ILLINOIS INSTITUTE OF TECHNOLOGY 1890

Carnegie Mellon University Computer Science Department

Carnegie Mellon University CyLab Security and Privacy Institute

Towards End-to-End Verified TEEs via Verified Interface Conformance and Certified Compilers

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Joint work with Zichao Zhang, Amit Vasudevan, and Limin Jia

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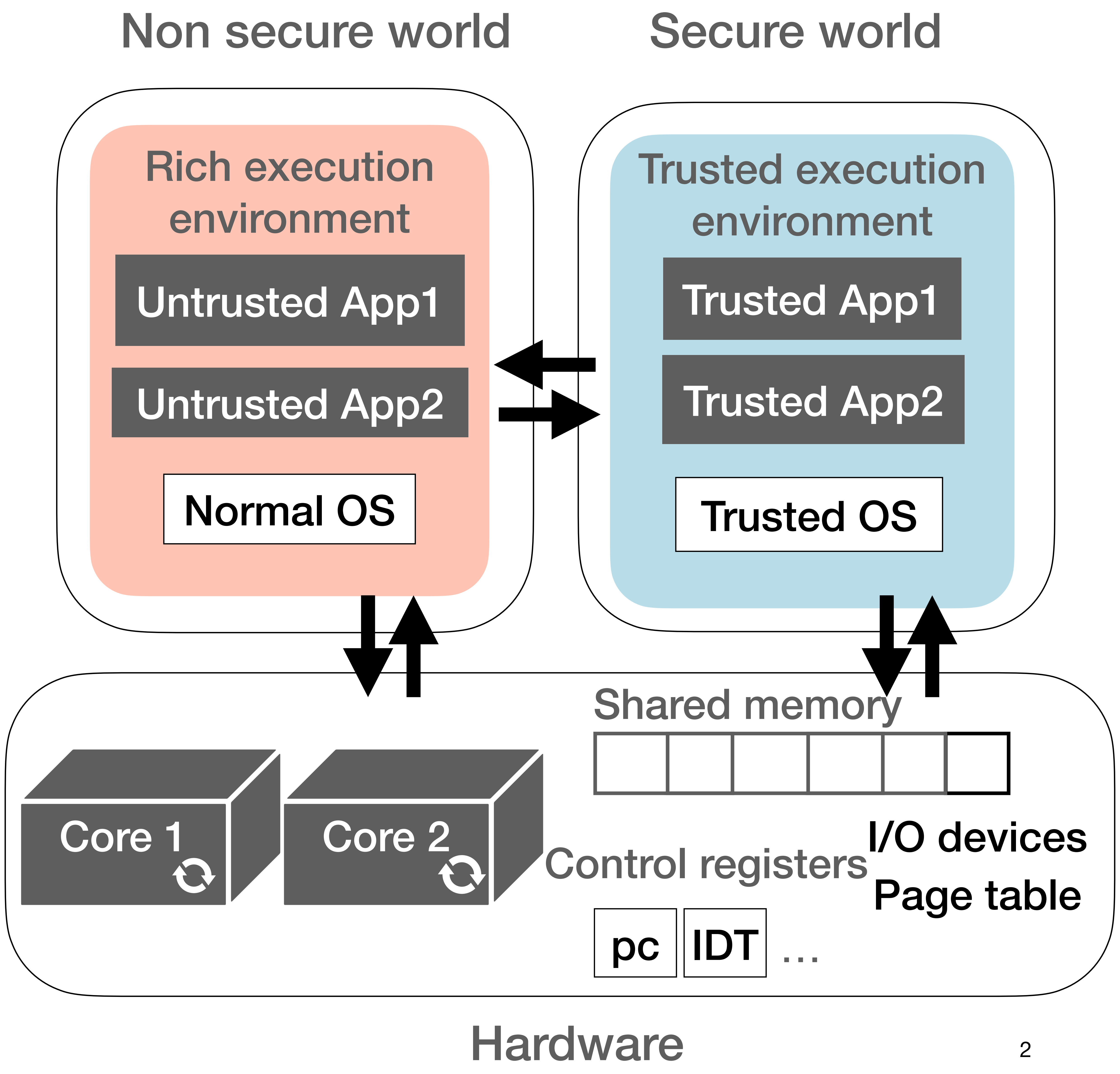
Trusted Execution Environments (TEE)



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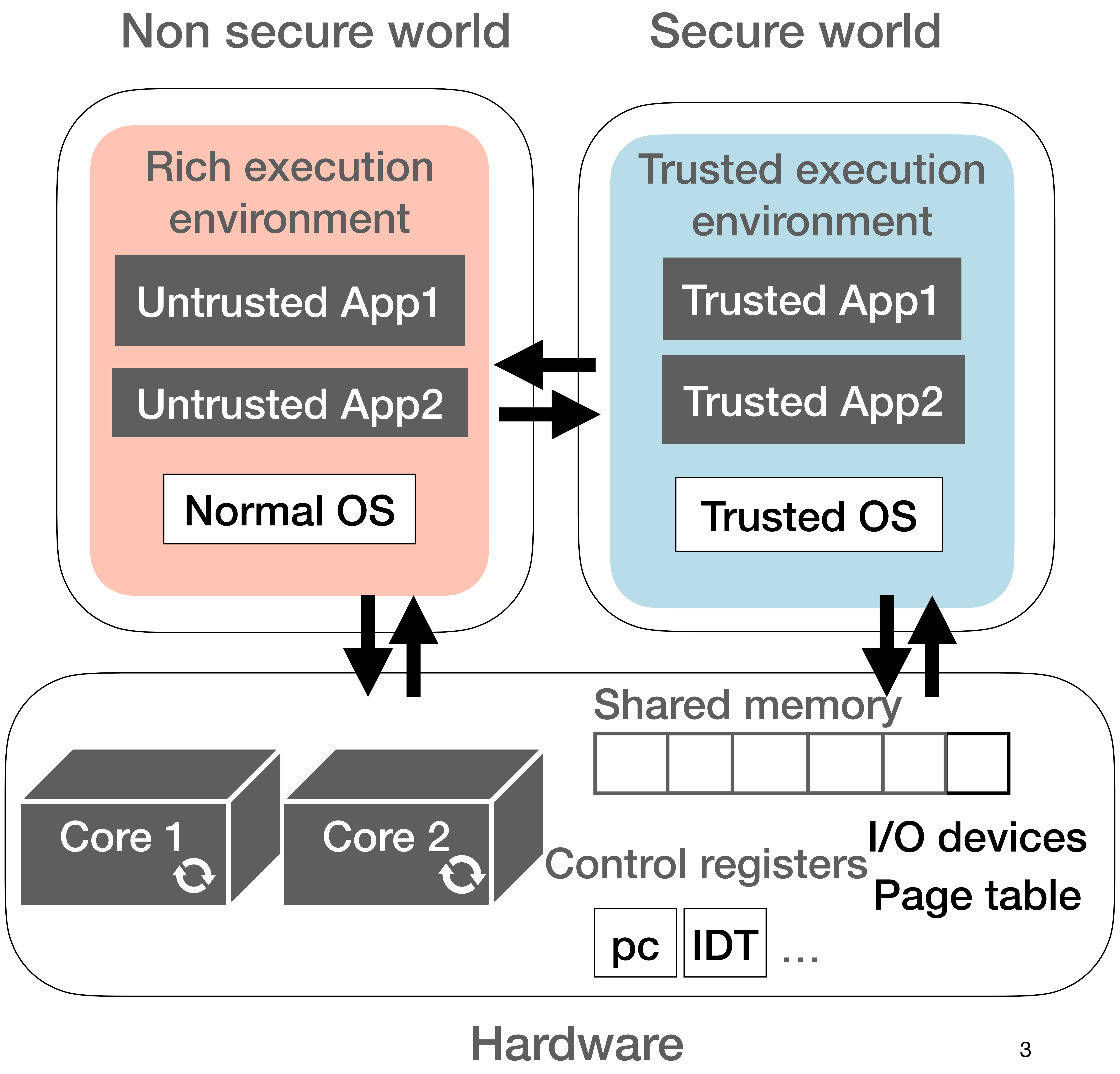

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- Run multiple mutually distrusting programs simultaneously on shared hardware.

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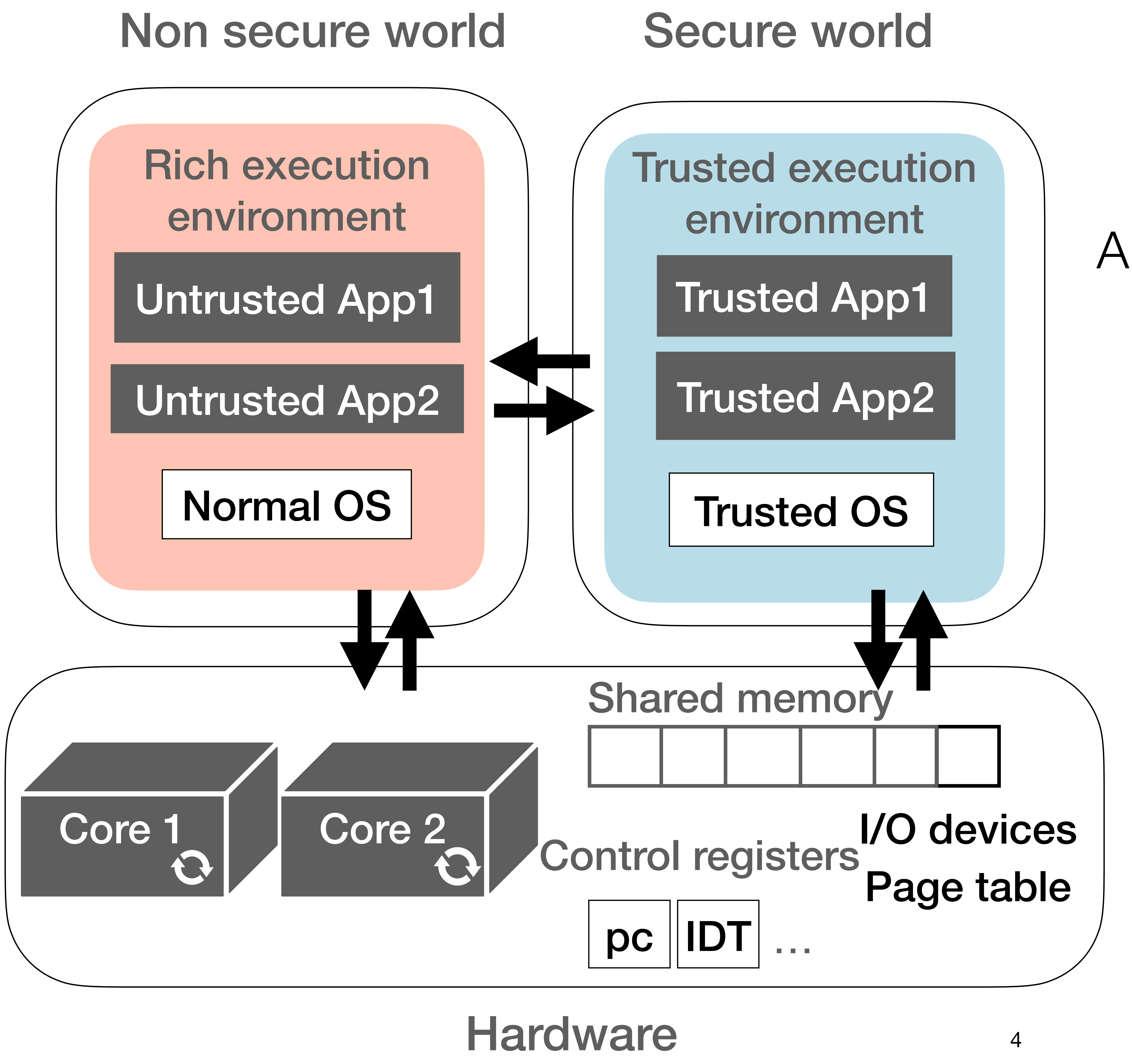

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- Secure banking

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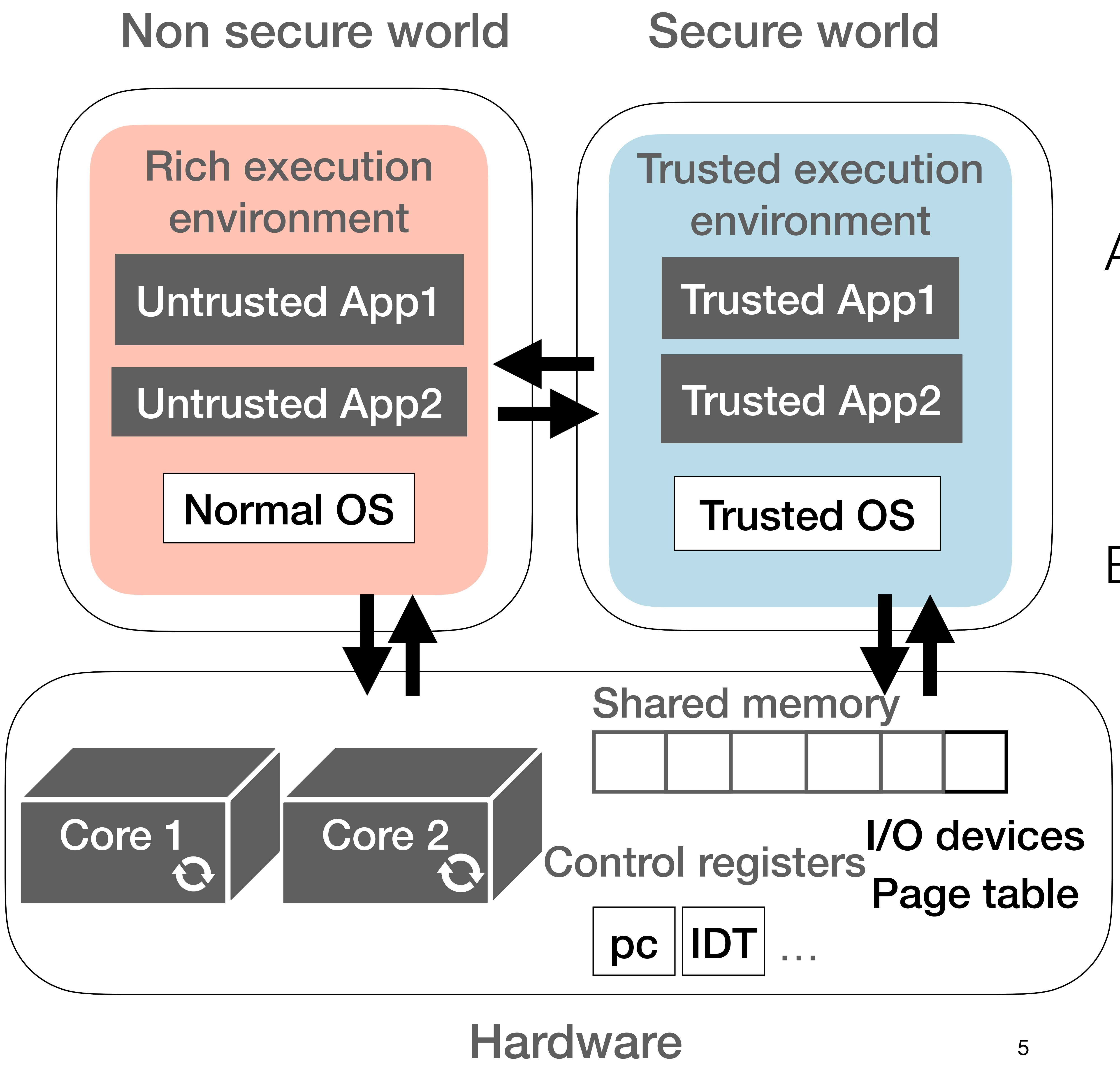

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Example Trusted OS

- Hypervisors
- Trusty for Android
- OP-TEE for Arm

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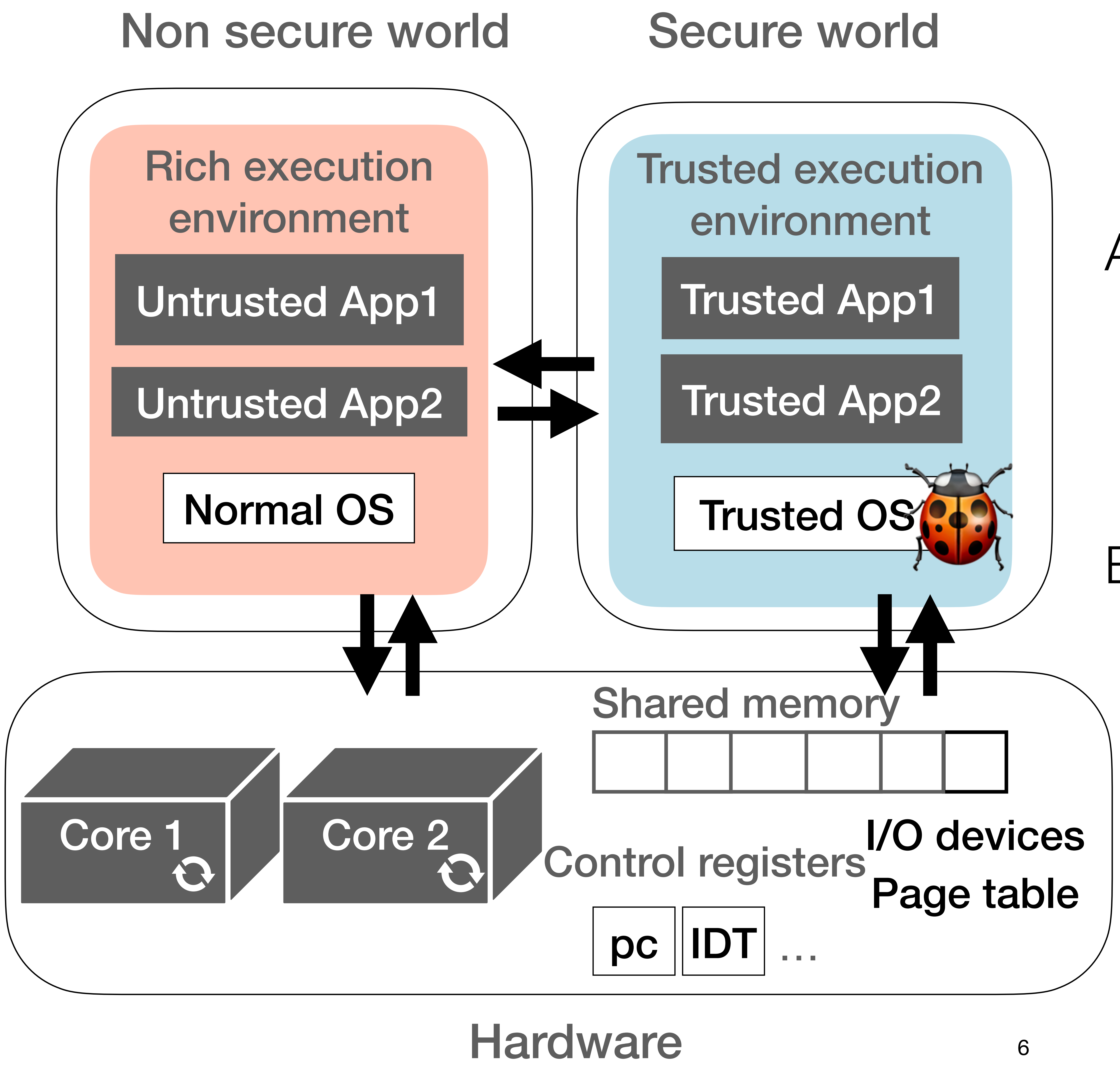

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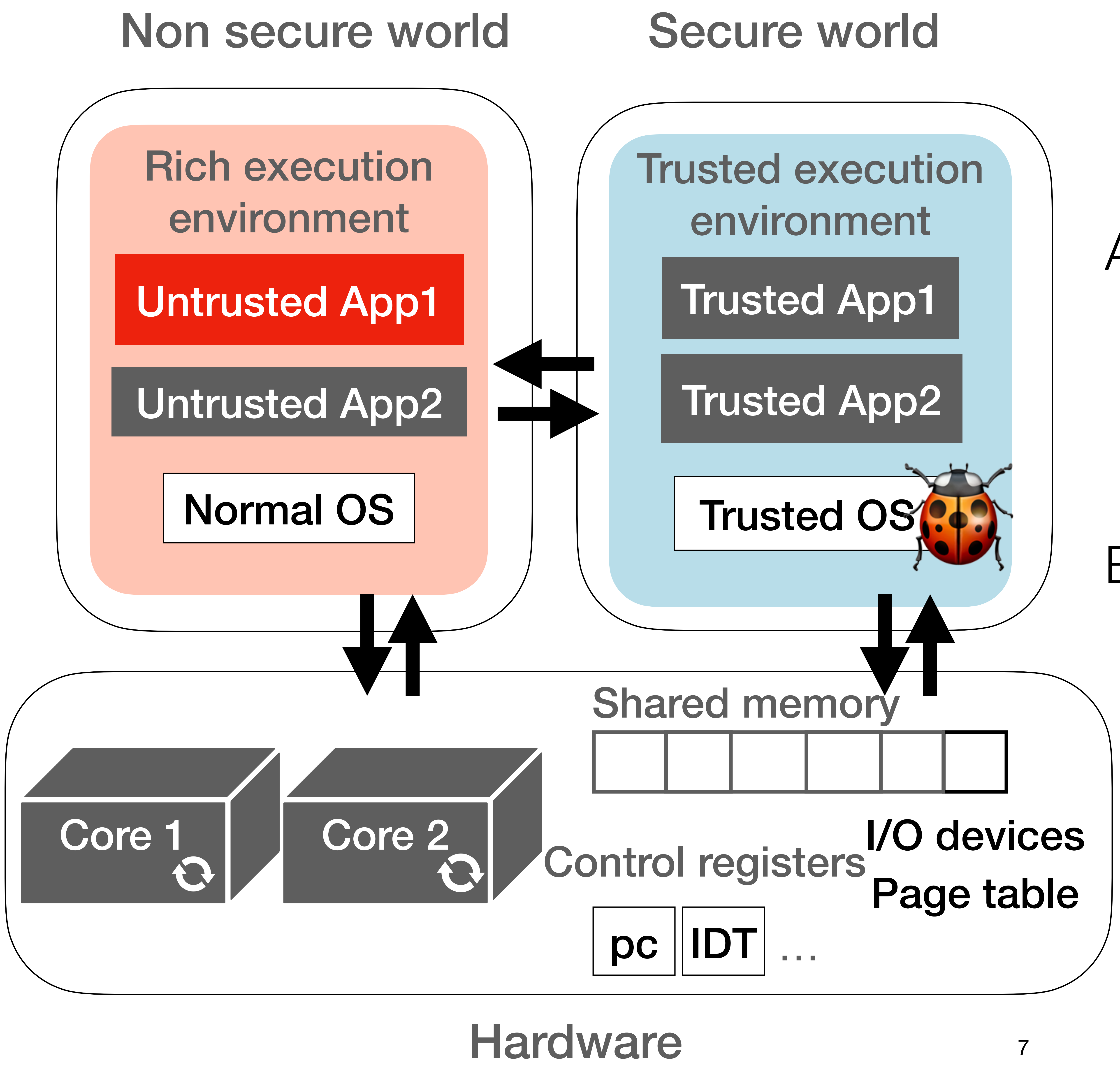

