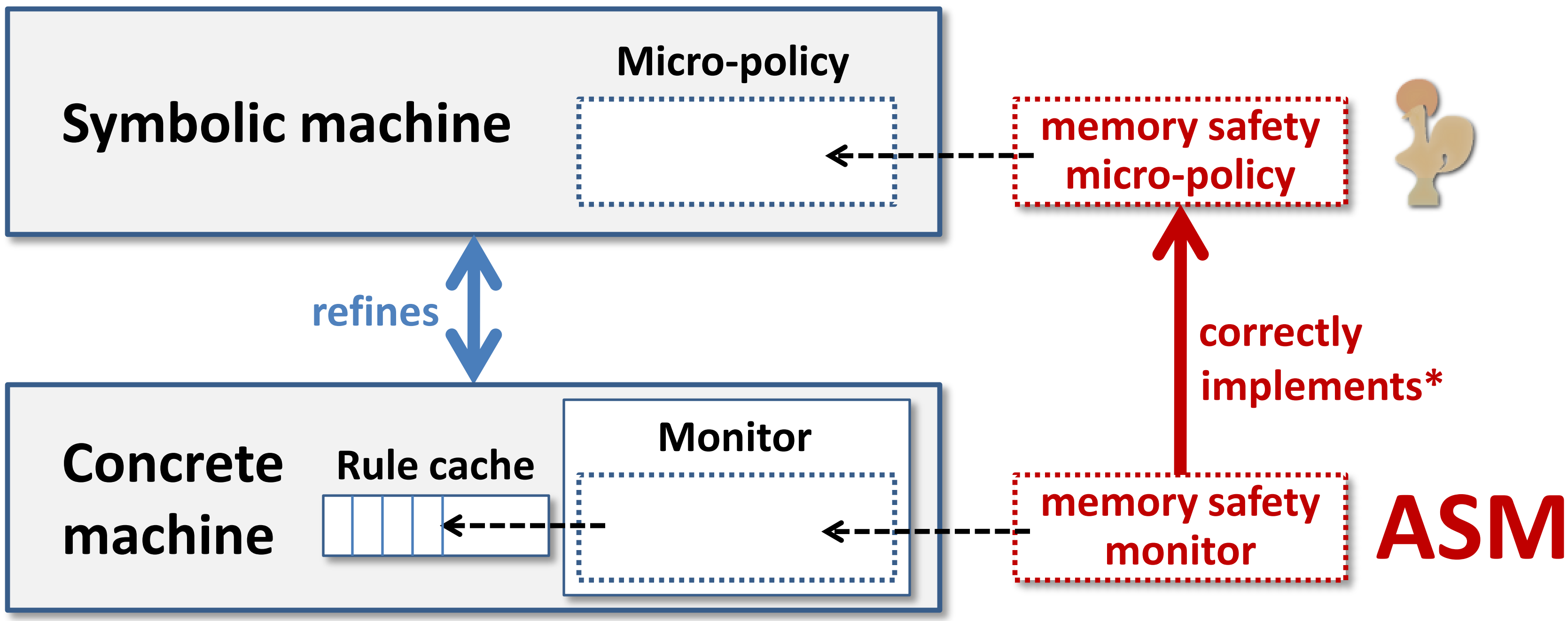


*only proved for IFC [POPL 2014]

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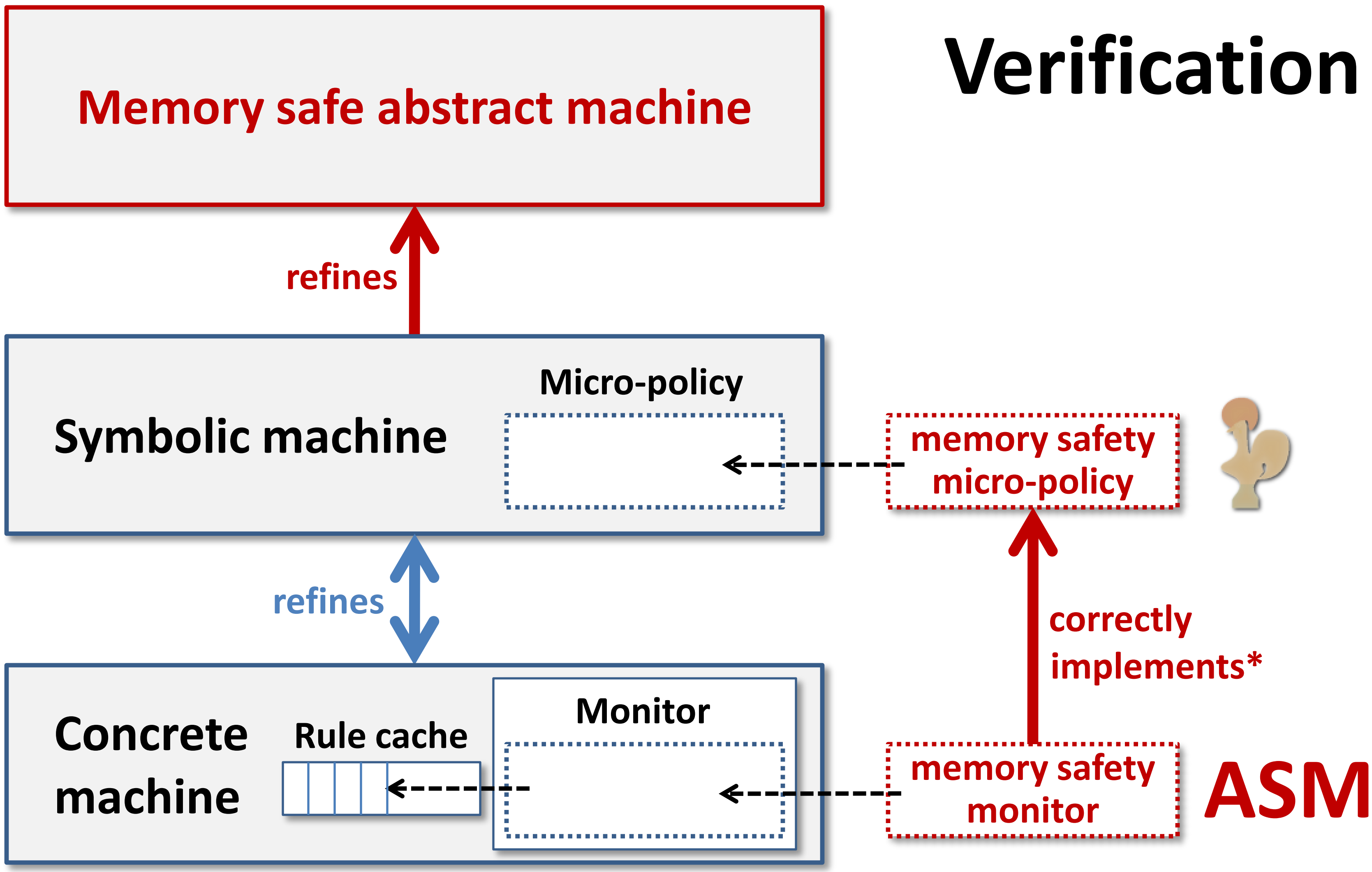