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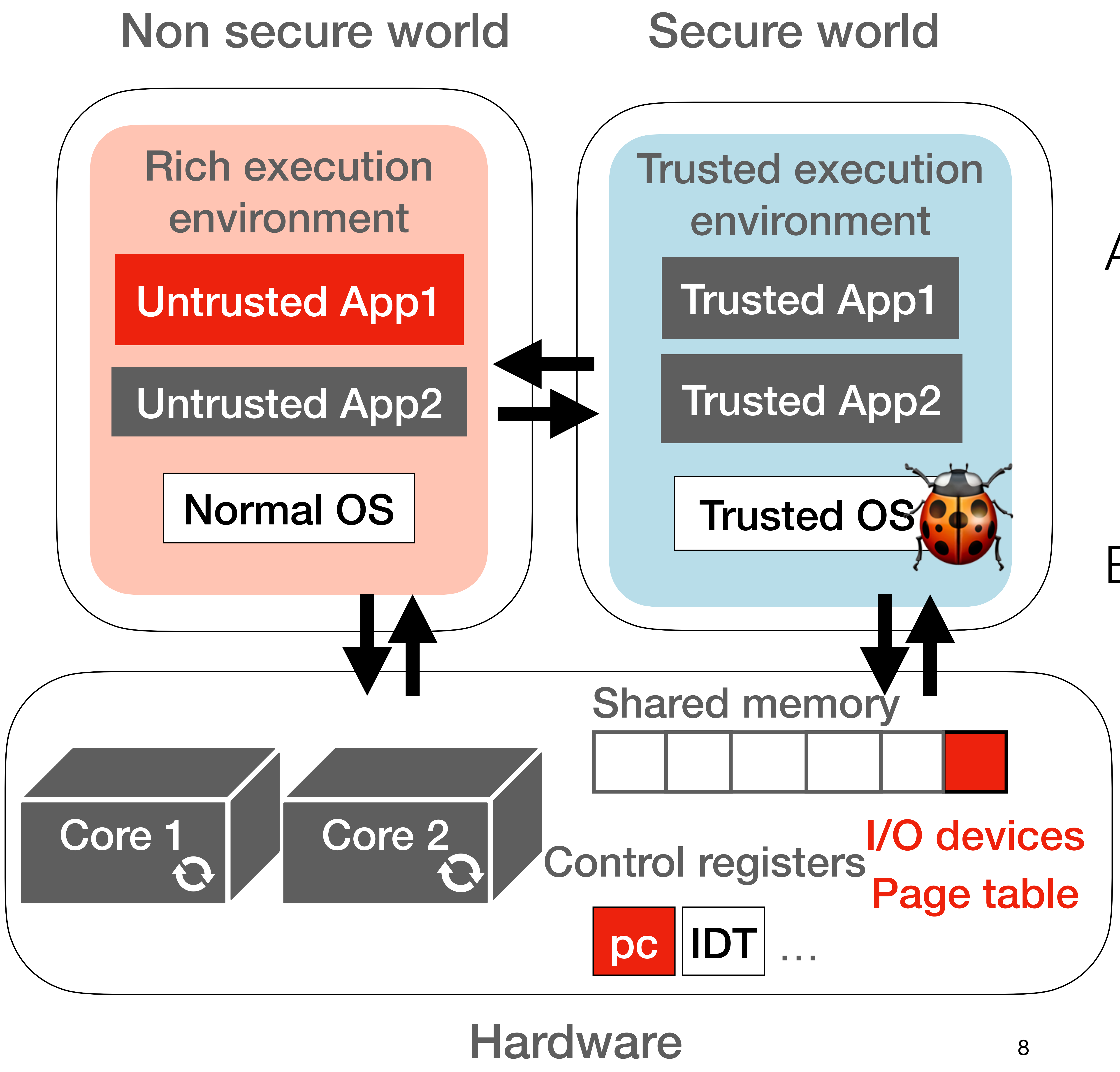

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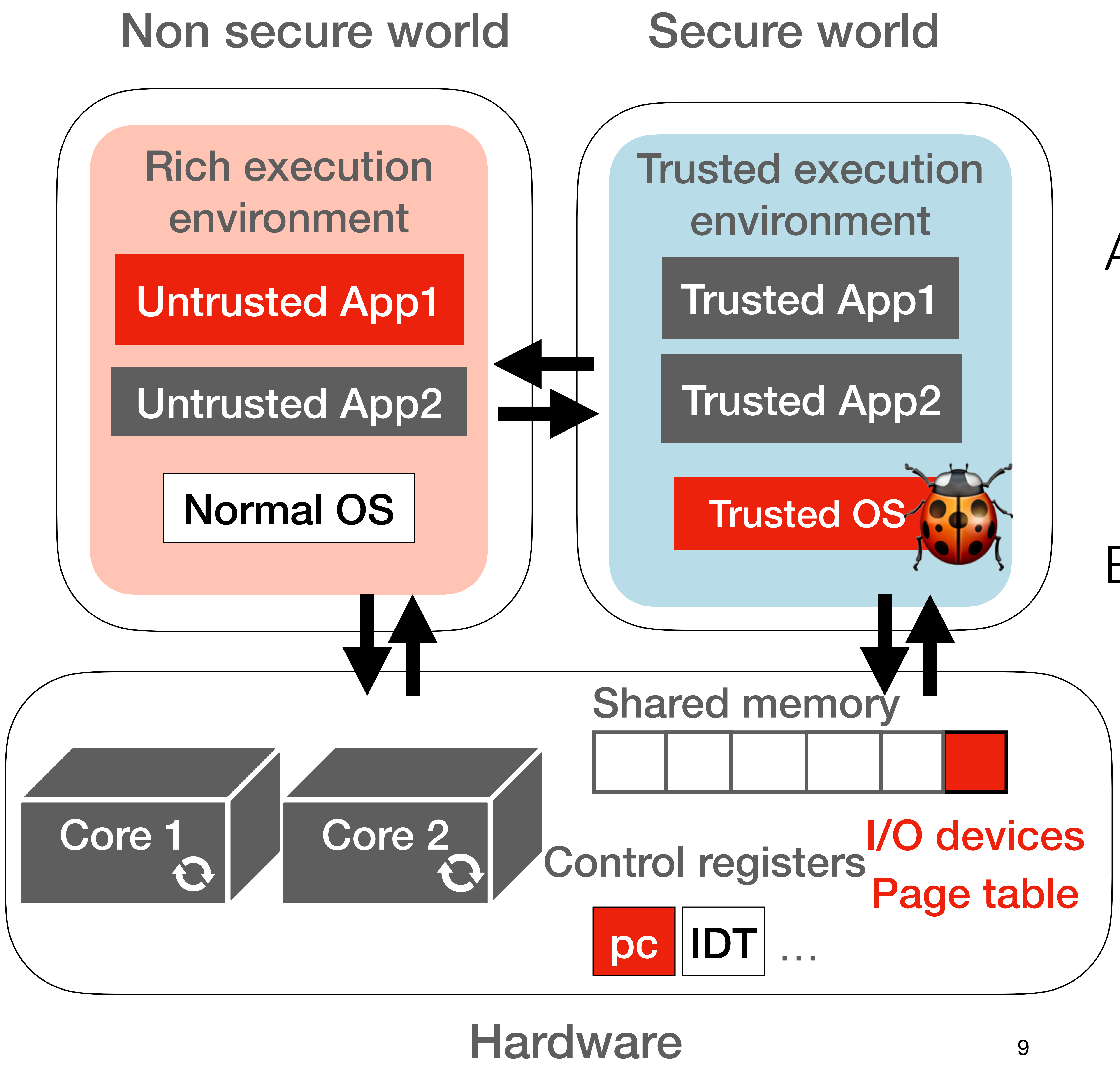

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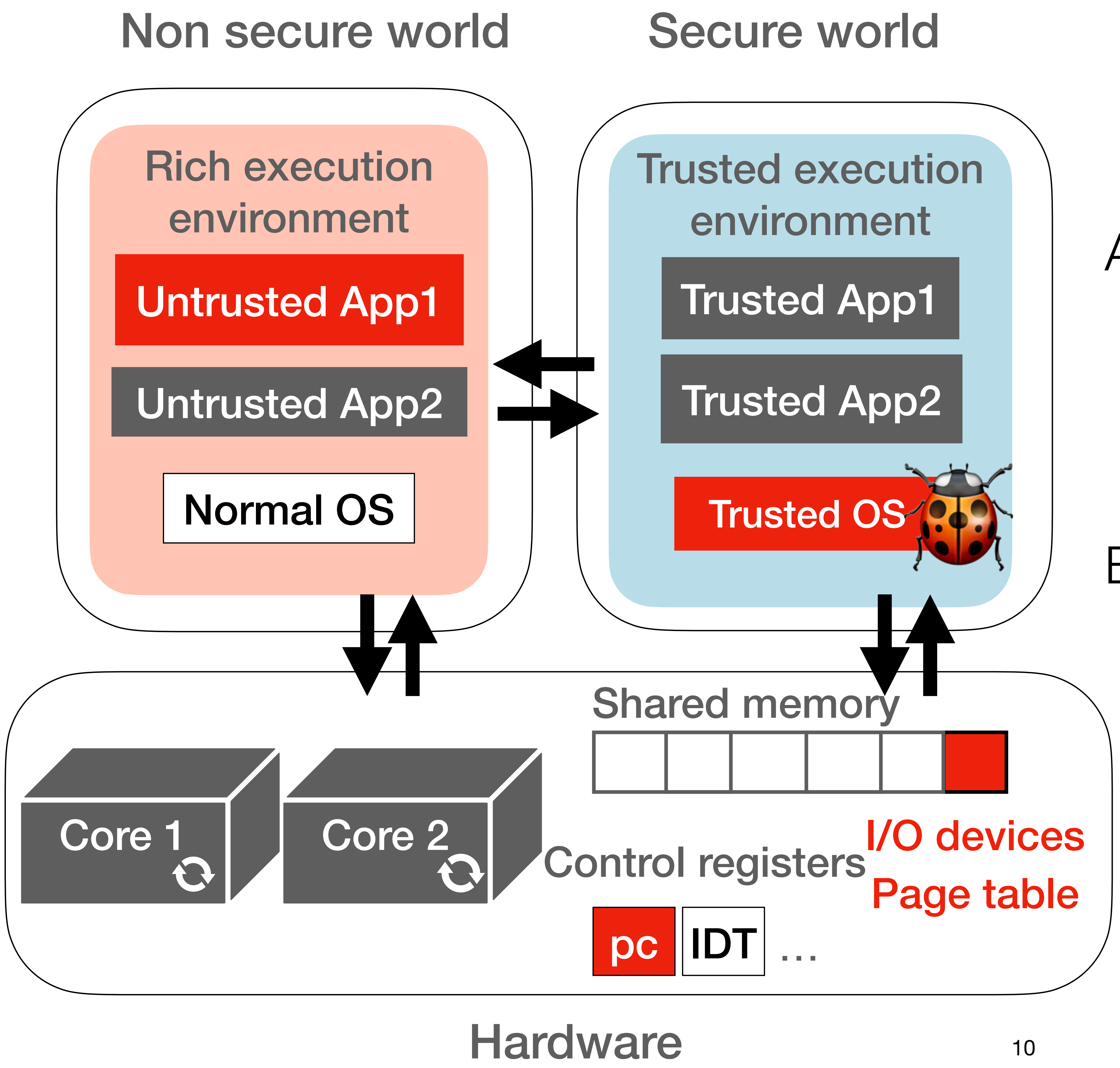

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Subversion of a TEE means the attacker takes full-control over the entire platform!

TEE formal verification removes many of the vulnerabilities

➡ Full functional correctness

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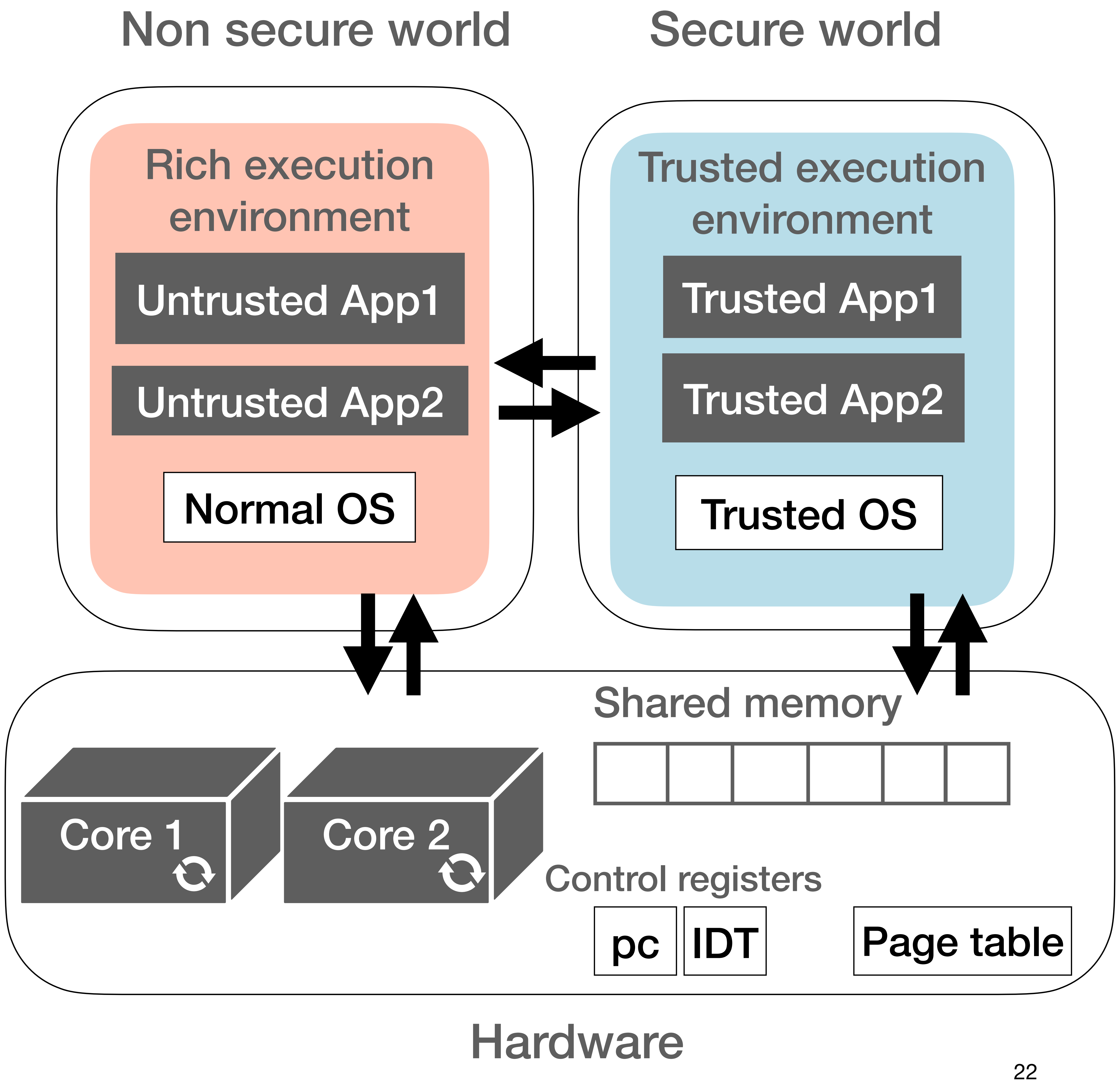
Prior approaches lack guarantees on the compiled code

Our approach - Compartmentalization and certified compilers to aid verification:

- Compartments as units for verification and compilation.
- Allows us to bring the security properties down to the compiled code.

Compartments schema



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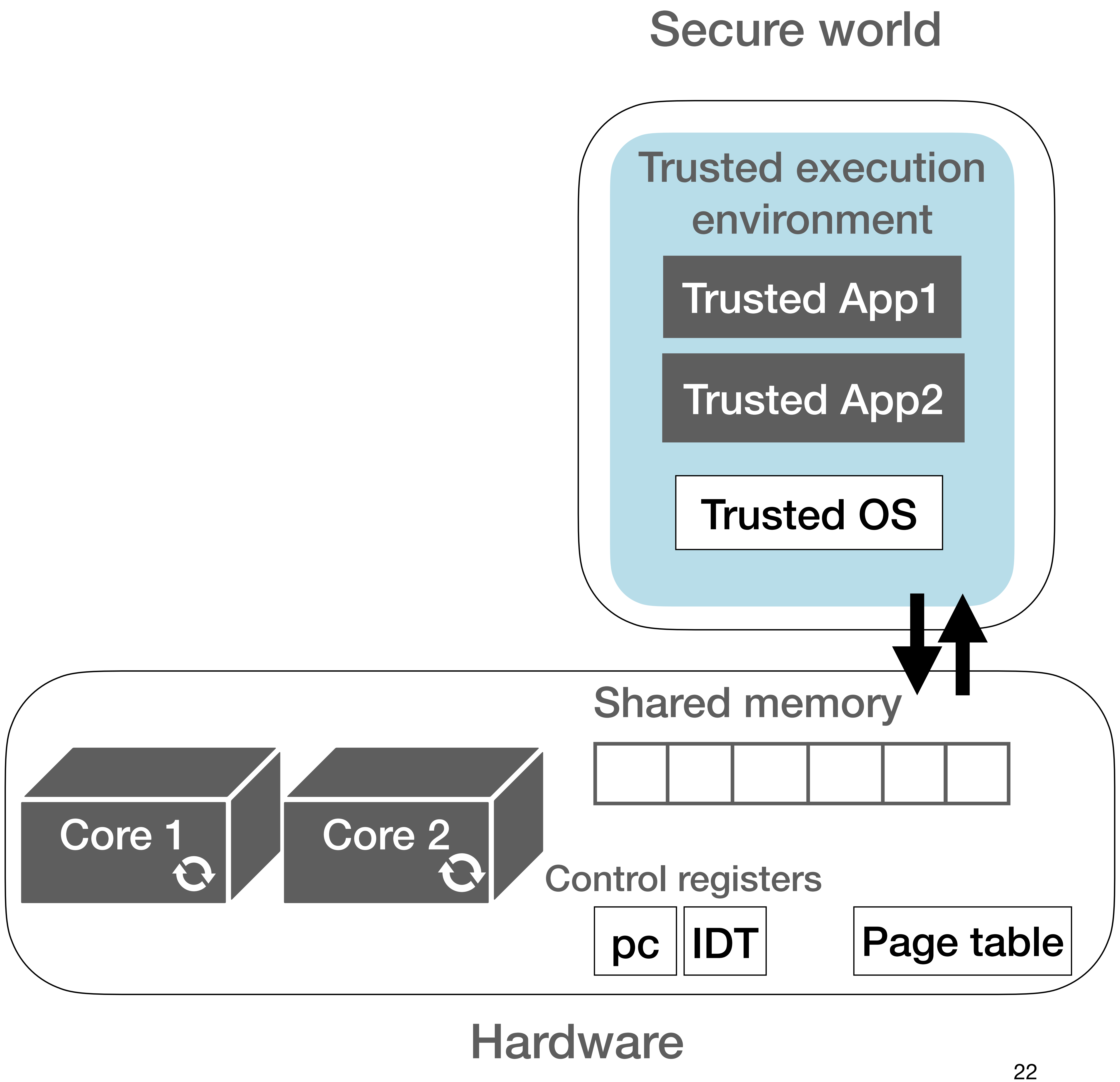

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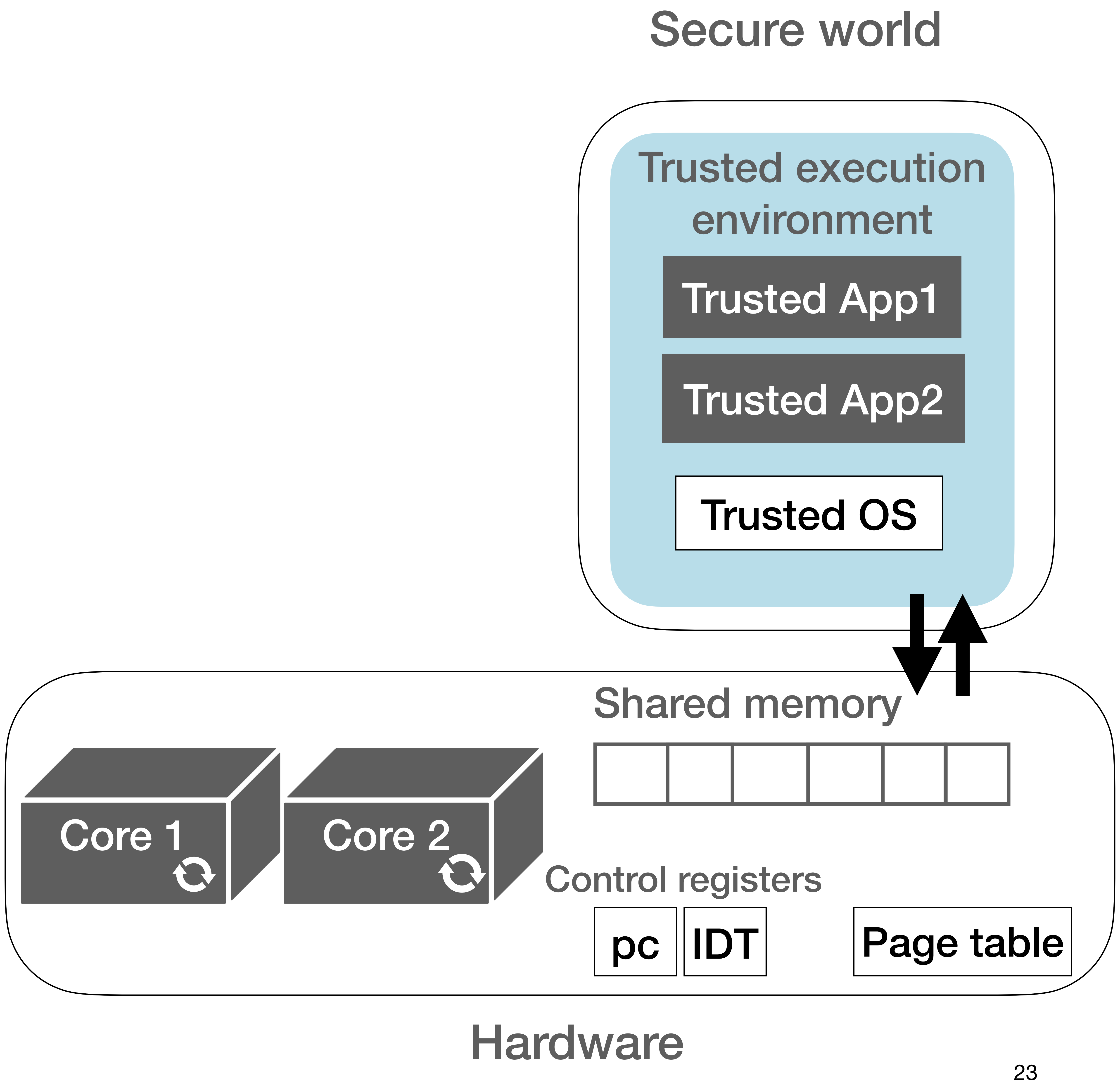

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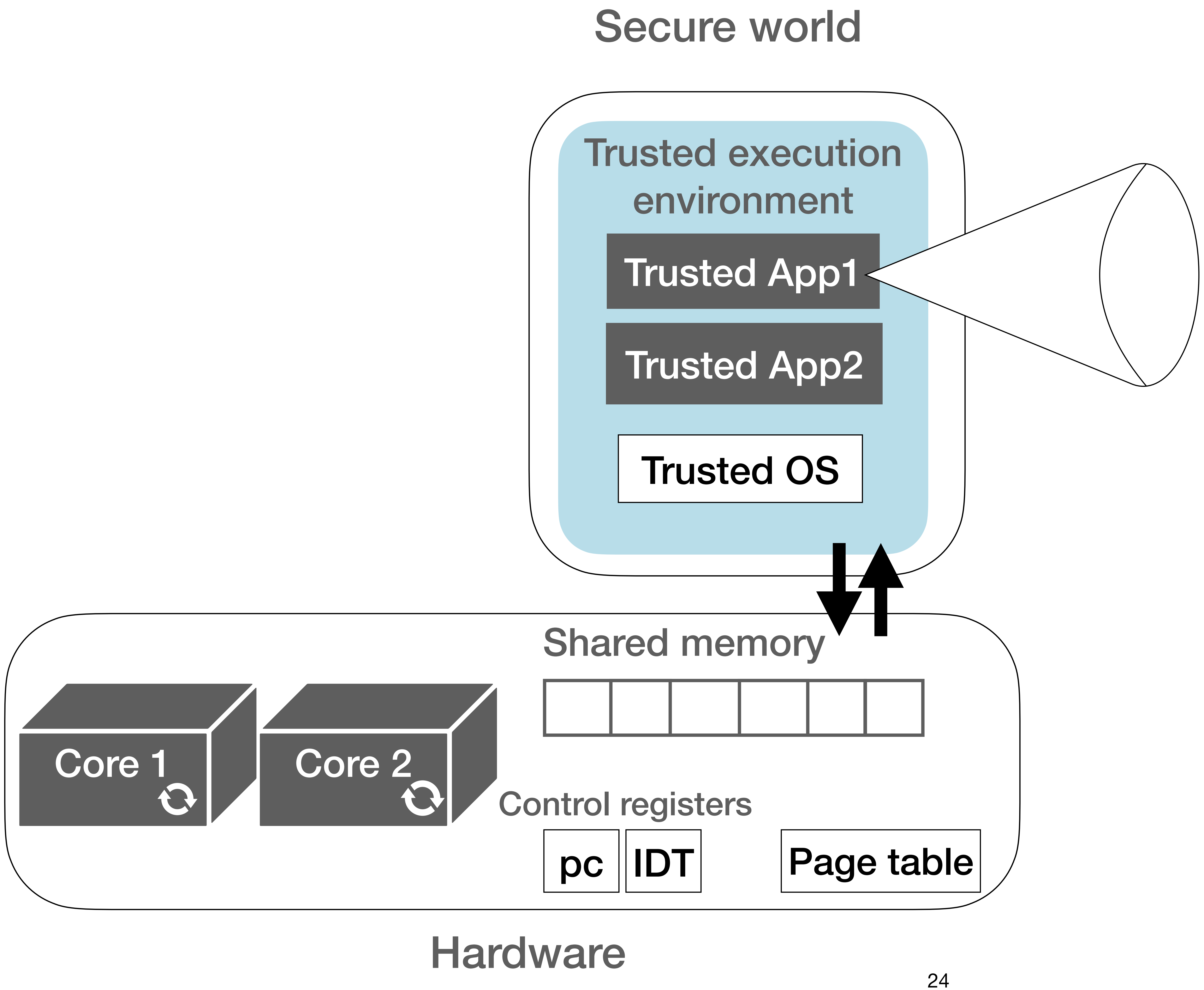

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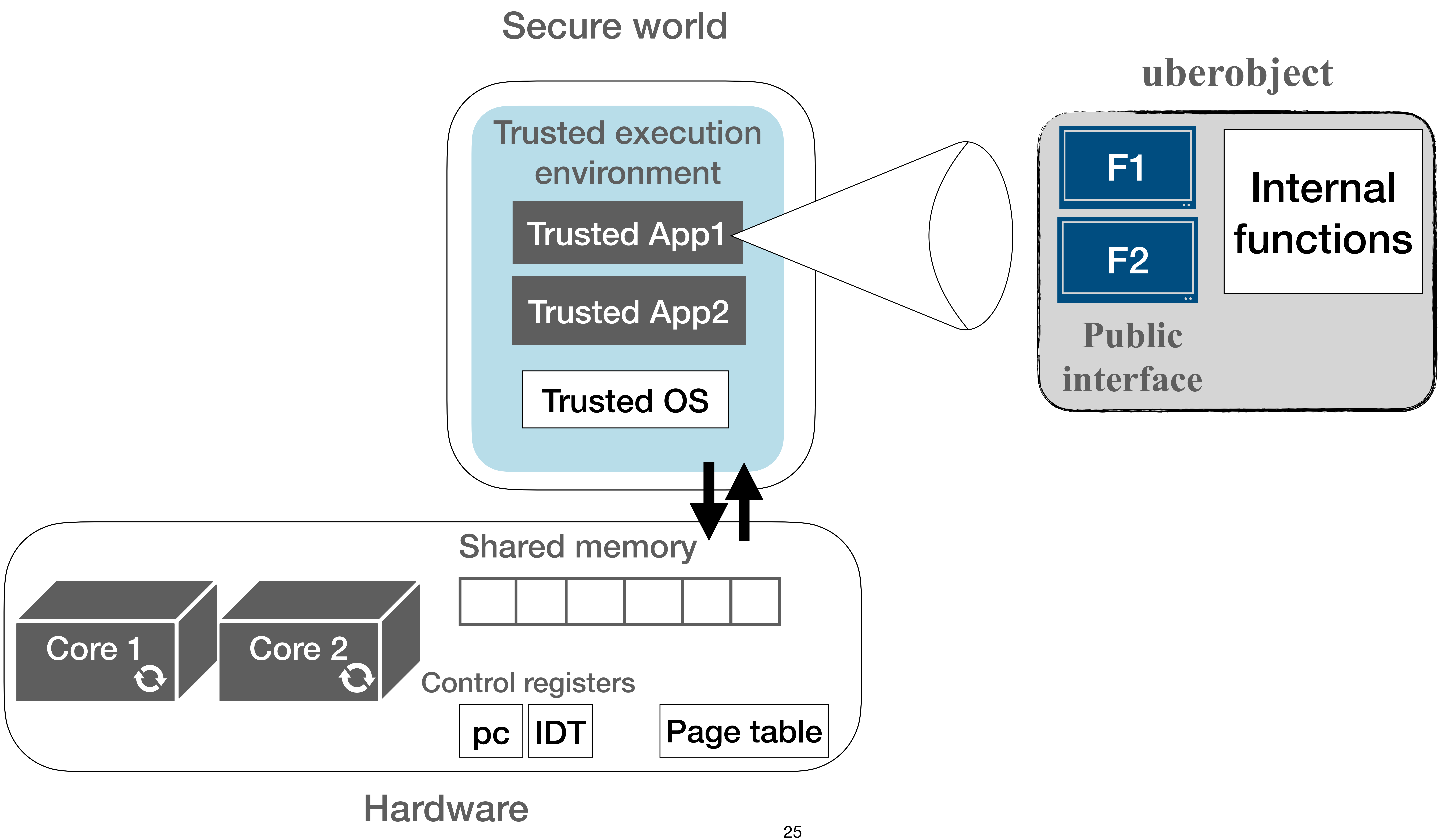

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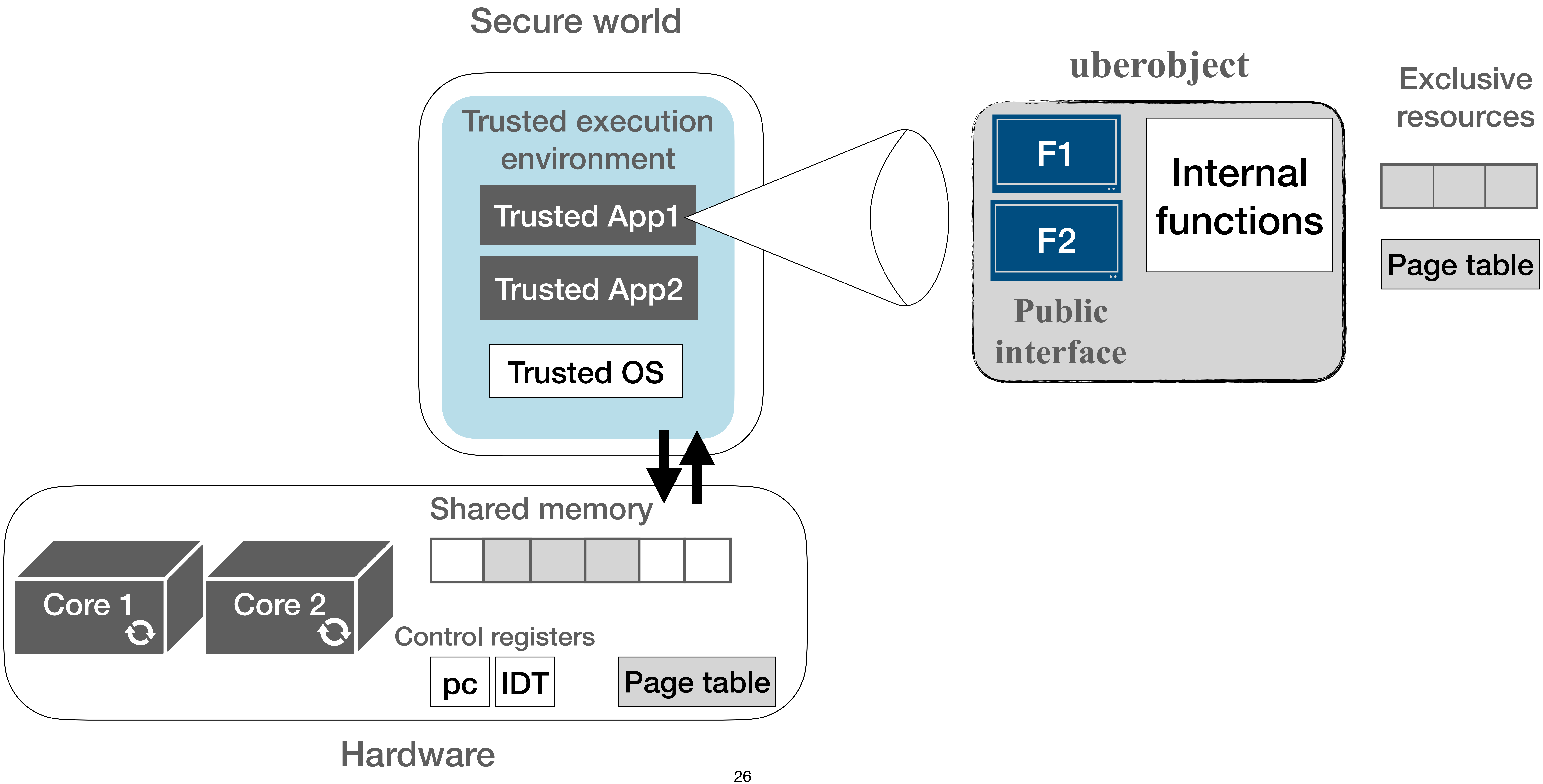

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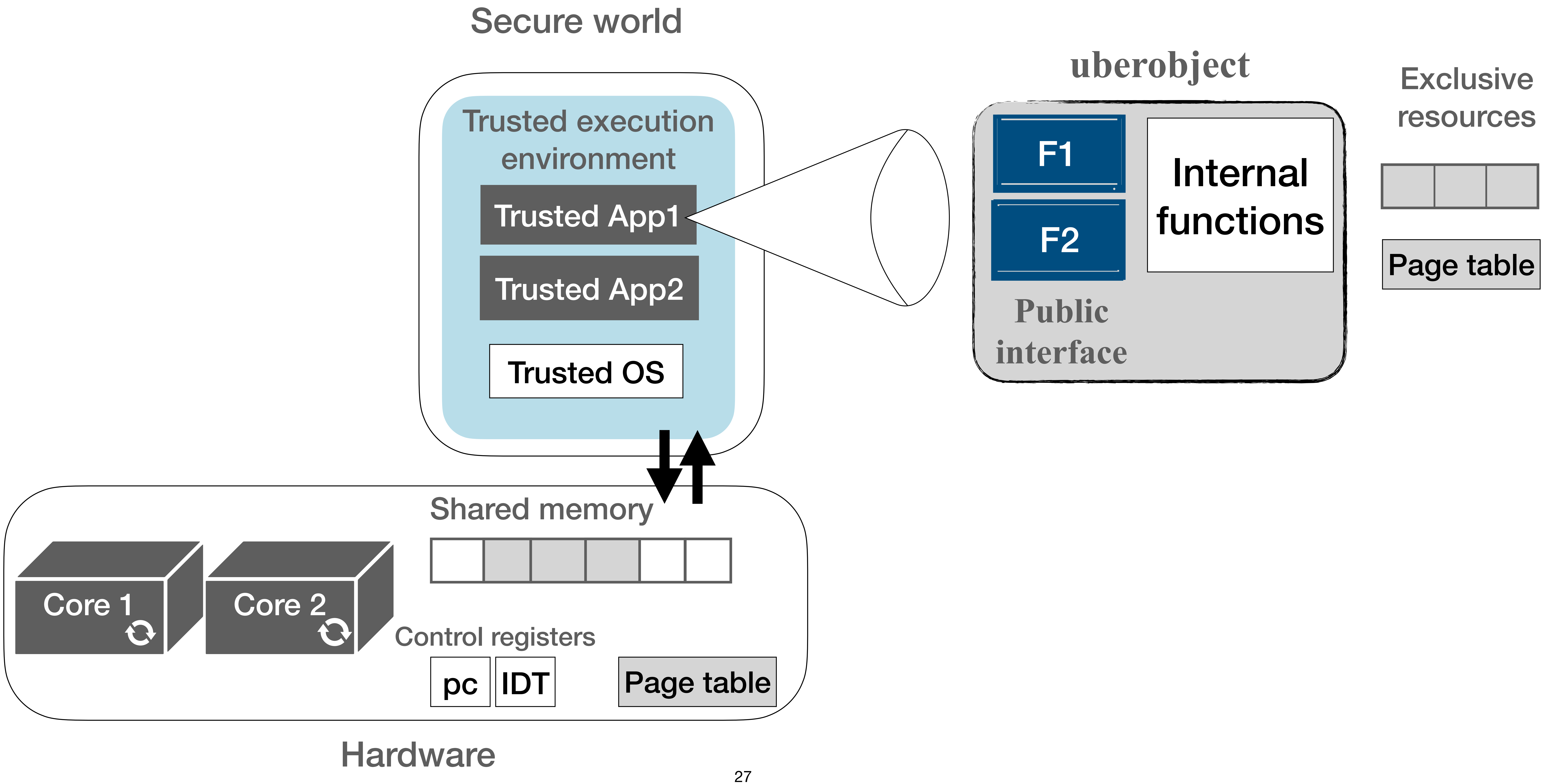

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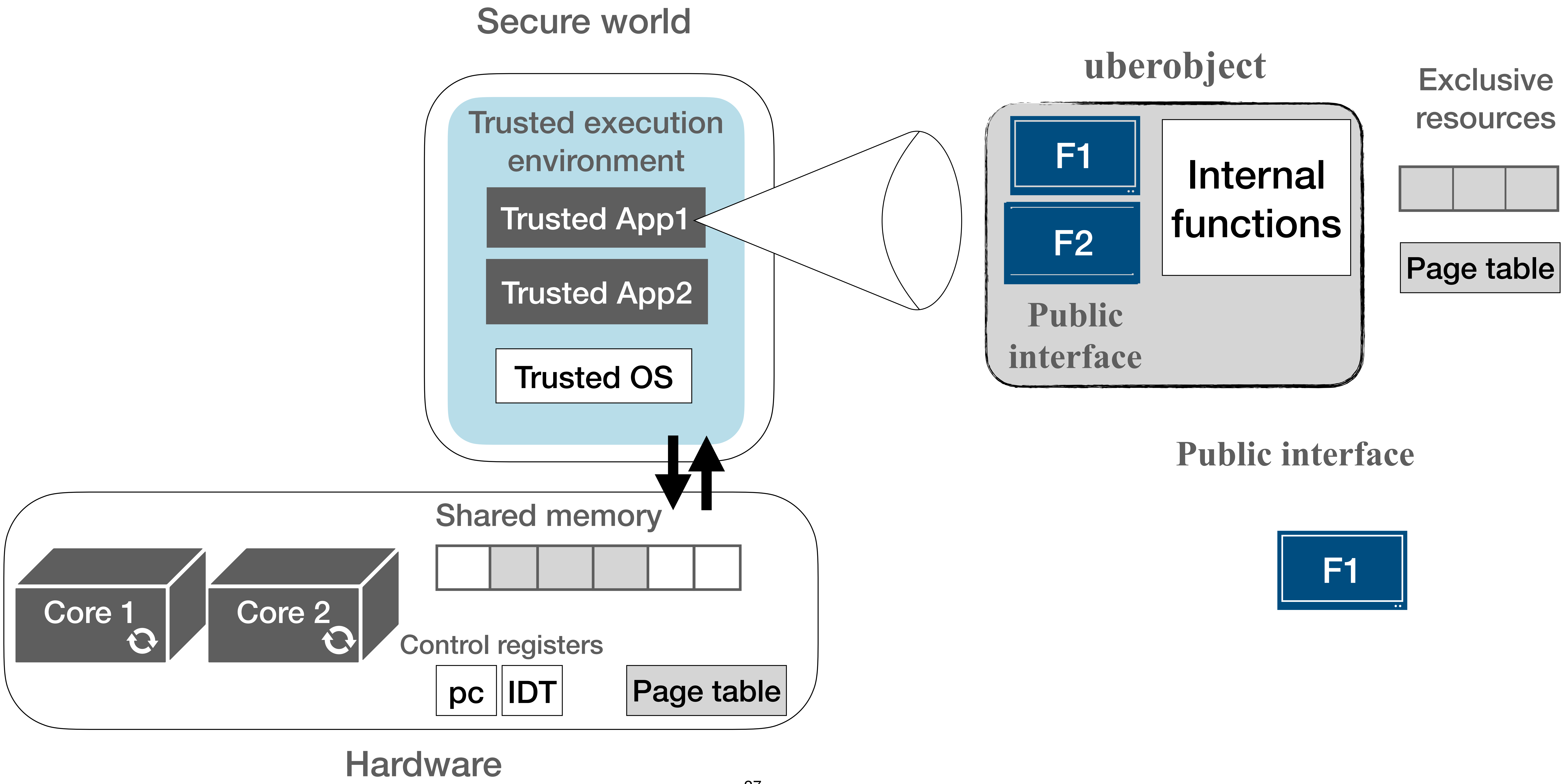


Secure world

Trusted execution environment

Trusted App1

Trusted App2

Trusted OS

Shared memory

Core 1

Core 2

Control registers

pc

IDT

Page table

Hardware

uberobject

F1

F2

Internal functions

Public interface

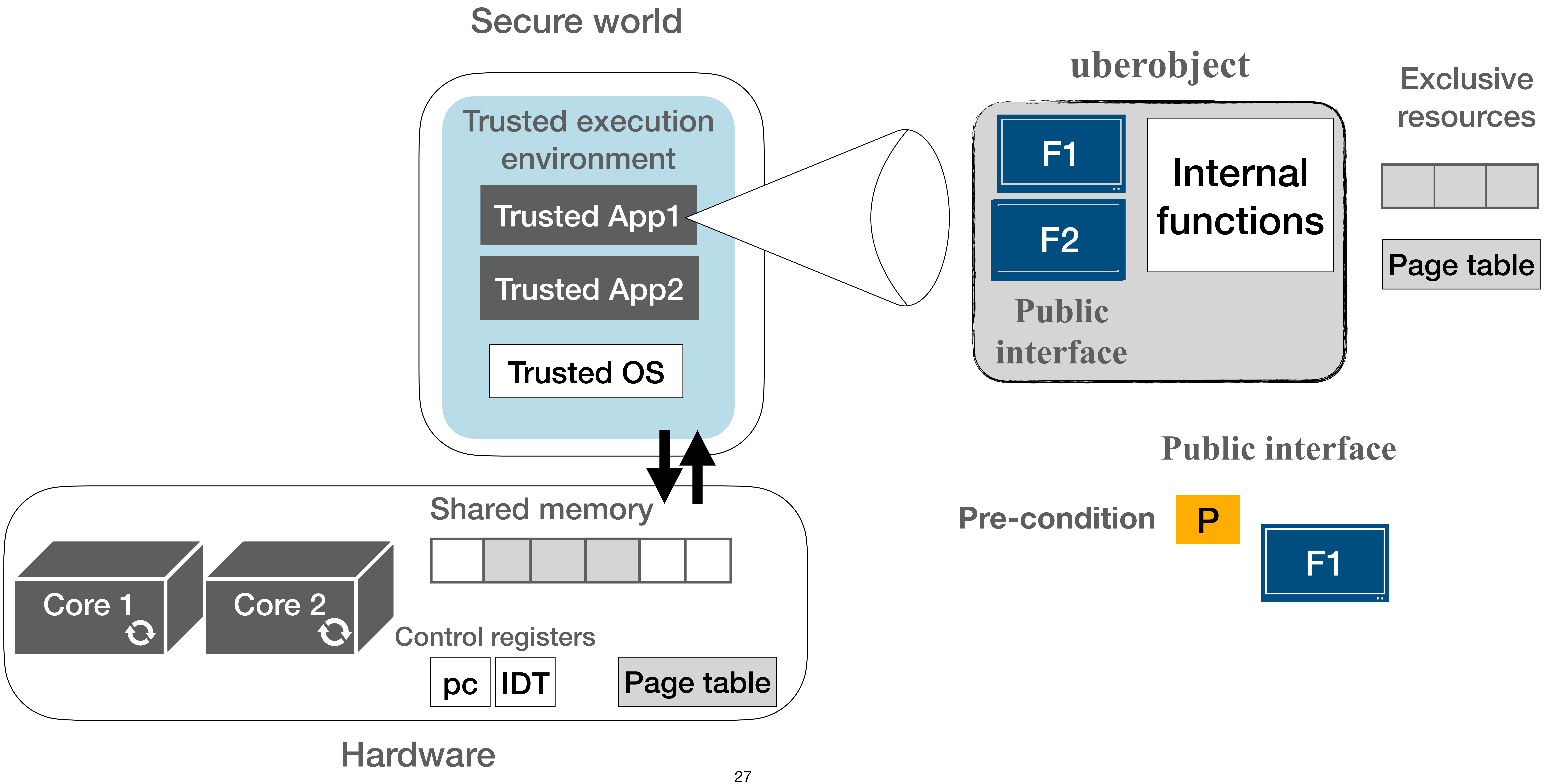
Exclusive resources

Page table

Public interface

F1

Compartments schema



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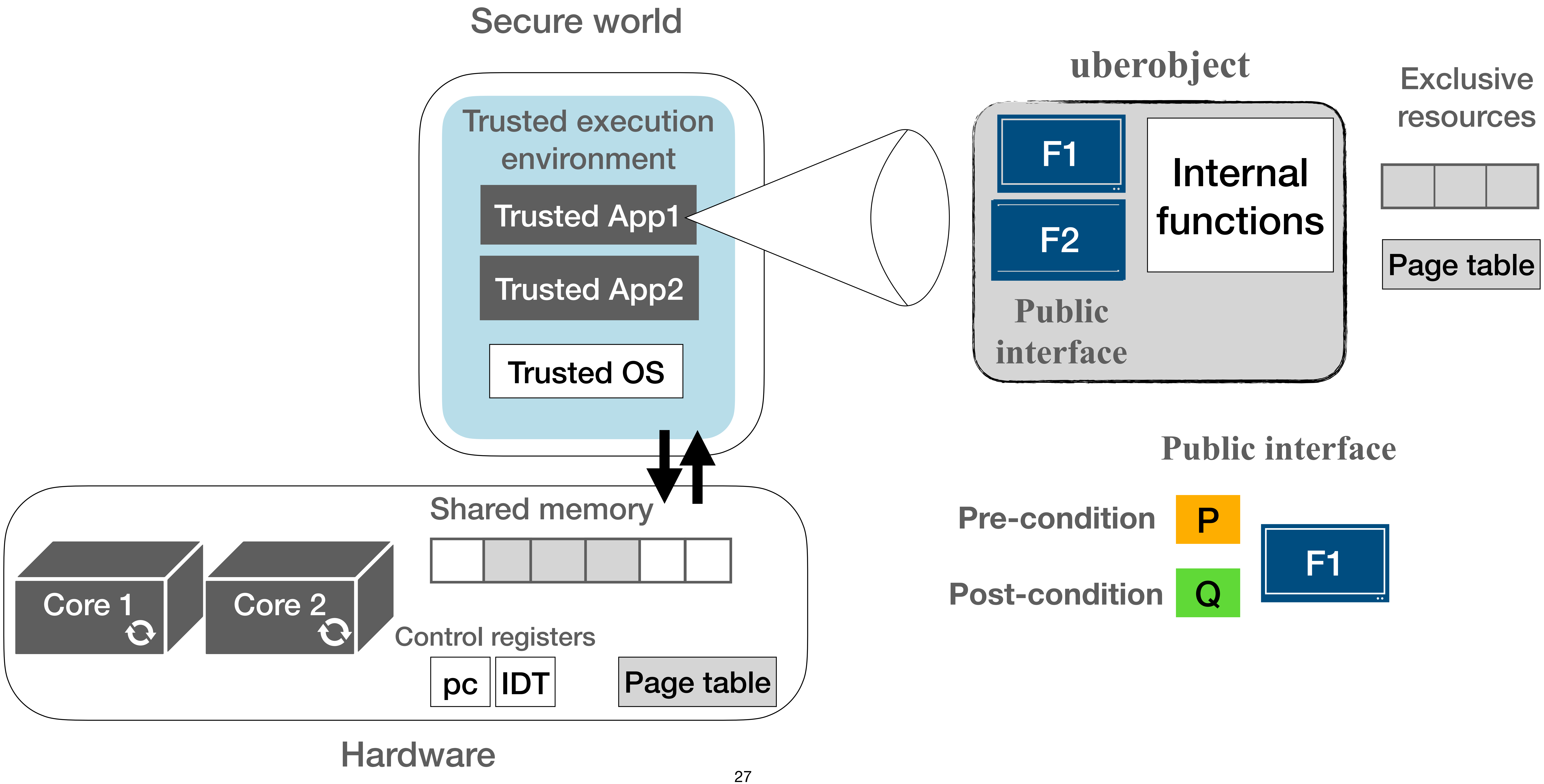