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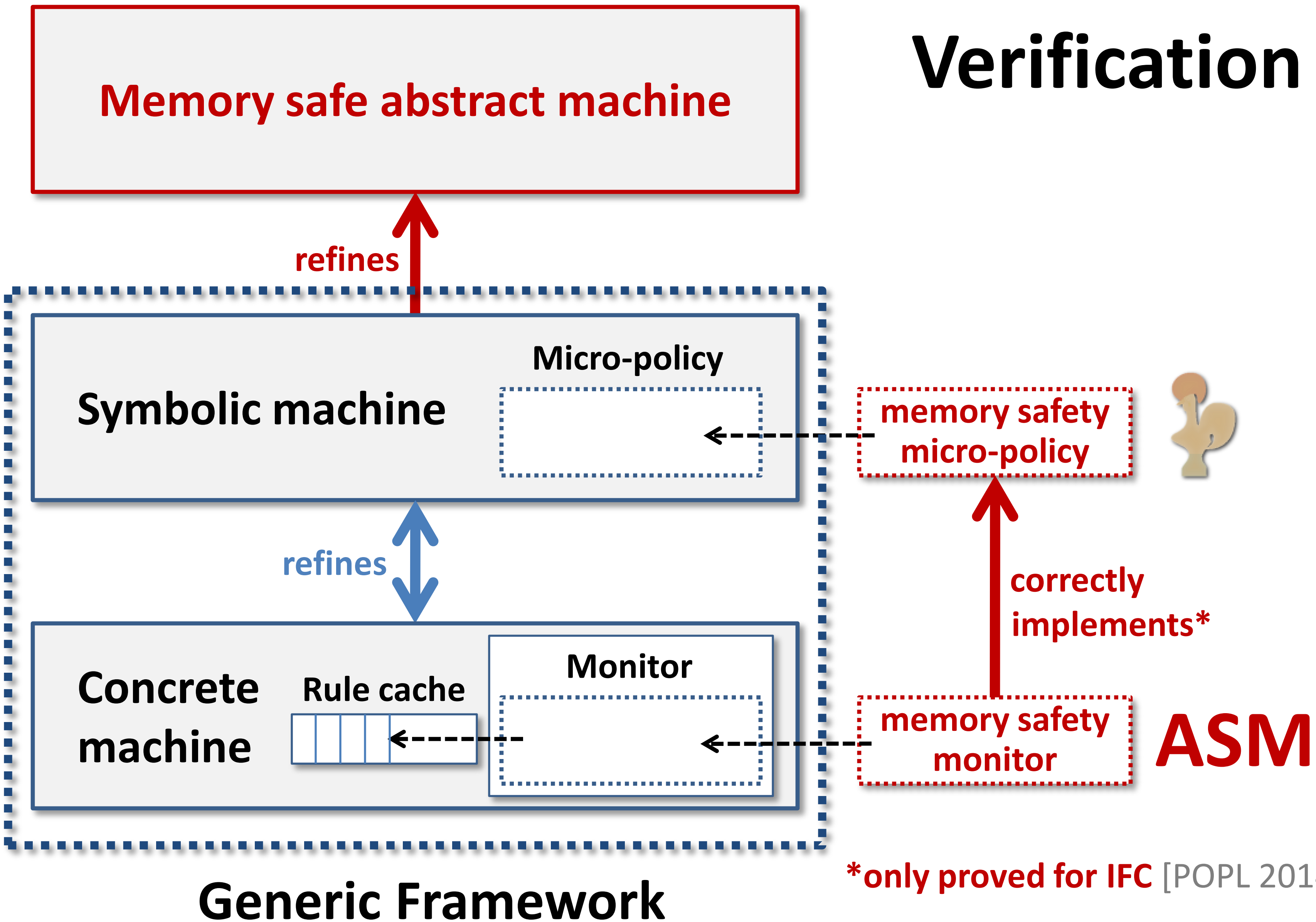


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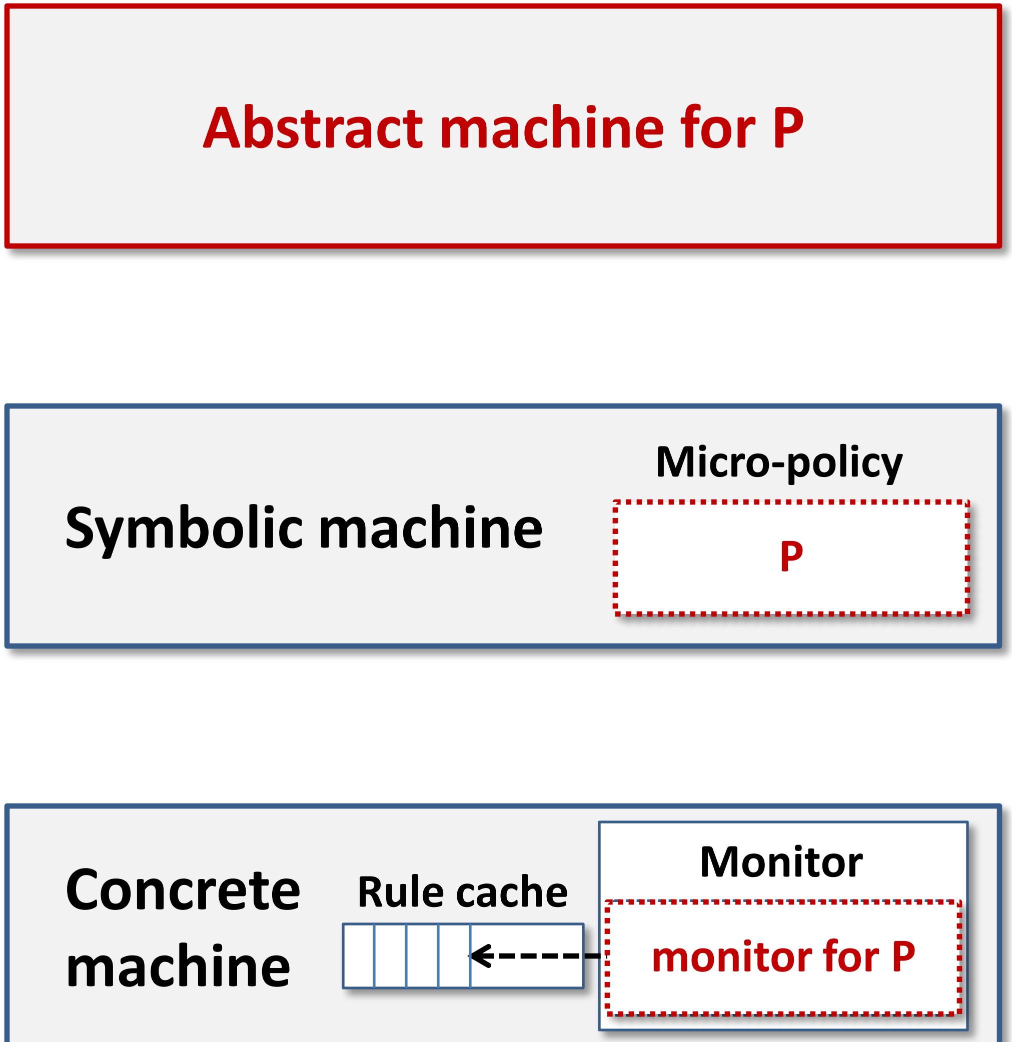