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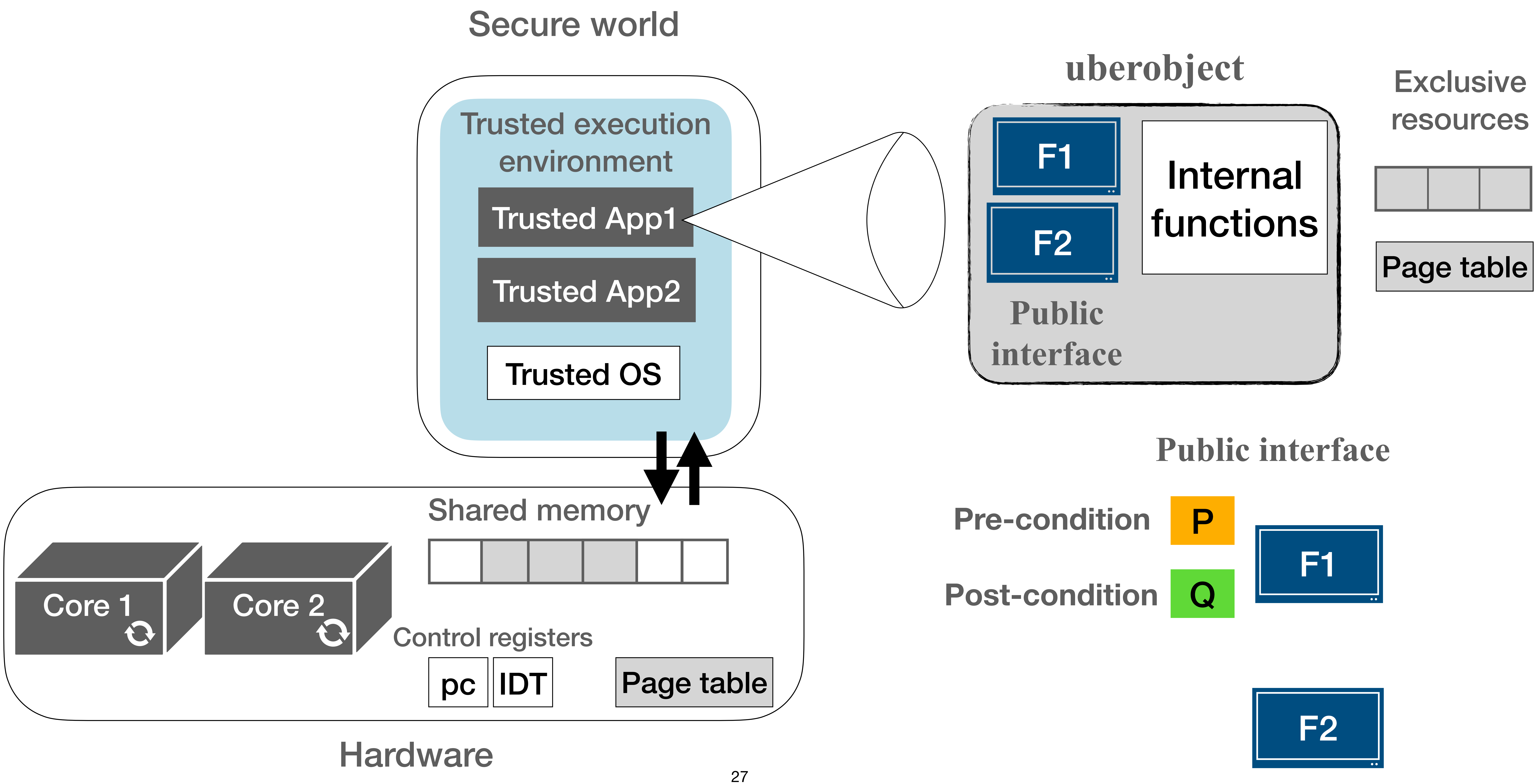

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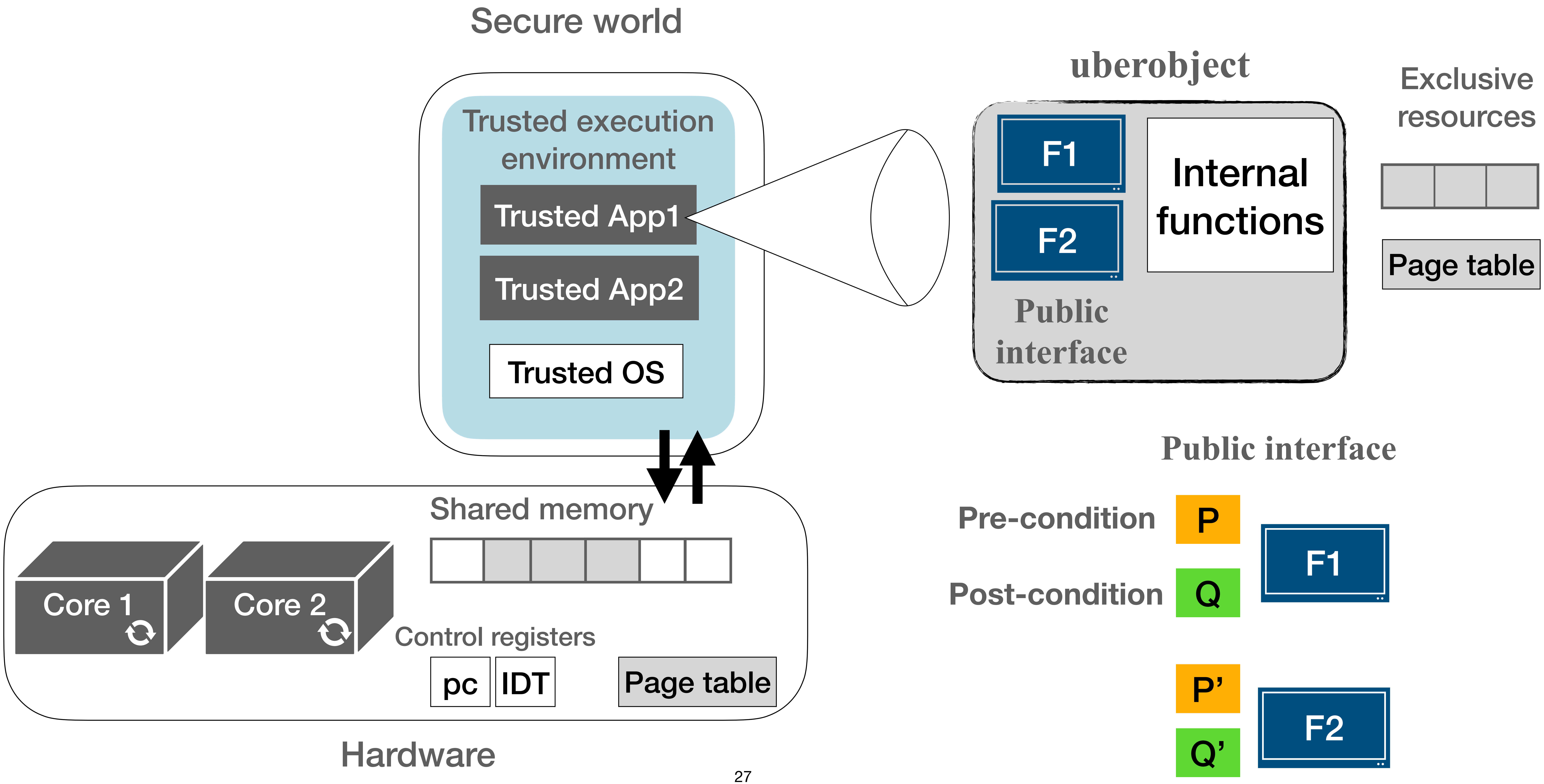

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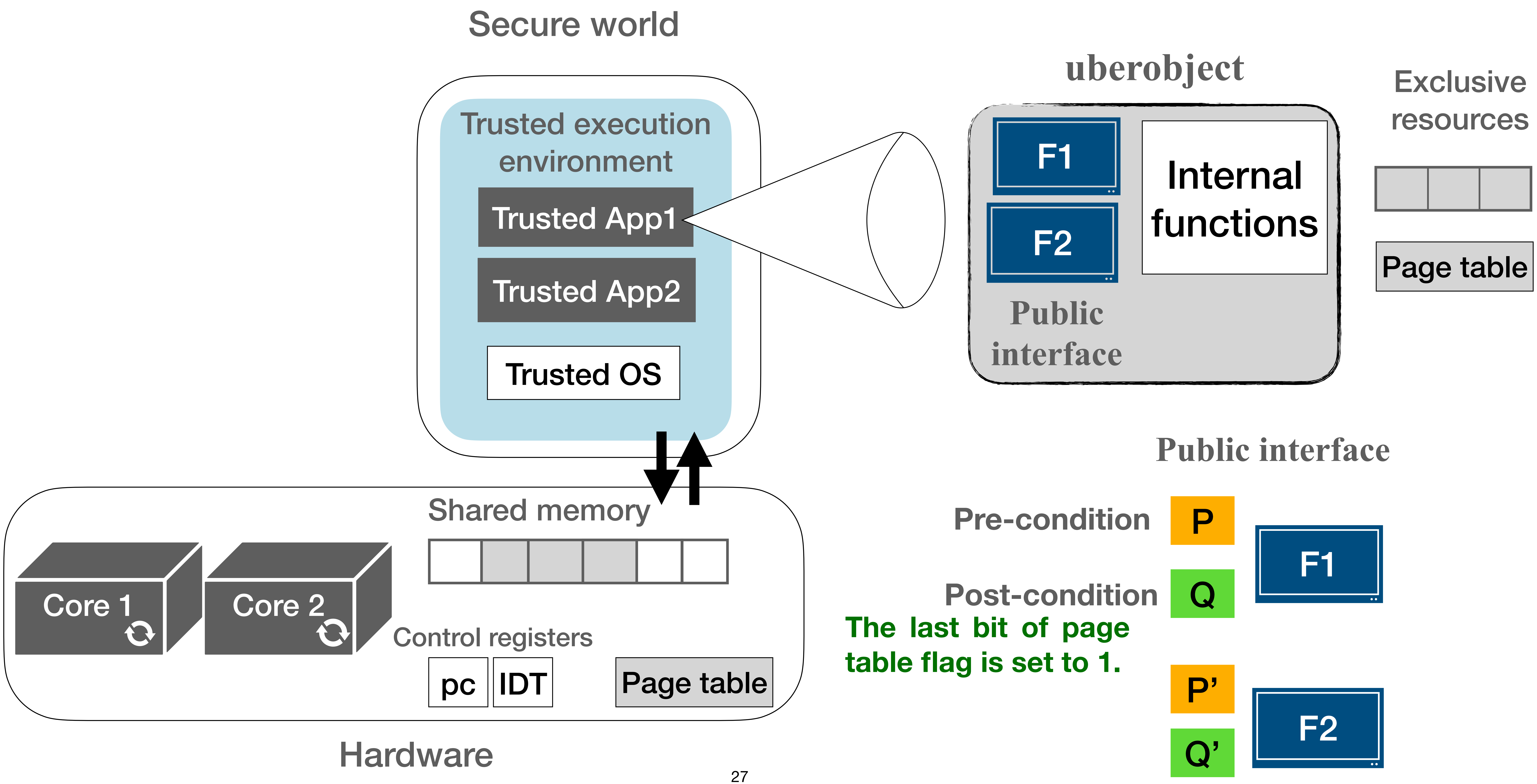
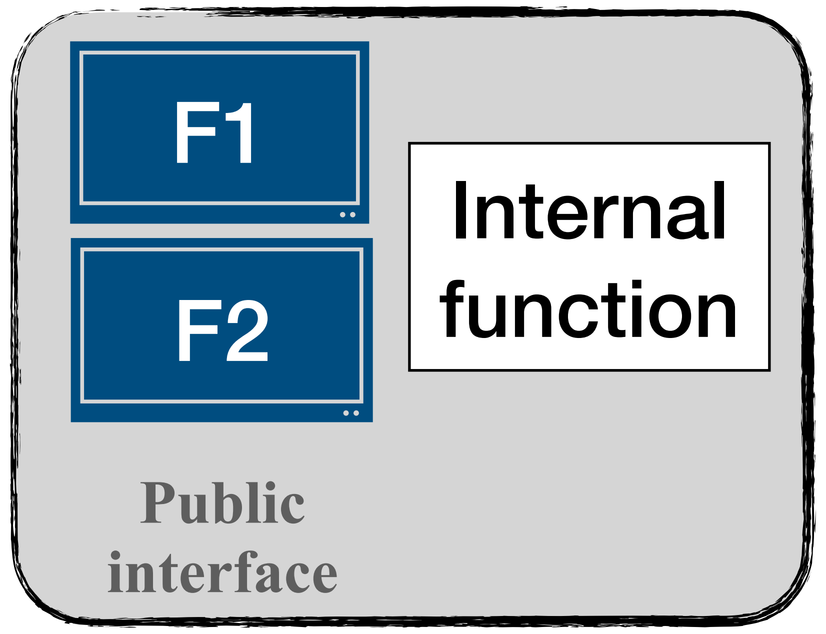


The last bit of page table flag is set to 1.

Compartments as units of verification and compilation

The last bit of page table flag is set to 1 (after function return)

Source-level compartments



uberobject 1

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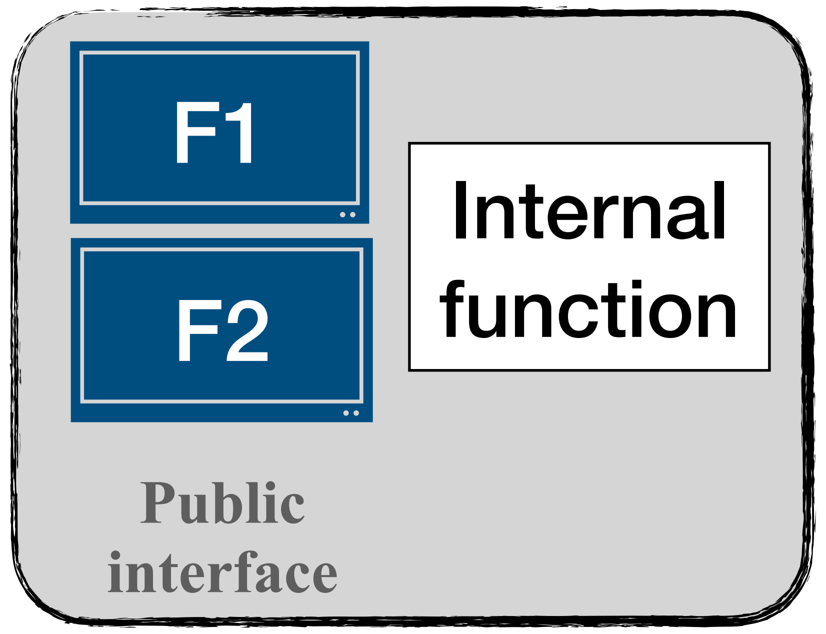
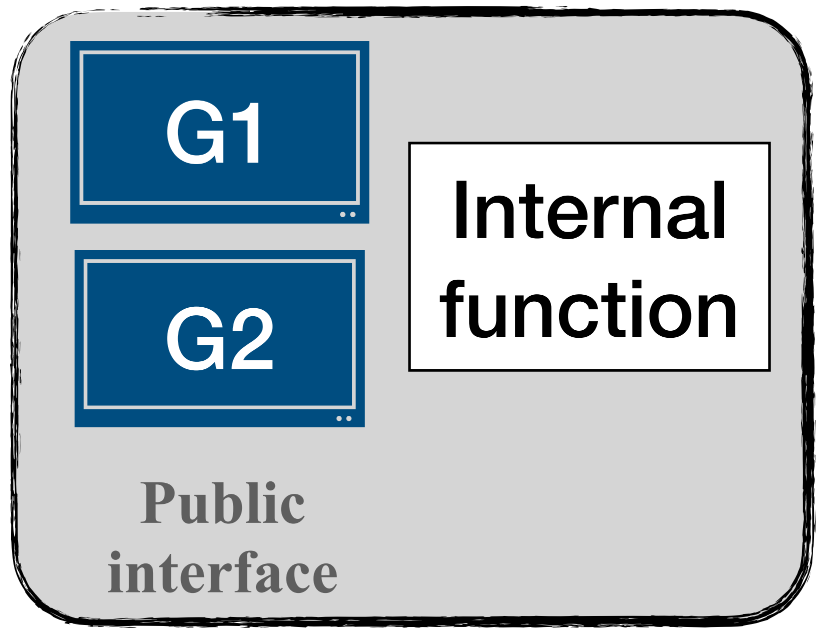


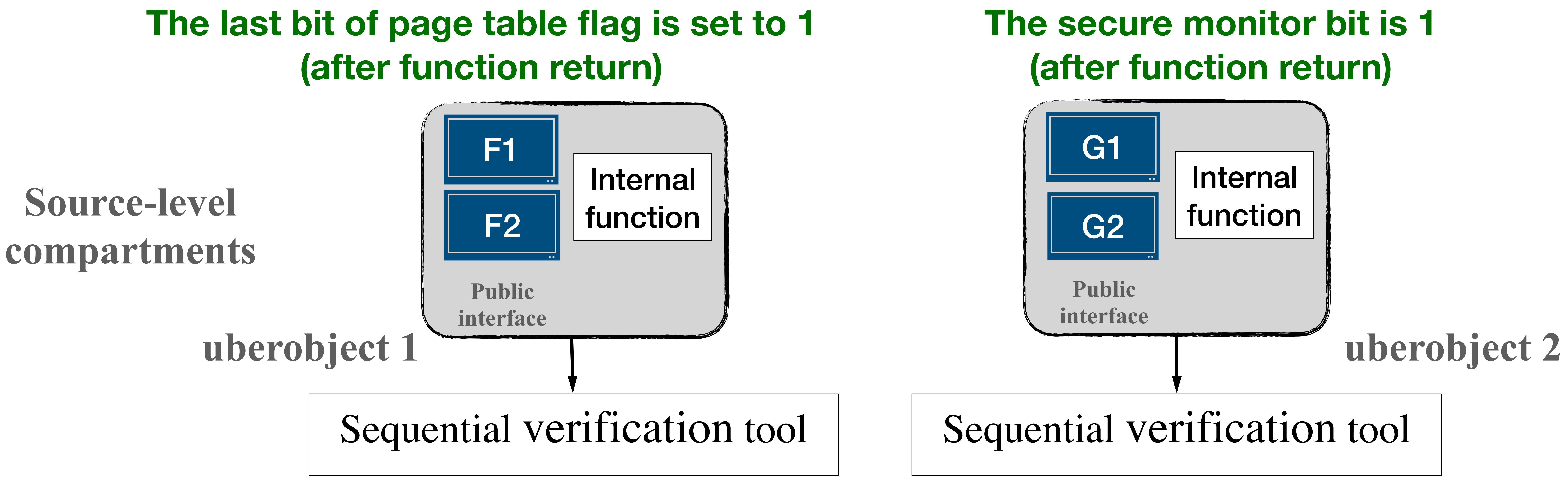
uberobject 1

The secure monitor bit is 1 (after function return)



uberobject 2

Compartments as units of verification and compilation



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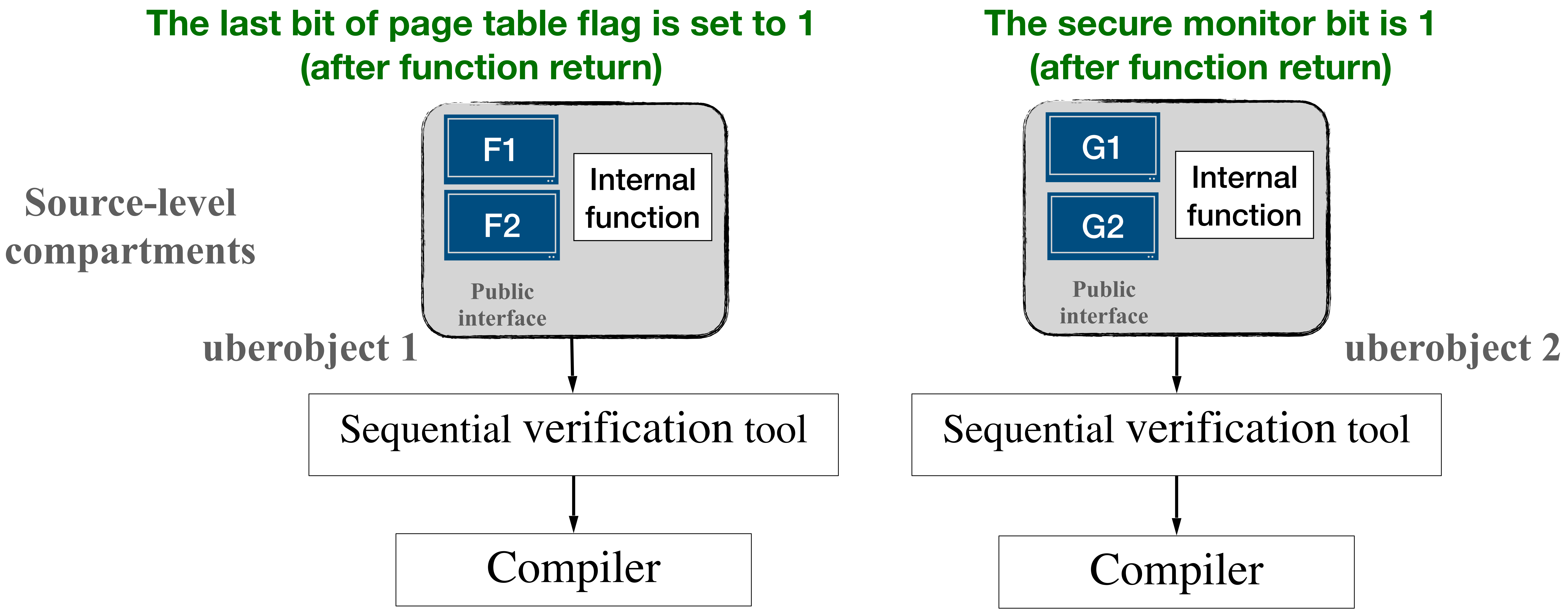

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Source-level compartments

F1

F2

Internal function

Public interface

uberobject 1

Sequential verification tool

Compiler

G1

G2

Internal function

Public interface

uberobject 2

Sequential verification tool

Compiler

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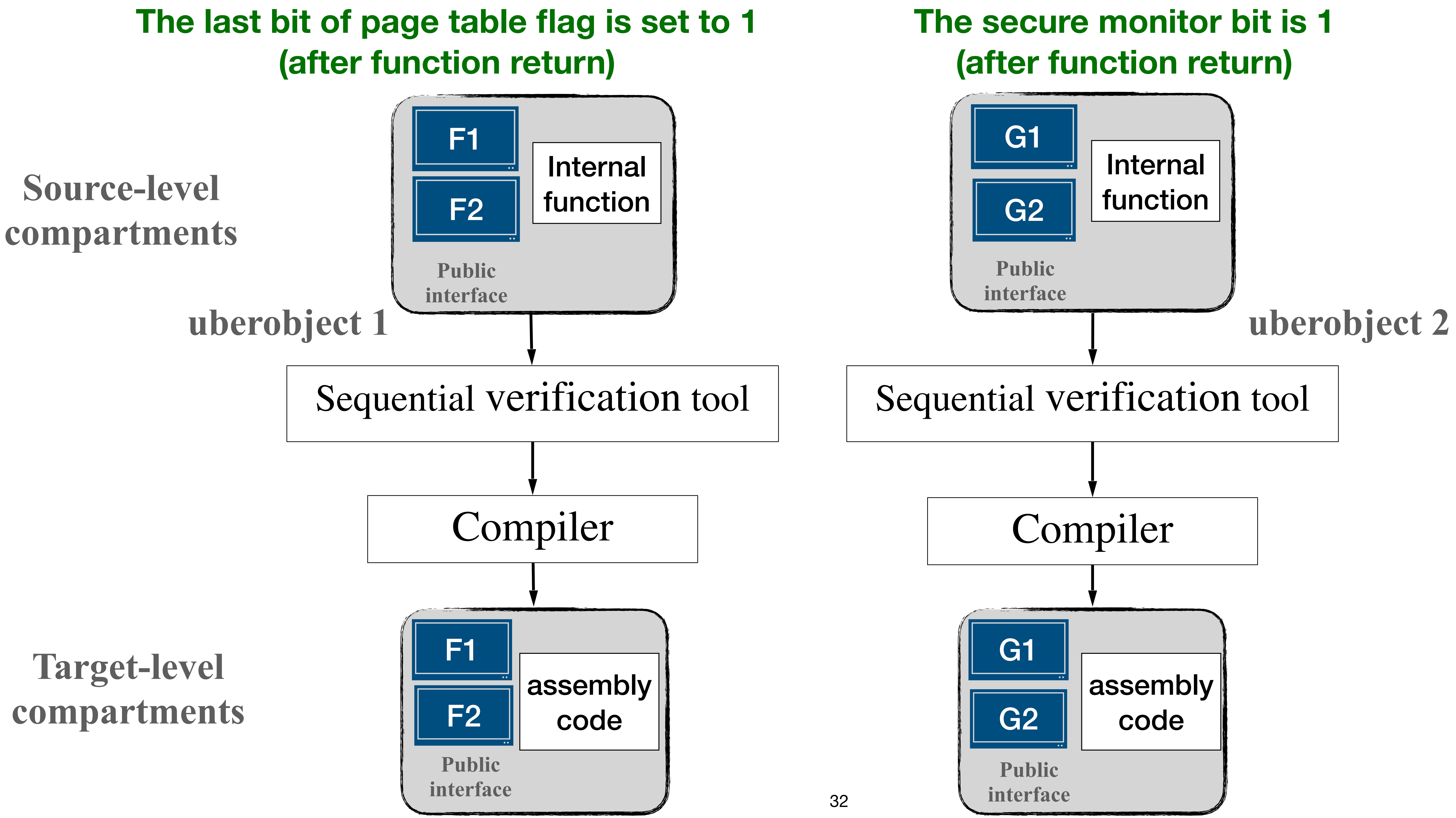

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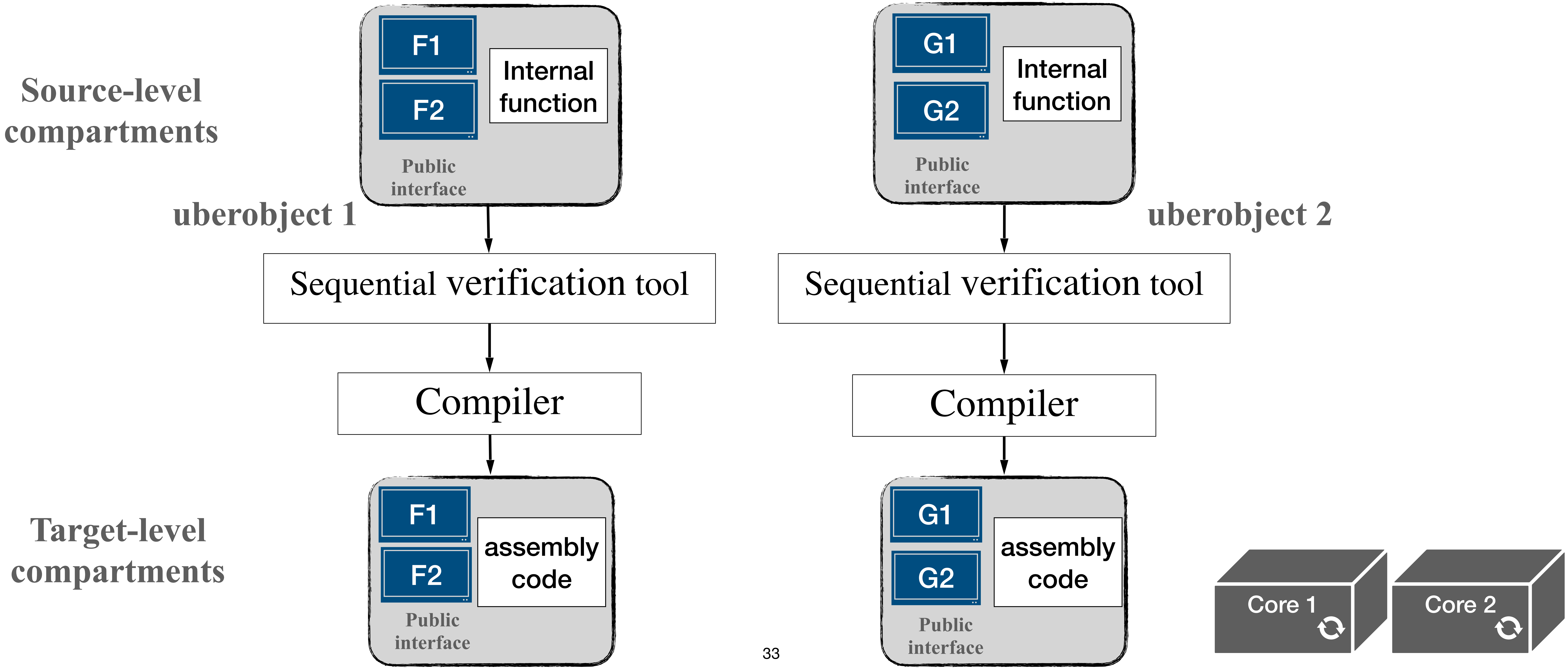

Source-level compartments

F1

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Internal function

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uberobject 1

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Compiler

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F2

assembly code

Public interface

G1

G2

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uberobject 2

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Public interface

Target-level compartments

Core 1

Core 2

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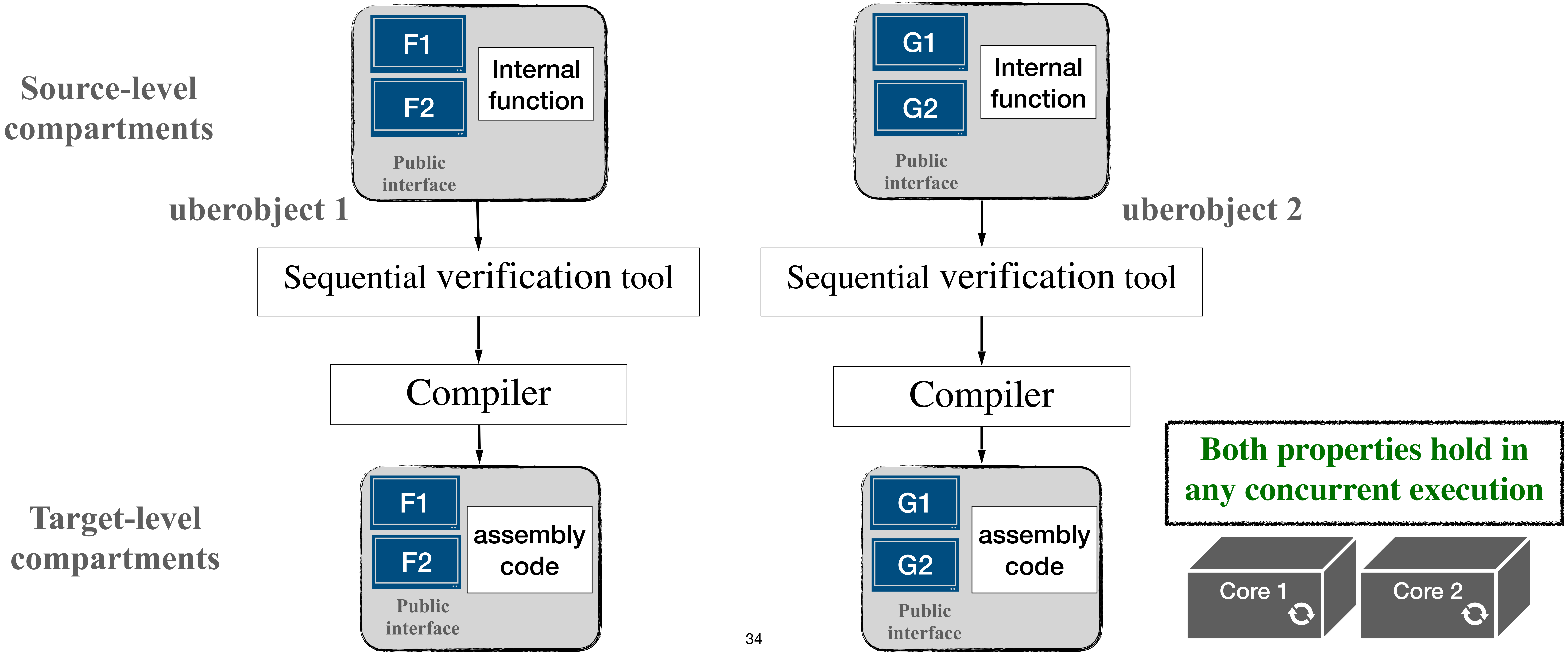

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F2

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Public interface

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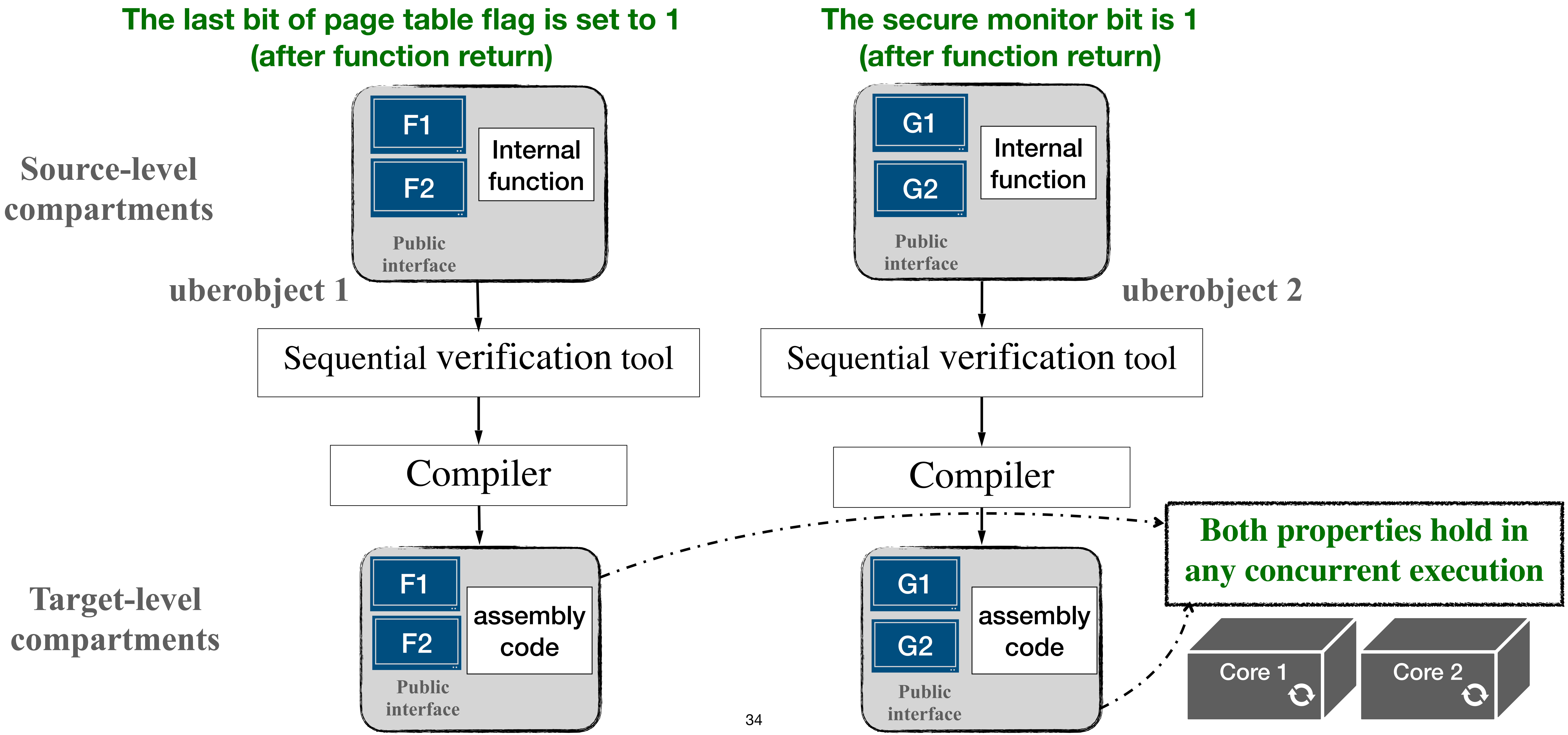
G2

assembly code

Public interface

Both properties hold in any concurrent execution

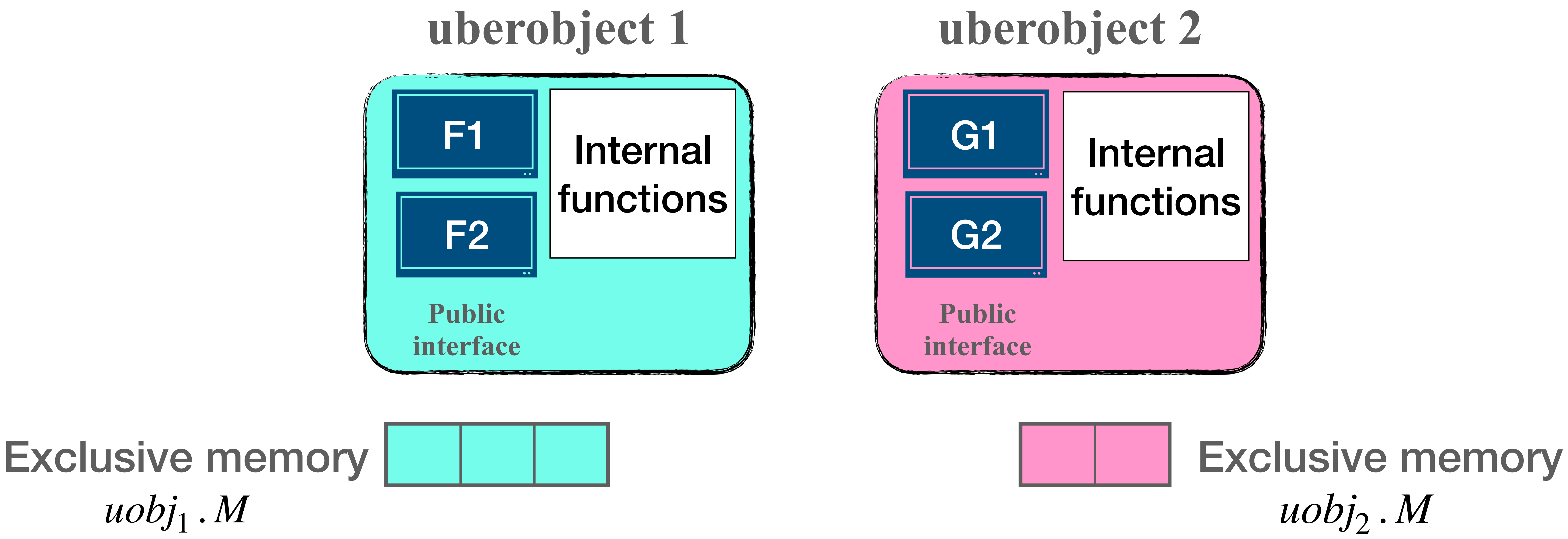
Compartments as units of verification and compilation



Outline

- **Concurrent execution** - an example
- **Verify source-level guarantees**
- **Preserve target-level guarantees**
- **Using off-the-shelf tools**
- **Case studies**
- **Related work**

Concurrent execution



uberobject 1

F1

F2

Internal functions

Public interface

Exclusive memory

$uobj_1 . M$

uberobject 2

G1

G2

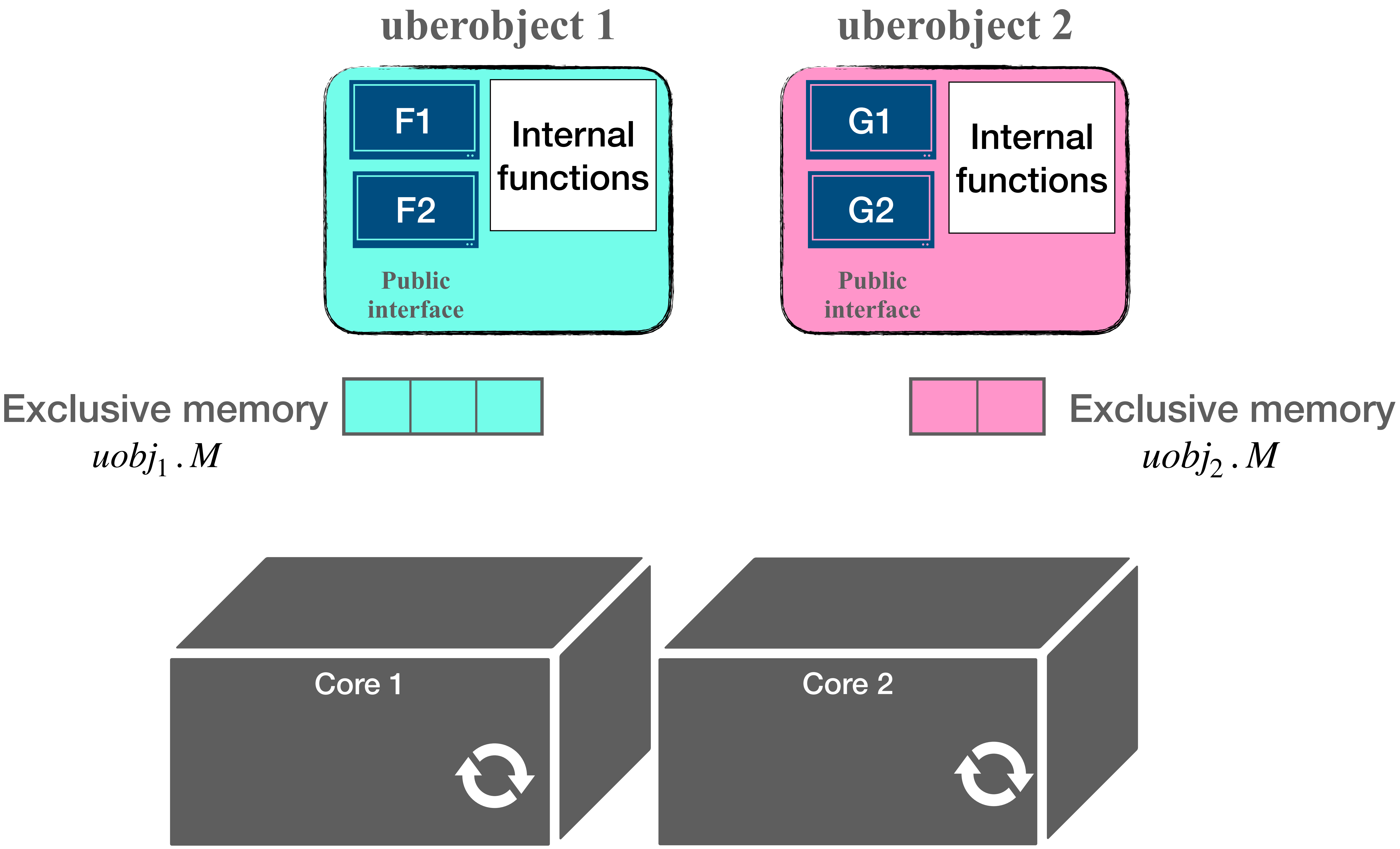
Internal functions

Public interface

Exclusive memory

$uobj_2 . M$

Concurrent execution



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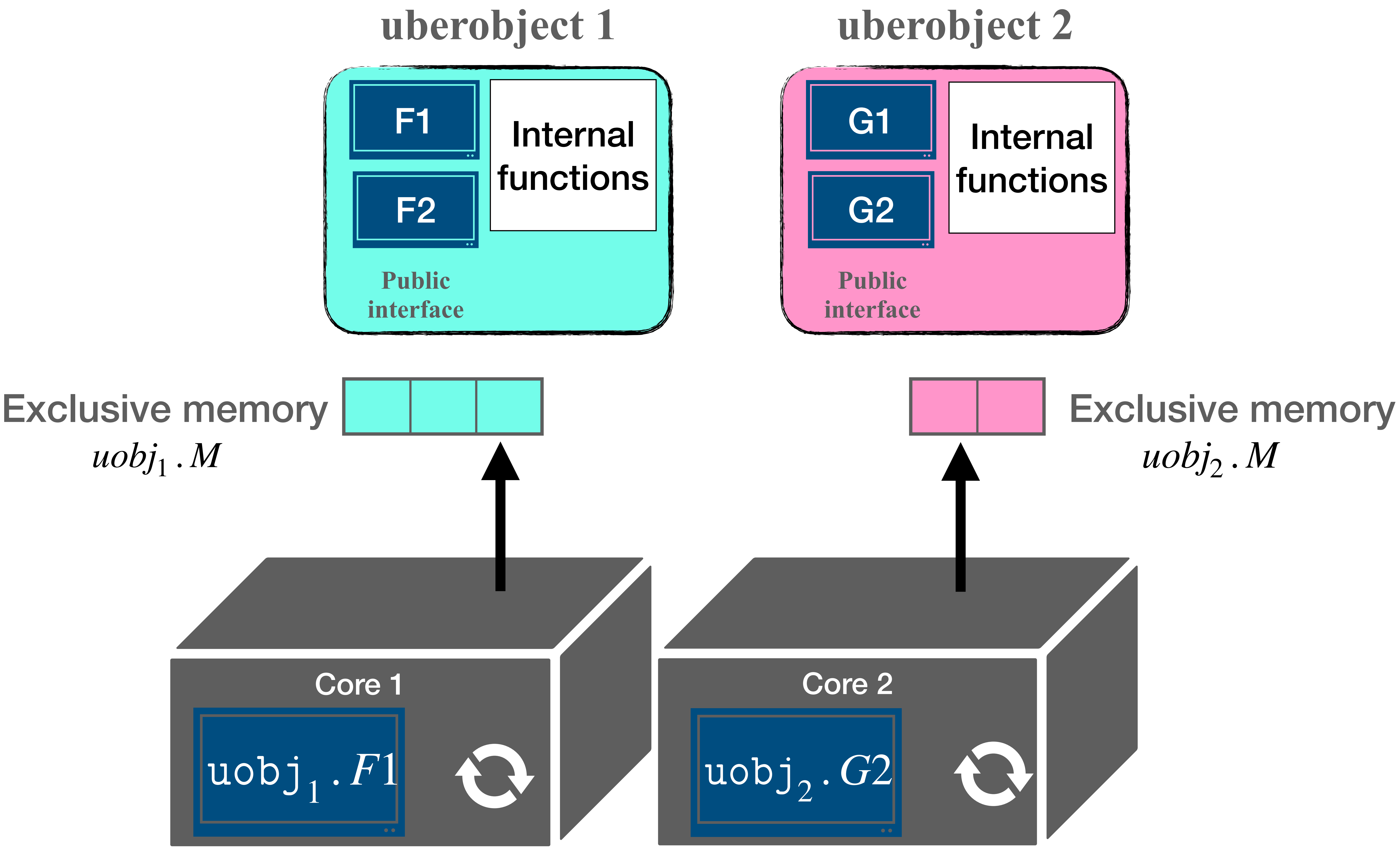