$\mathsf{P} \in \{IFC, CFI\}$



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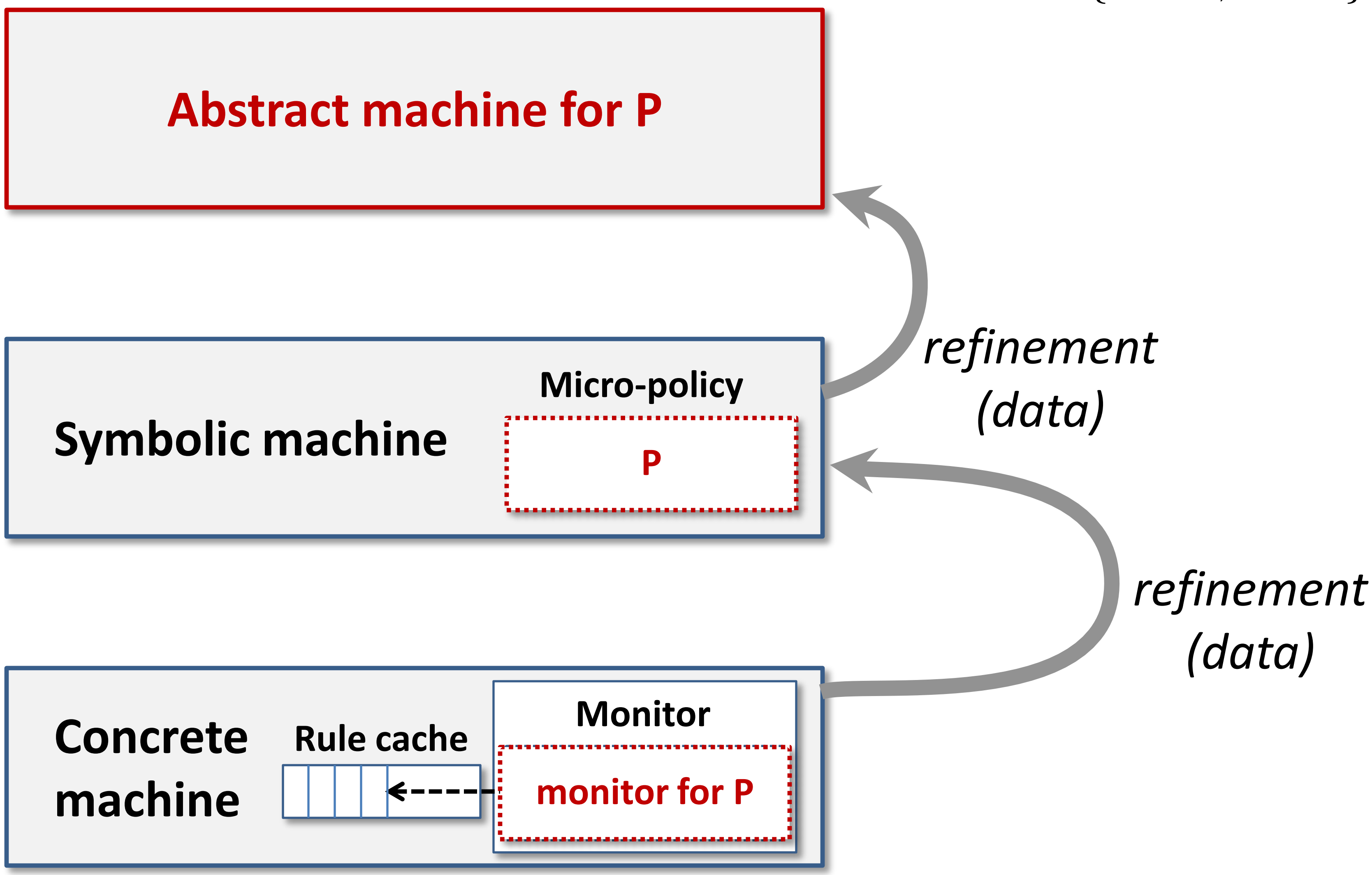

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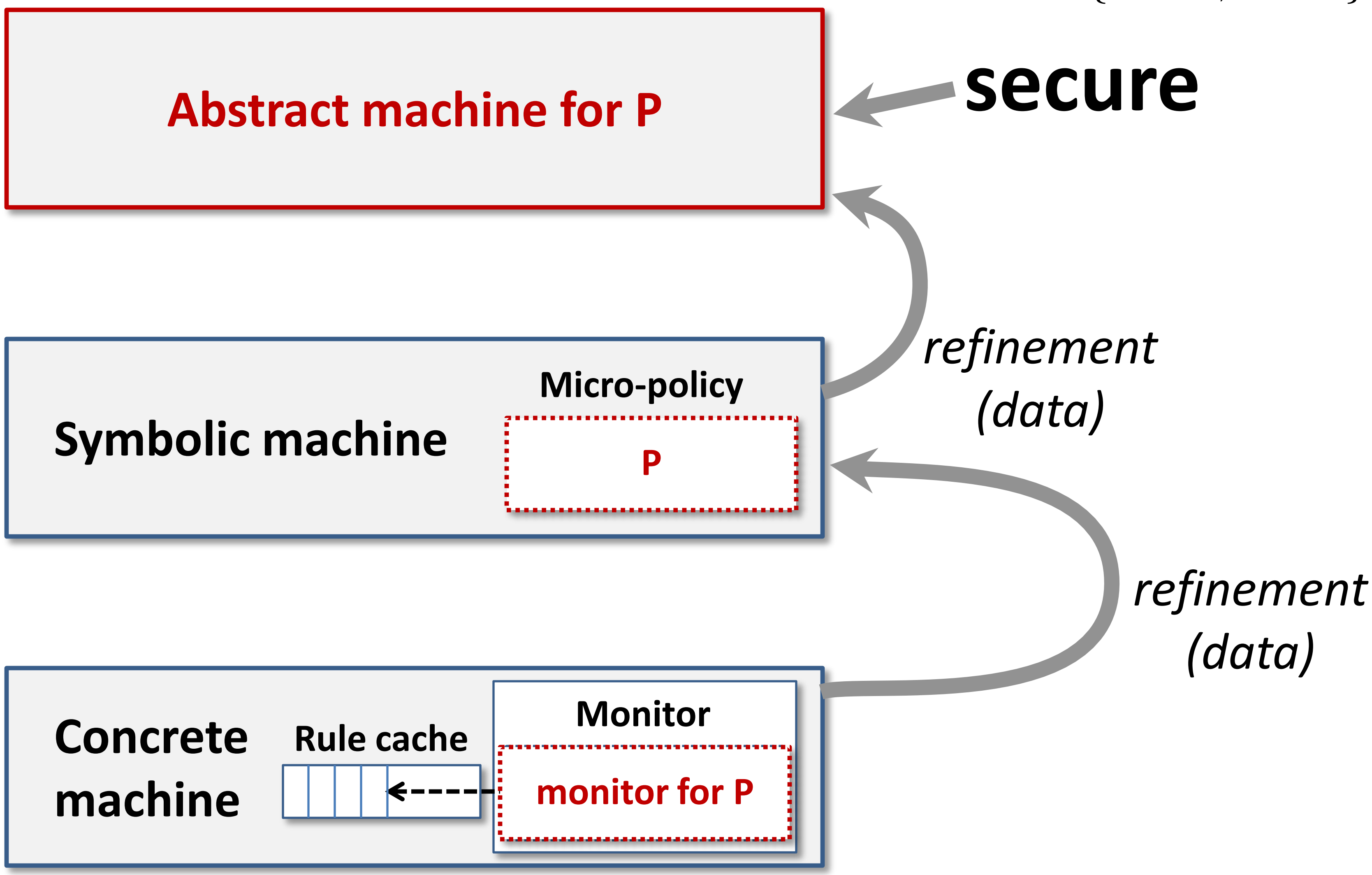