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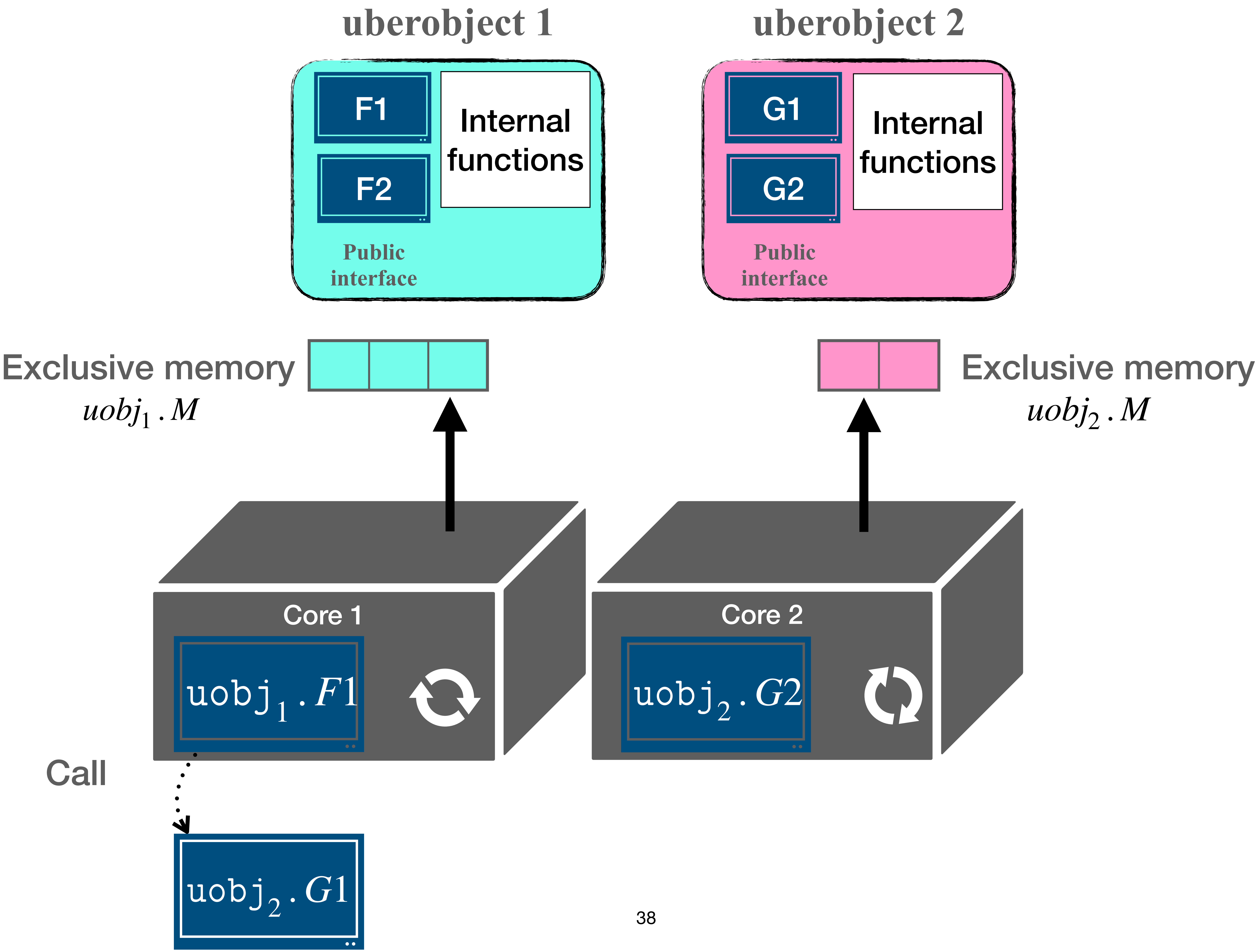

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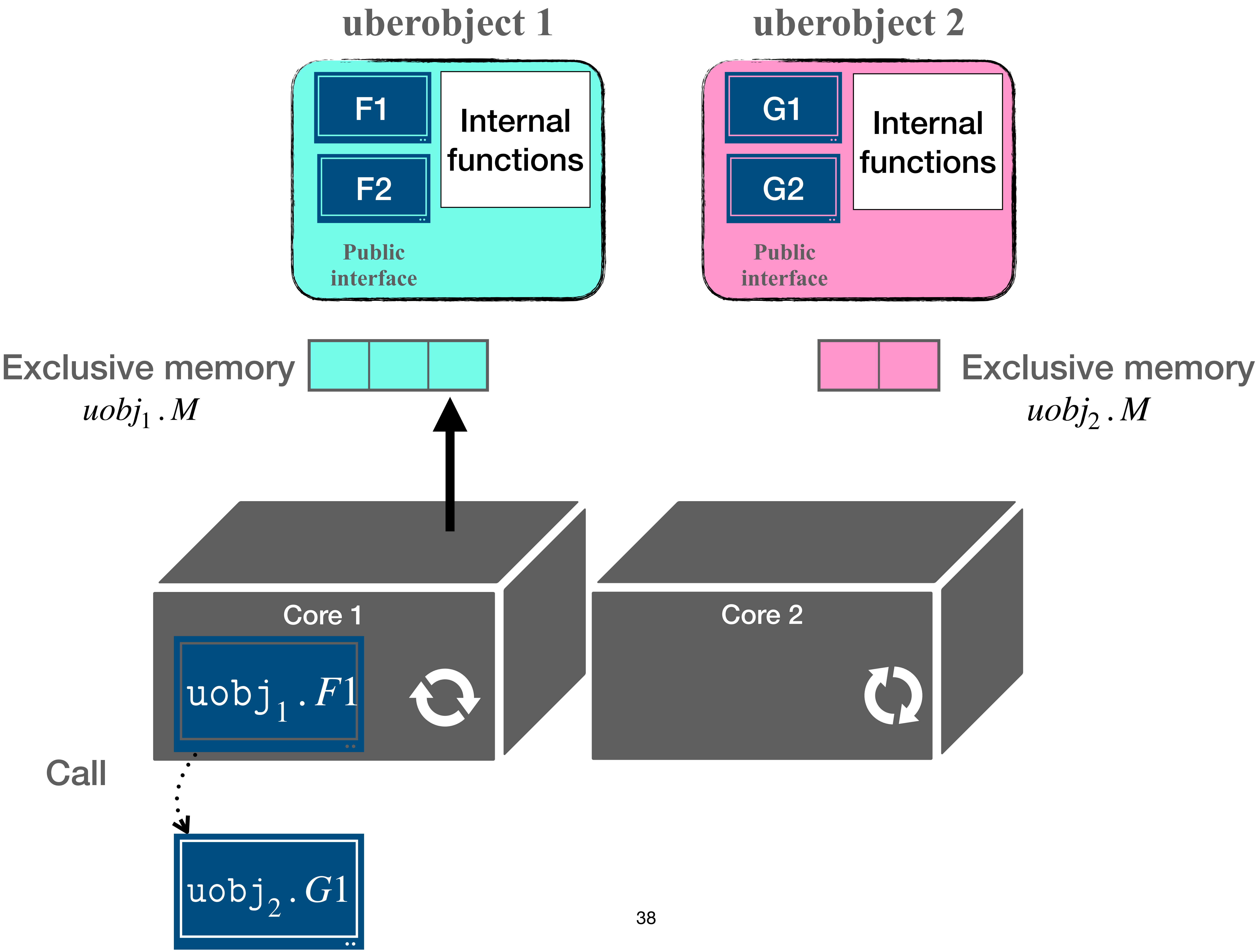

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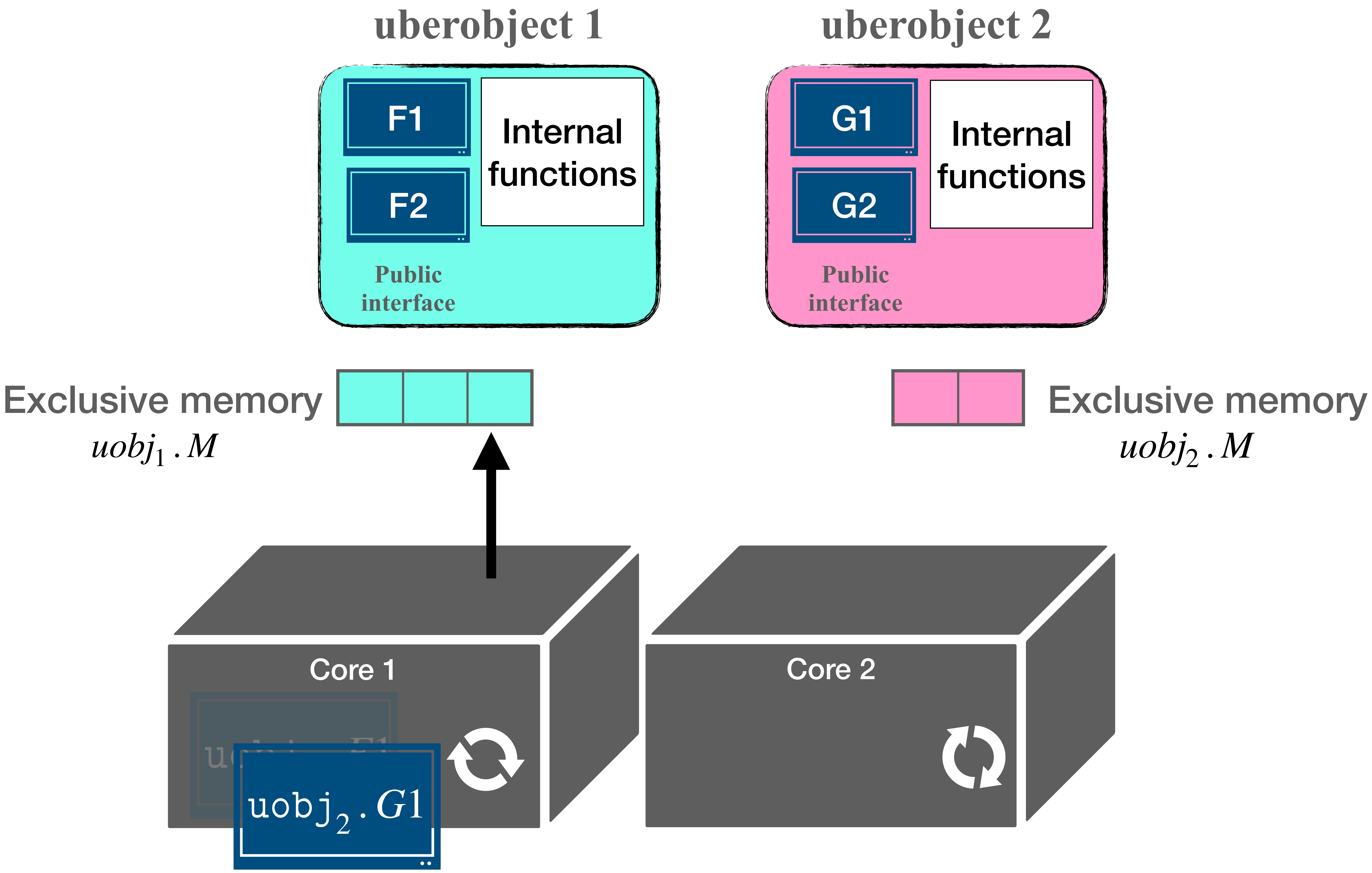

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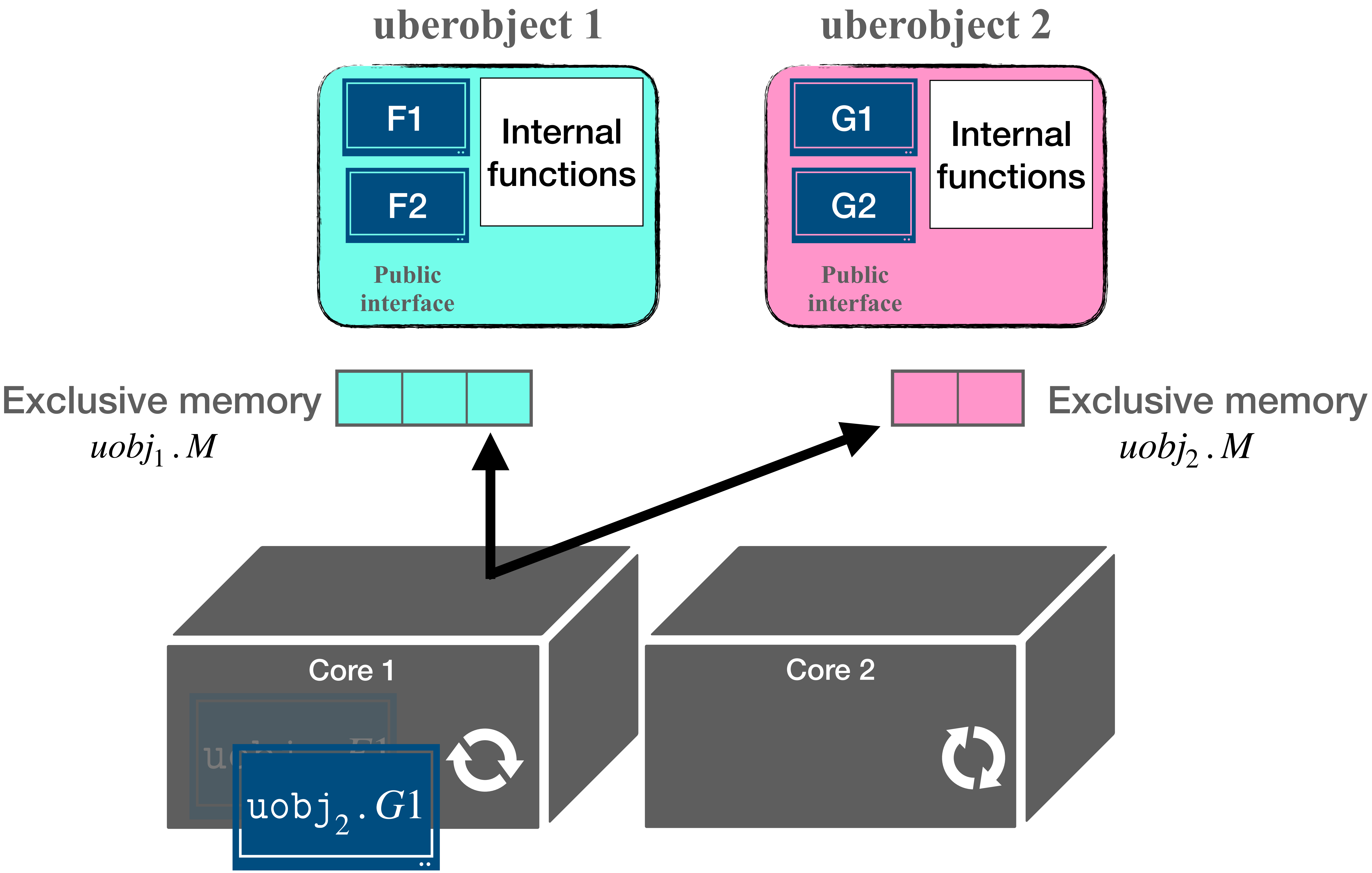

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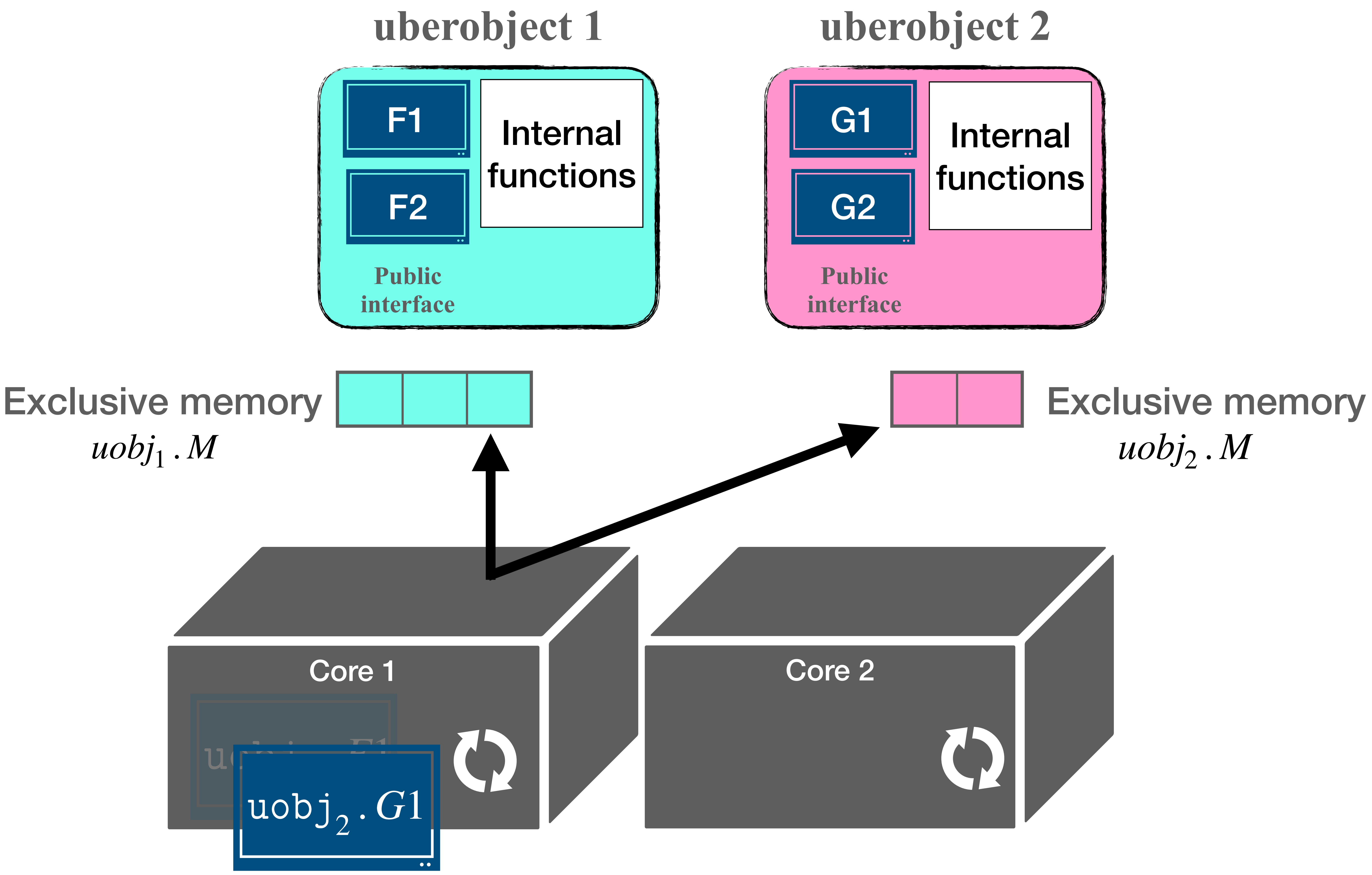

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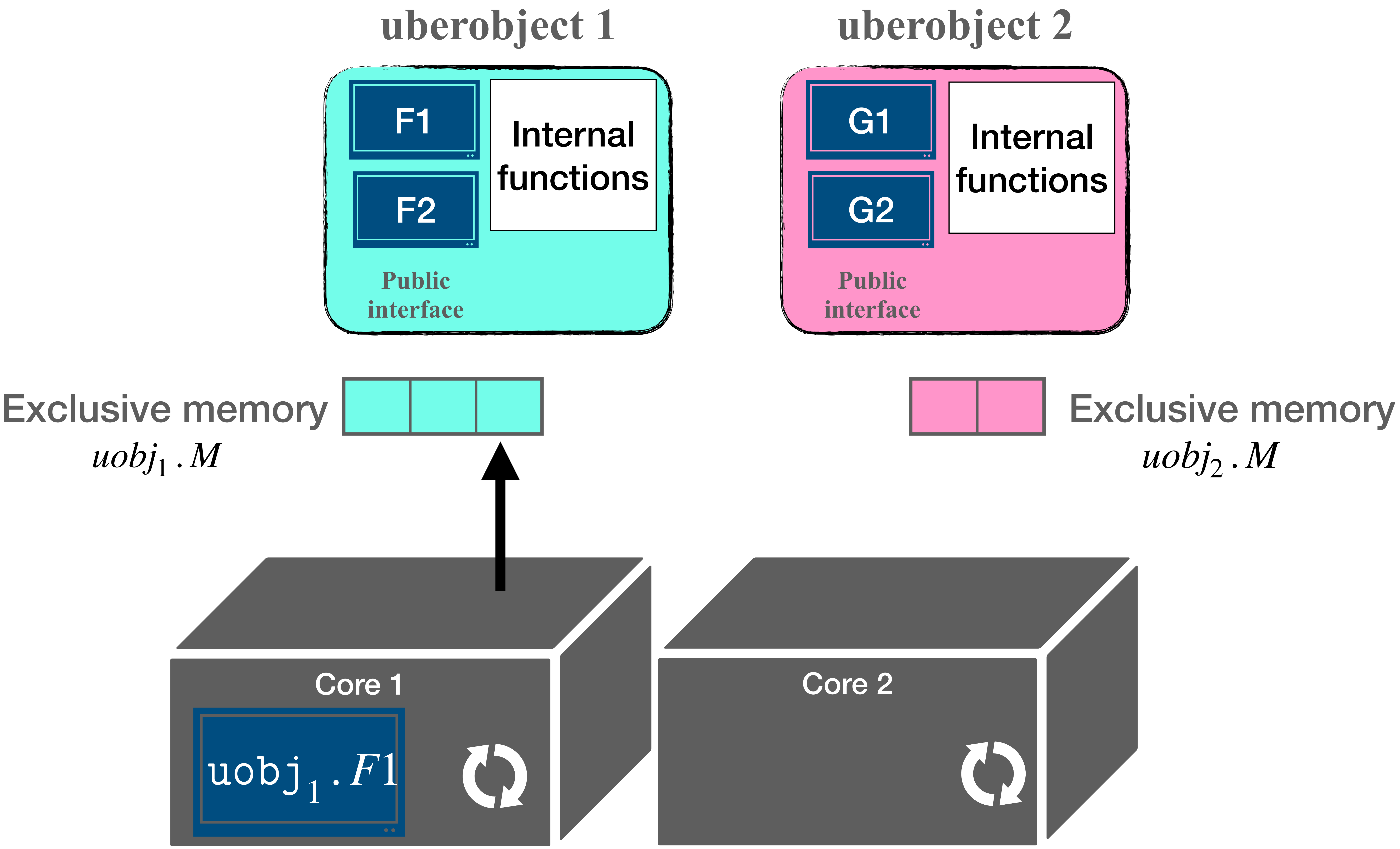

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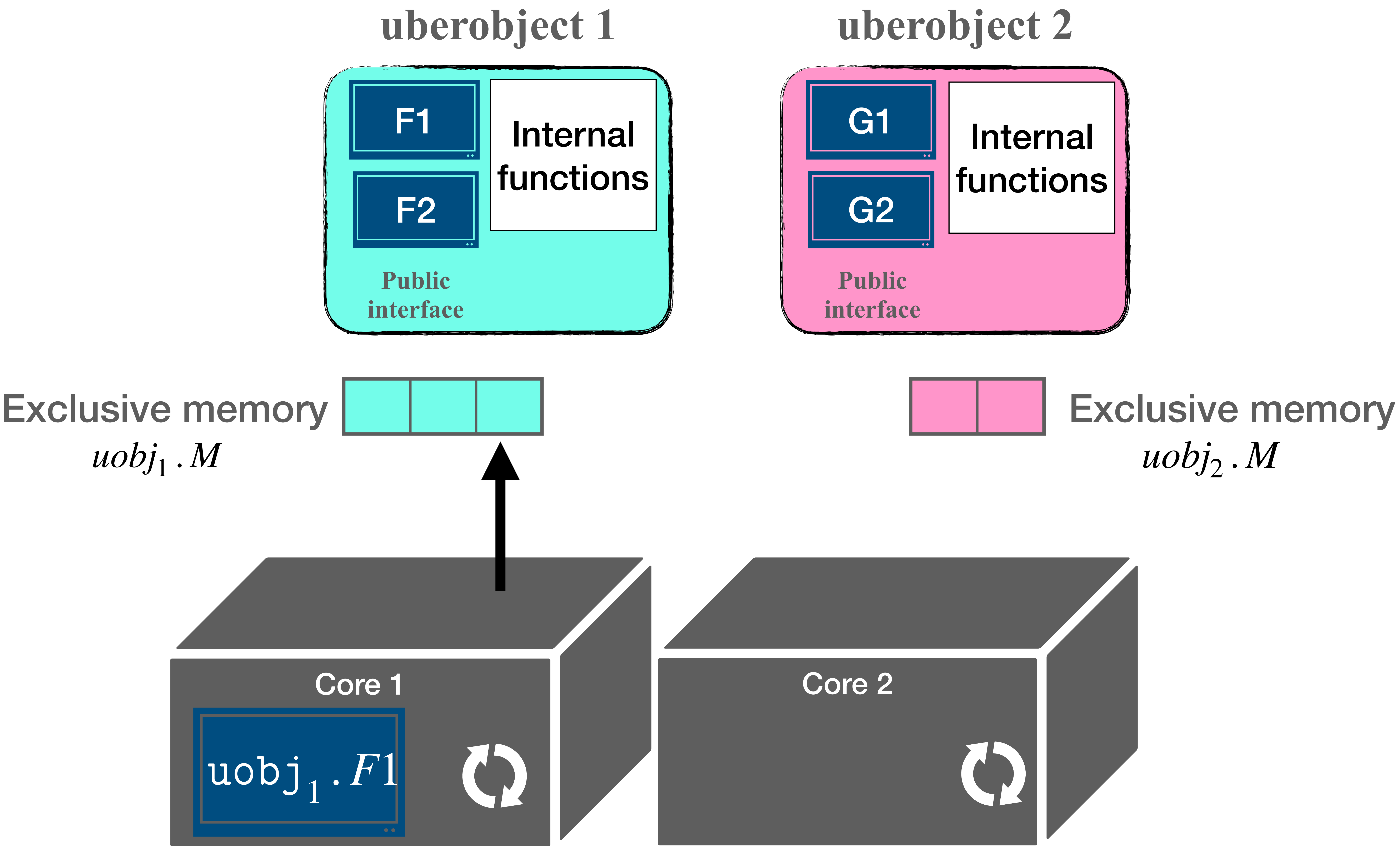

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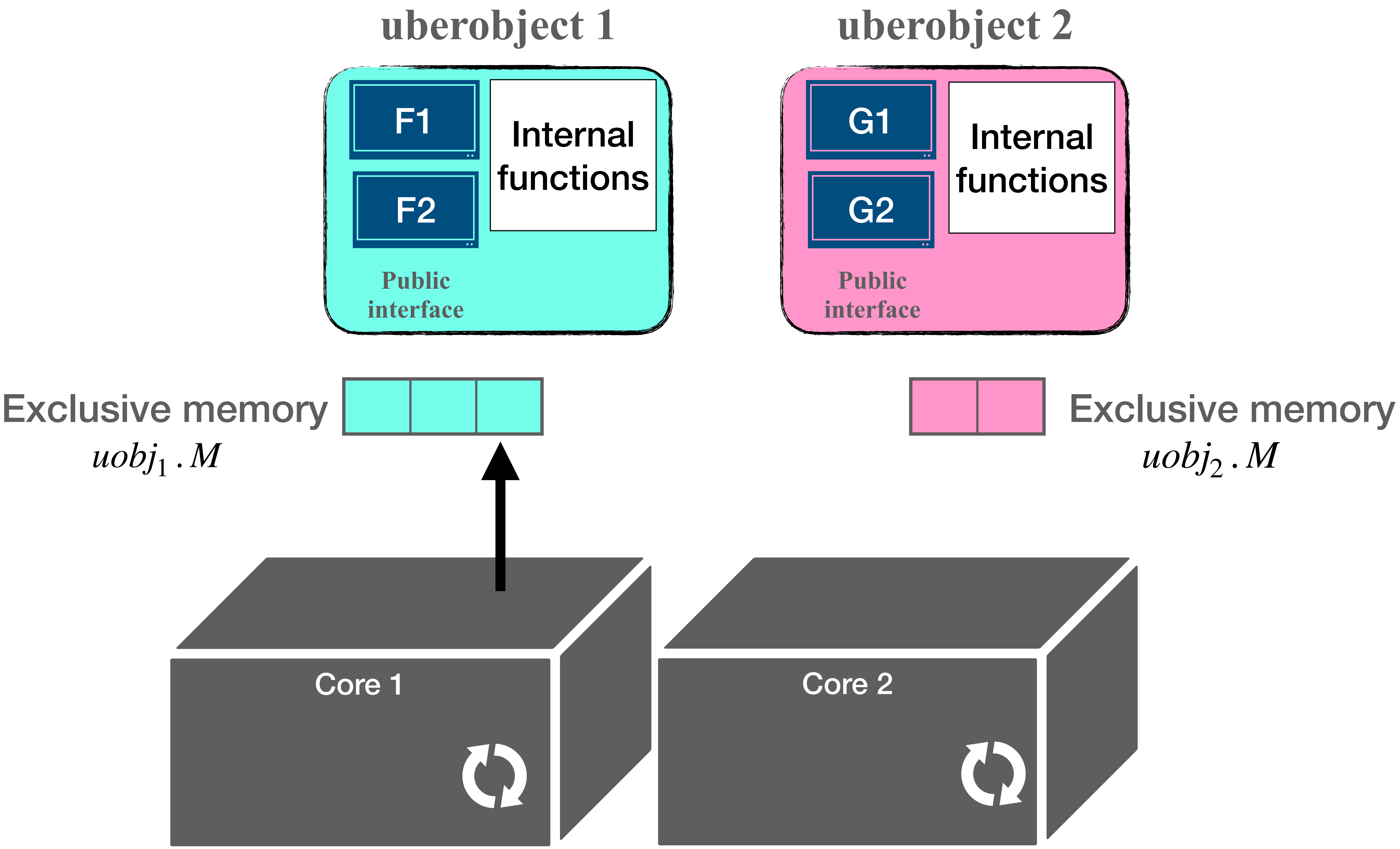

Source-level guarantees via verification of each compartment

— Respecting the interface —

Requirement from a source-level compartment—Respecting the interface

$\texttt{uobj}_1.F1$

$\texttt{uobj}_2.G2$

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Guarantee: Any internal step of *this uberobject* can only read from/write to its own exclusive memory.

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Requirement from a source-level compartment—Respecting the interface

Guarantee: Any internal step of *this uberobject* can only read from/write to its own exclusive memory.

Rely: Any internal step of *other uberobjects* will never read from/write to this uberobject's exclusive memory.

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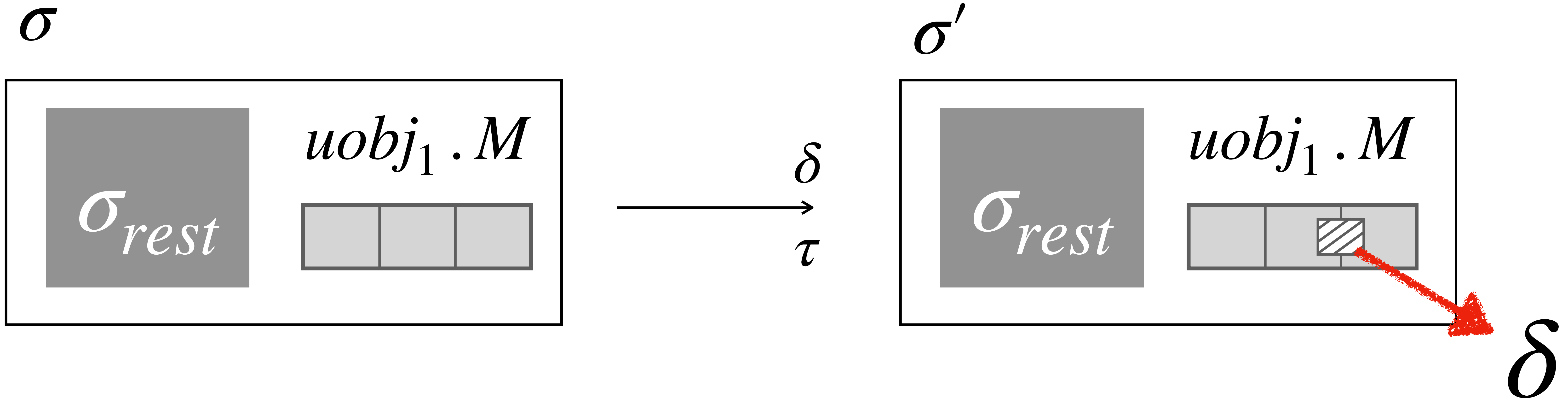
Requirement from a source-level compartment—Respecting the interface

Guarantee:
Internal steps



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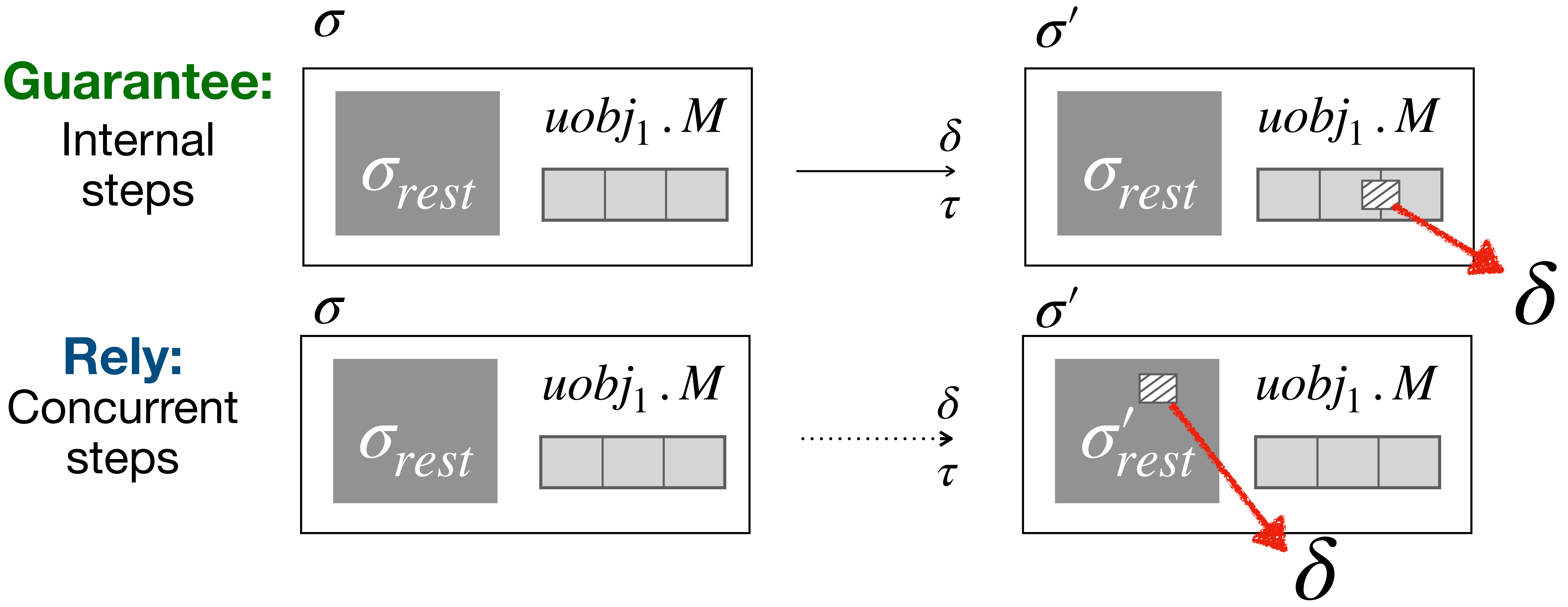

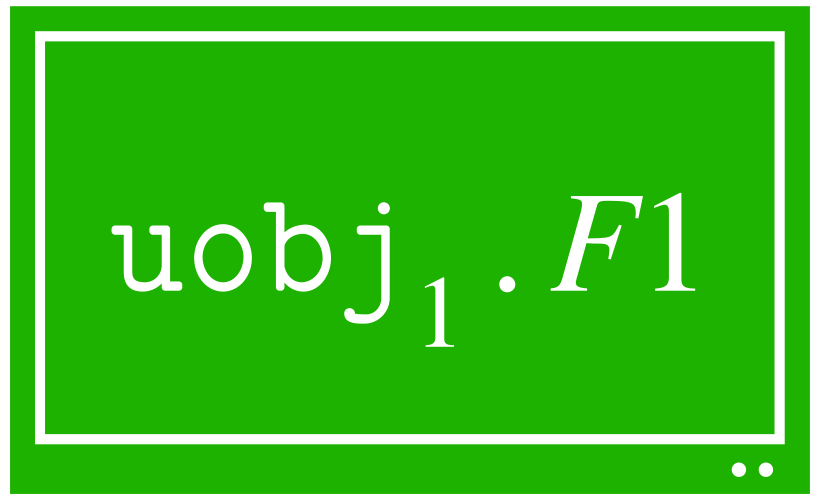

Verifying Pre and Post conditions—Respecting the interface

Guarantee:

1. If *this object calls* other uberobject’s public interfaces, it will satisfy their pre-condition.

2. When a function in *this uberobject terminates*, its post-condition holds.

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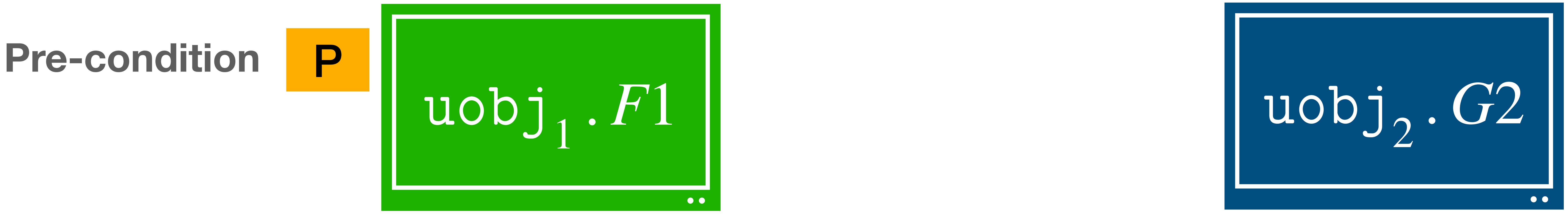

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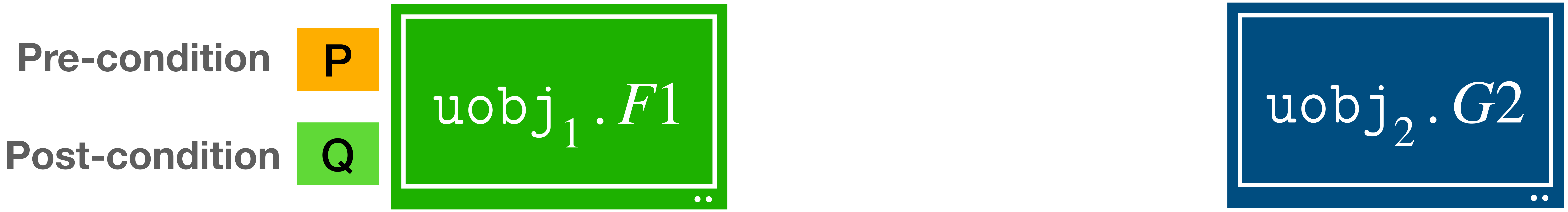

Pre-condition P

Post-condition Q

$\texttt{uobj}_1.F1$

$\texttt{uobj}_2.G2$

Verifying Pre and Post conditions—Respecting the interface

Guarantee:

1. If *this object calls* other uberobject’s public interfaces, it will satisfy their pre-condition.

2. When a function in *this uberobject terminates*, its post-condition holds.

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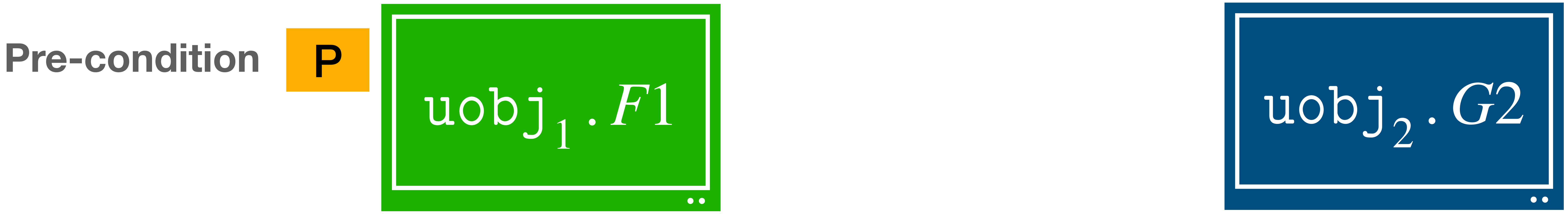

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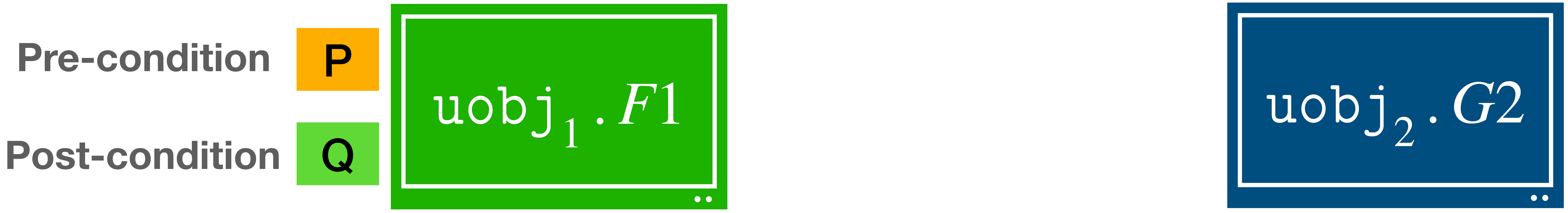

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Pre-condition P'

Post-condition Q'

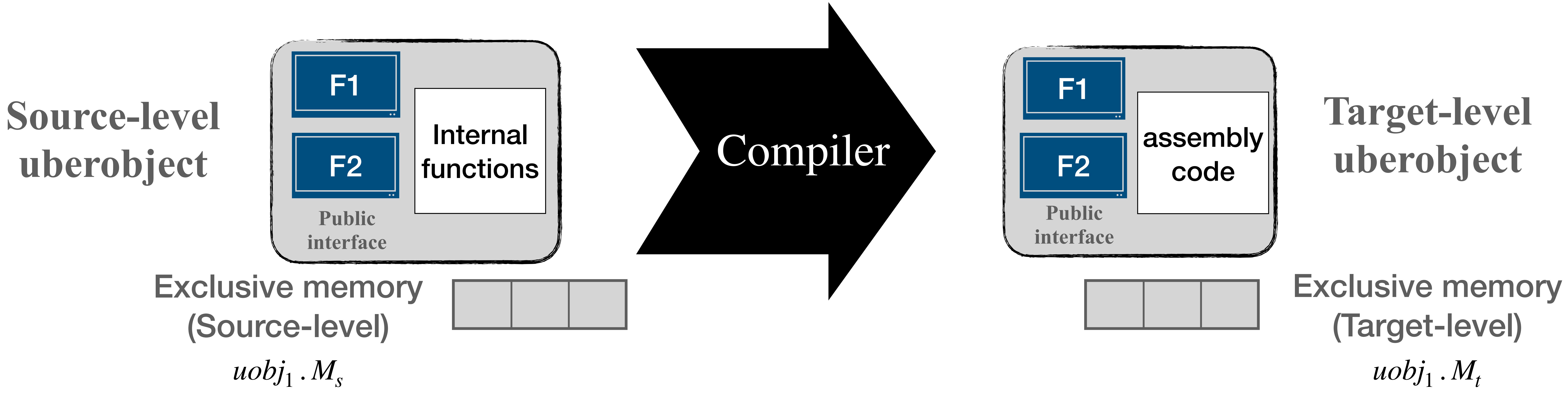
Verification result at the source-level:

If each uberobject in a system respects the interface, then:

- In any concurrent run, the **pre-conditions upon the call** and the **post-condition upon return** hold for all functions.
- Any concurrent execution is **data race free**, i.e., no two threads access a location concurrently when at least one of the accesses is a write.