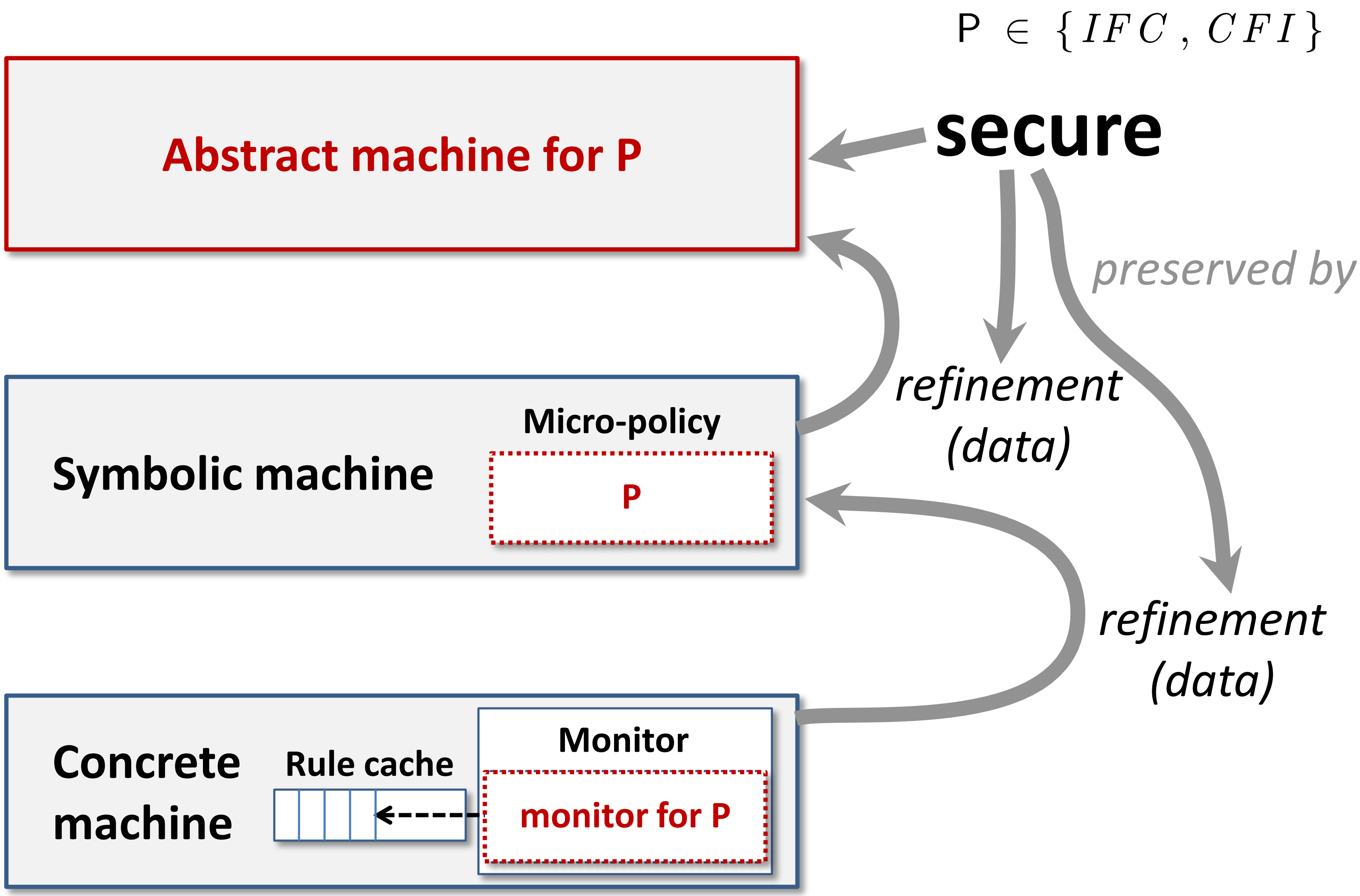
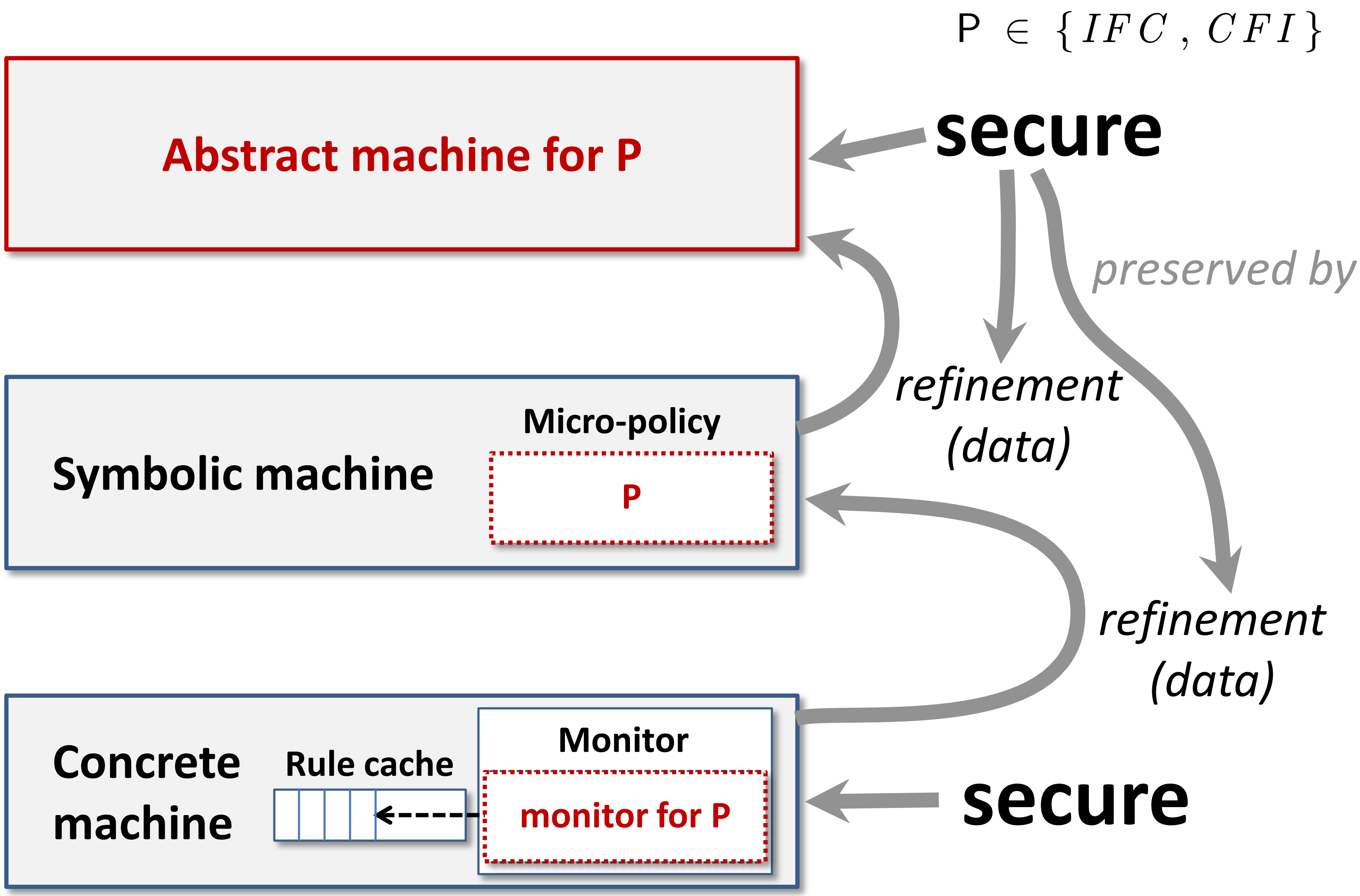




$P \in \{IFC, CFI\}$
secure
preserved by
Abstract machine for P
refinement
(data)
Symbolic machine
Micro-policy
P
refinement
(data)
Concrete machine
Rule cache
Monitor
monitor for P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Abstract machine for P
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machine
Rule cache
Monitor
monitor for P
secure

# Future verification challenges

1. Proofs for **real RISC architecture** (e.g. ARM)
2. Verify all monitors down to **machine-code level**
3. Formally study micro-policy **composition**
4. Devise **generic meta-language** for micro-policies
5. Study **more micro-policies** (e.g. stack protection, ...)
6. Formally study **expressive power** of micro-policies
7. Interaction with **loader** and **compiler** (static + dynamic)
8. ... and **operating system** (e.g. protect the OS itself)