Target-level guarantees via certified compilers — Preserving the interface —

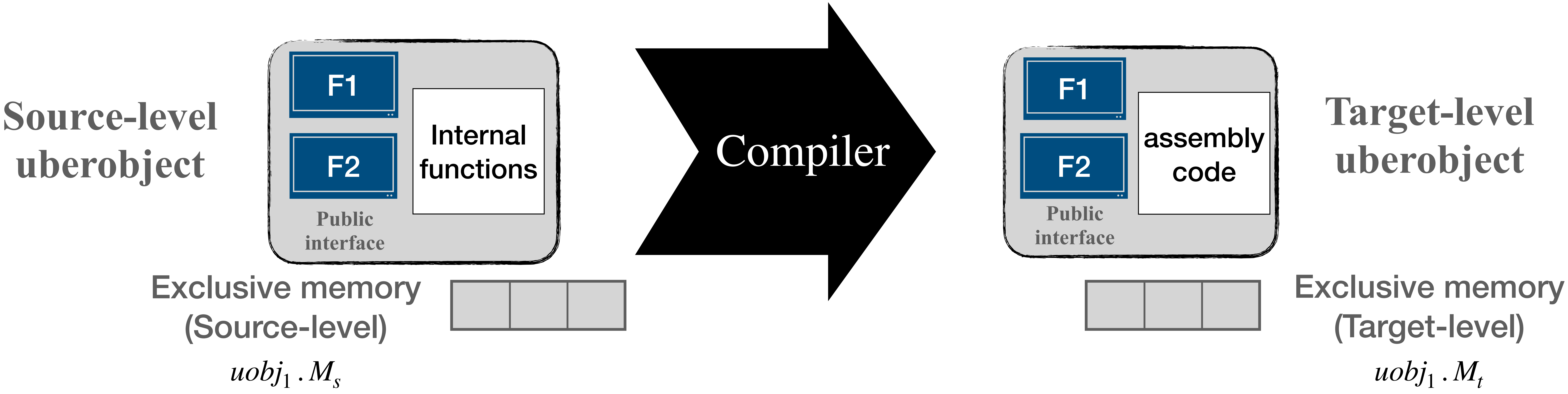
Requirement from a compiler—Preserving the interface



Requirement from a compiler—Preserving the interface

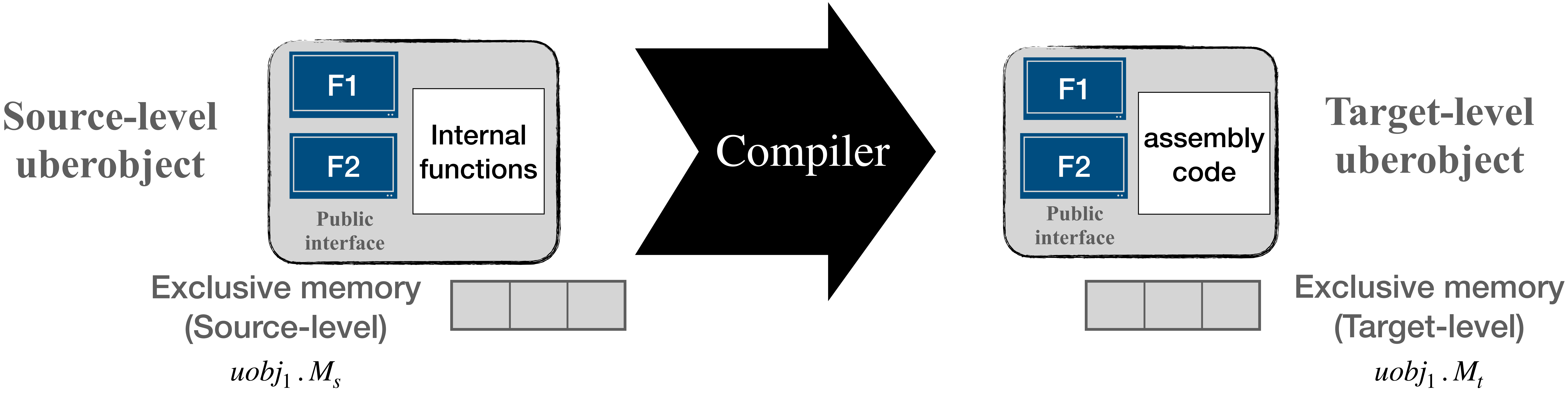
- Memory transformation function:

- Code transformation function:



Requirement from a compiler—Preserving the interface

- Memory transformation function:
  - **Well-defined: Total and injective on heap locations, and map source-level heap locations to target-level heap locations.**
- Code transformation function:



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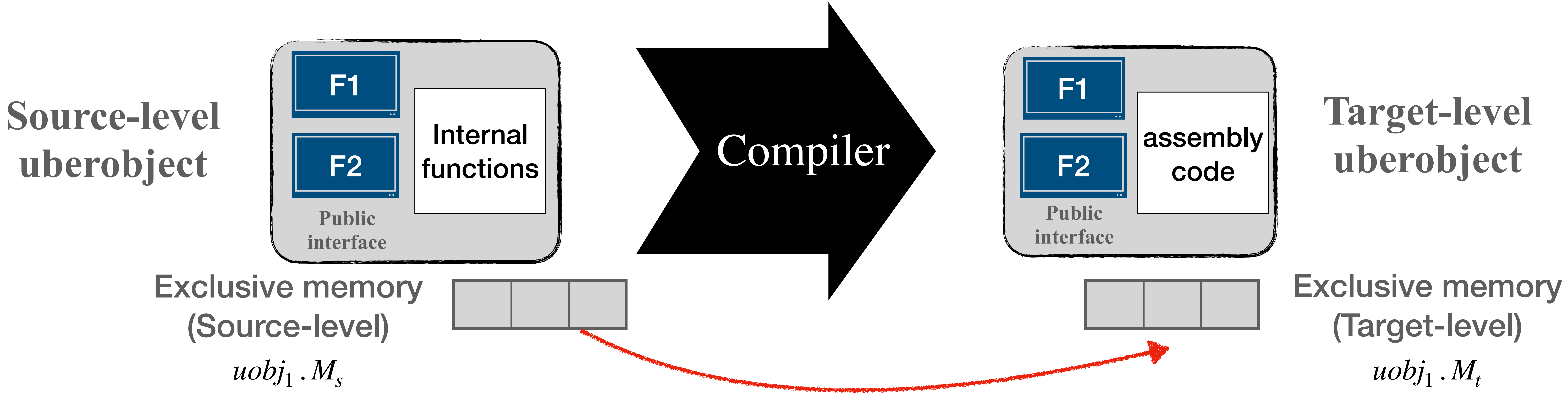


Source-level uberobject

F1

F2

Internal functions

Public interface

Exclusive memory (Source-level)

$uobj_1 . M_s$

Compiler

F1

F2

assembly code

Public interface

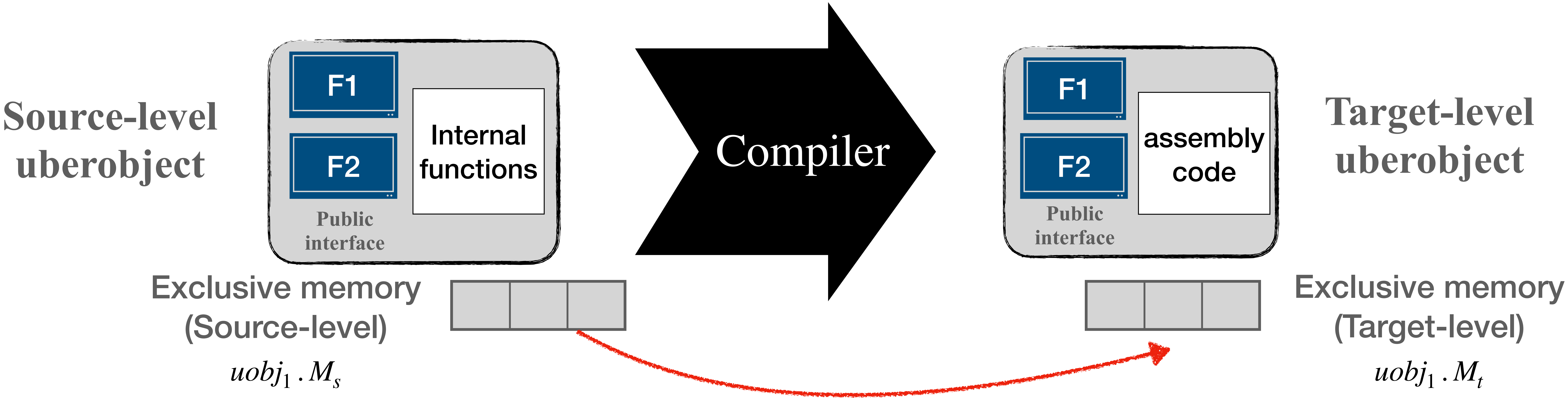
Target-level uberobject

Exclusive memory (Target-level)

$uobj_1 . M_t$

Requirement from a compiler—Preserving the interface

- Memory transformation function:
    - **Well-defined: Total and injective on heap locations, and map source-level heap locations to target-level heap locations.**
- Code transformation function:
    - **Interface-preserving: If an uobj respects the interface at the source level, then its compiled version respects the interface at the target level.**



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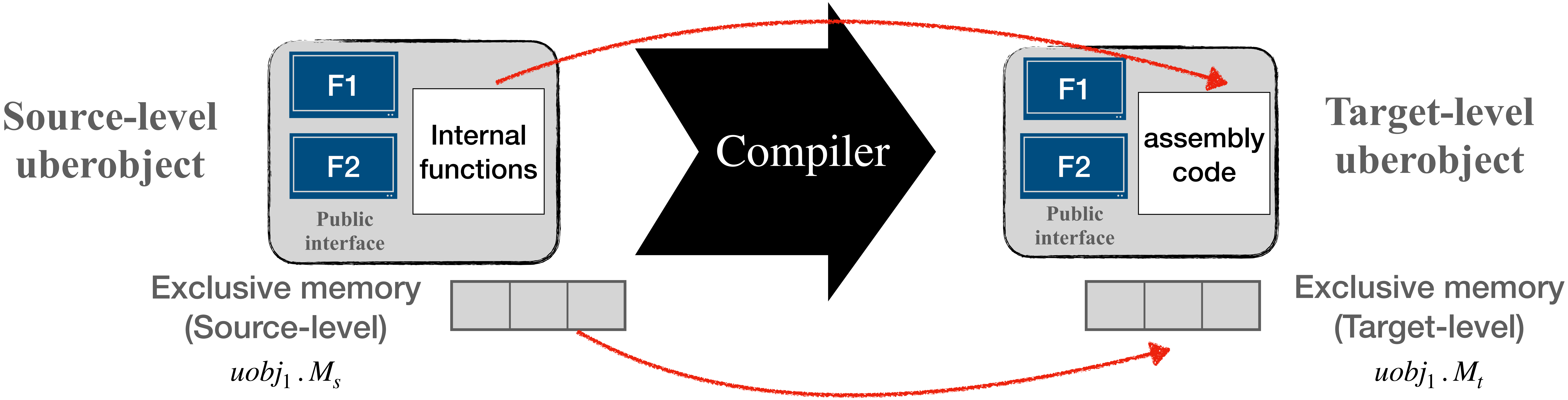


Target-level guarantees via interface preserving compilers

If each source-level uberobject in a system respects the interface and all compilers are interface-preserving, then

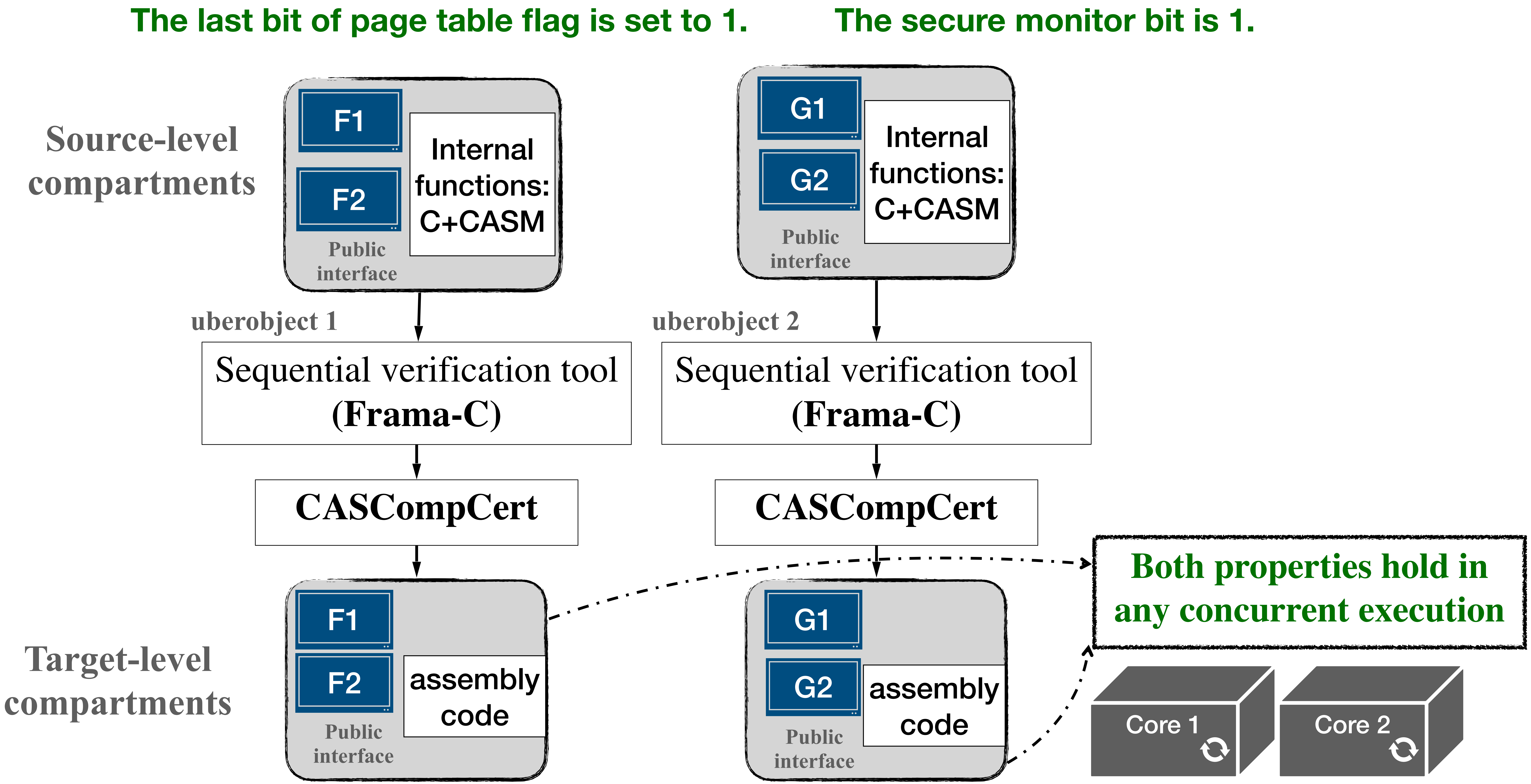
In any concurrent run at the target-level, the security properties hold:

All functions satisfy their post-conditions upon return.

CAS-Compcert is an interface-preserving compiler.

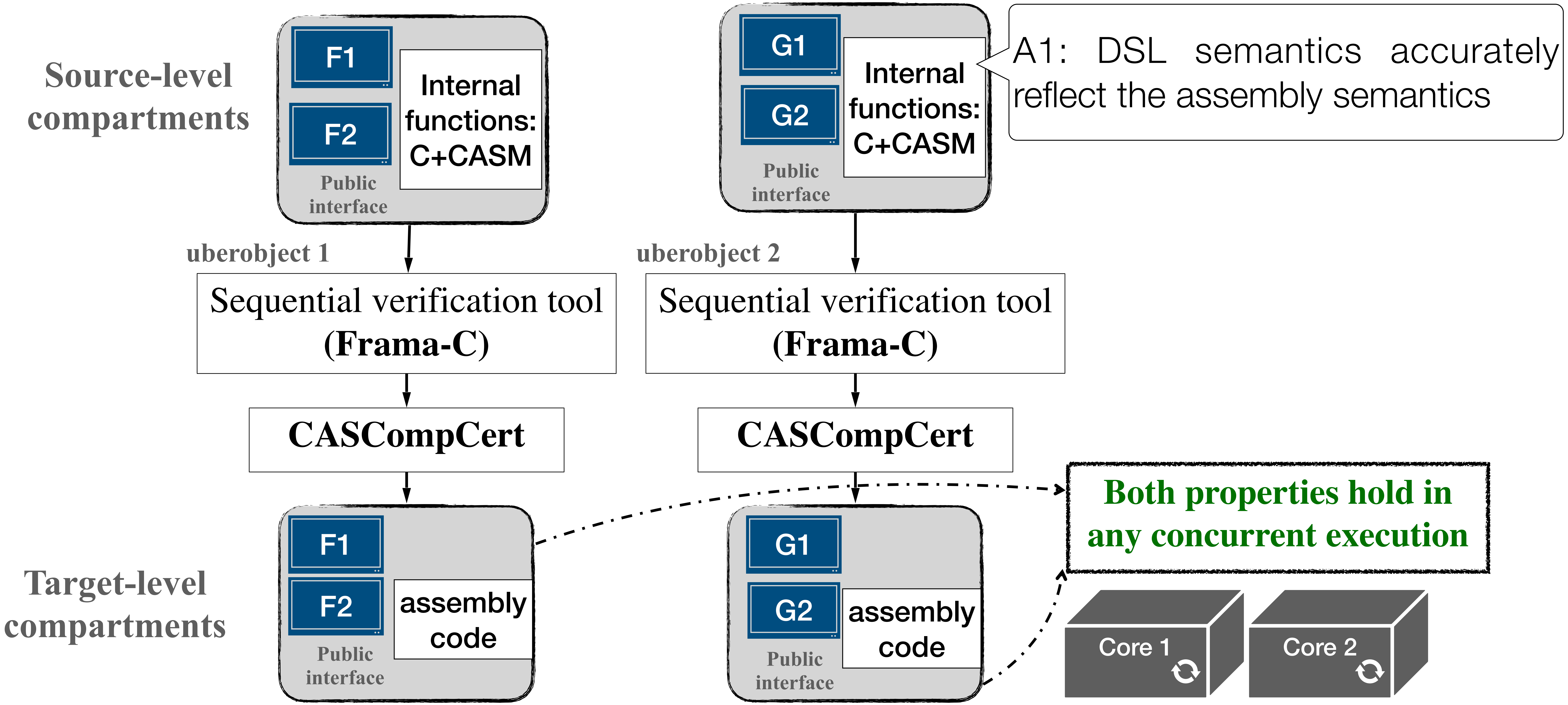
(PLDI'2019)

Our proposed tool-chain and its assumptions


The last bit of page table flag is set to 1.
The secure monitor bit is 1.
Source-level compartments
F1
F2
Internal functions: C+CASM
Public interface
G1
G2
Internal functions: C+CASM
Public interface
uberobject 1
uberobject 2
Sequential verification tool (Frama-C)
Sequential verification tool (Frama-C)
CASCompCert
CASCompCert
Both properties hold in any concurrent execution
Target-level compartments
F1
F2
assembly code
Public interface
G1
G2
assembly code
Public interface
Core 1
Core 2

Our proposed tool-chain and its assumptions

The last bit of page table flag is set to 1. **The secure monitor bit is 1.**



Source-level compartments
F1
F2
Internal functions: C+CASM
Public interface
G1
G2
Internal functions: C+CASM
Public interface
A1: DSL semantics accurately reflect the assembly semantics
uberobject 1
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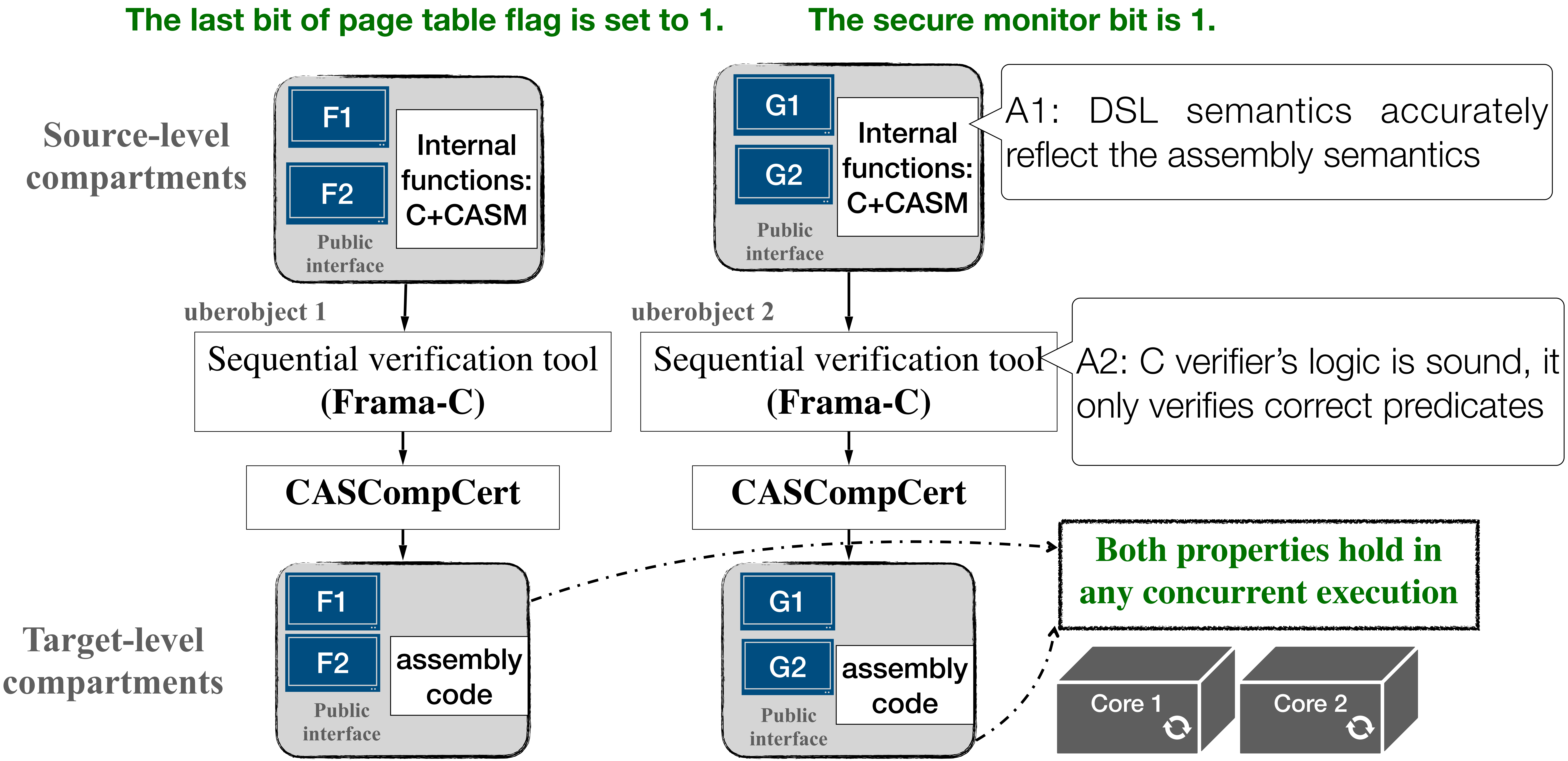

The last bit of page table flag is set to 1.

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A1: DSL semantics accurately reflect the assembly semantics

A2: C verifier's logic is sound, it only verifies correct predicates

Both properties hold in any concurrent execution

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F2
Internal functions: C+CASM
Public interface
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Our proposed tool-chain and its assumptions

The last bit of page table flag is set to 1.

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Source-level compartments

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F2

Internal functions: C+CASM

Public interface

G1

G2

Internal functions: C+CASM

Public interface

A1: DSL semantics accurately reflect the assembly semantics

uberobject 1

Sequential verification tool (Frama-C)

uberobject 2

Sequential verification tool (Frama-C)

A2: C verifier's logic is sound, it only verifies correct predicates

A3: C semantics used by the C analysis tool and the CASCompCert compiler agree.

CASCompCert

CASCompCert

Both properties hold in any concurrent execution

Target-level compartments

F1

F2

assembly code

Public interface

G1

G2

assembly code

Public interface

Case studies

➡ UberXMHF TEE: Open source micrphypervisor TEE (x86 32-bit hardware)

- An execution environment for an untrusted OS
- Verify the security property of guest memory separation: page table permissions bit is set correctly.

➡ Trustzone TEE: A light-weight open-source Trustzone TEE (ARM 32-bit)

- An execution environment for a simple guest OS running at the highest privilege level
- Verify correct setup to get guest memory separation: the secure monitor mode is set correctly.

Related work

➡Verified TEEs

- Sel4 - S&P'2013
- CertiKOS - USENIX OSDI'2016
- XMHF - S&P '2013
- uberXMHF - USENIX Security '2016
- Security MIcrovisor - TDSCM '2019
- Contiki - DDECS '2015

➡Certified compilers:

- CASCompCert - PLDI'2019 , …

➡Compartmentalization:

- Secure Compartmentalizing compilation (SCC) - CSF'2016
- Robustly Safe Compartmentalizing Compilation (RSCC) - CCS'2018
- CHERI compartmentalization - SP '2015

Conclusion

➡ Summary:

- Compartmentalization for implementing TEEs enables us to:
    - achieve compositional verification results at the source level, and
    - leverage certified compilers to preserve the guarantees at the target level.
- Two case studies

➡ What else is in the paper?

- DSL semantics for assembly
- Interrupts
- Noninterference

Our proposed tool-chain and its assumptions

The last bit of page table flag is set to 1 (after function return)

The secure monitor bit is 1 (after function return)

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Internal functions: C+CASM

Public interface

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