überSpark

Enforcing Verifiable Object Abstractions for Automated Compositional Security Analysis of a Hypervisor

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http://uberspark.org

Problem

- Extensible Hypervisors raise significant security concerns
  - Number of bugs goes up with code size
  - Number of bugs goes up with frequency of updates
  - Number of bugs goes up with logical complexity
  - Number of bugs goes up with control-flow complexity
- Both complex VMMs and micro-hypervisors are prone to bugs
  - E.g., VMware [VMSA-2009-006,Cloudburst], Xen [CVE-2008-3687], SecVisor [Franklin et. Al,2010]

- Verified hypervisor is accompanied by proof of desirable (security) properties

Why aren't we already doing this?

- Cost of verification grows with
  - The size of the code-base
  - The number of separate components
  - The number of configurations
  - The rate of revisions
- Benefit of verification shrinks with
  - Steep learning curve of developer-unwieldy programming
  - Lack of commodity hardware integration
  - Magnitude of the runtime overhead

Compositionality

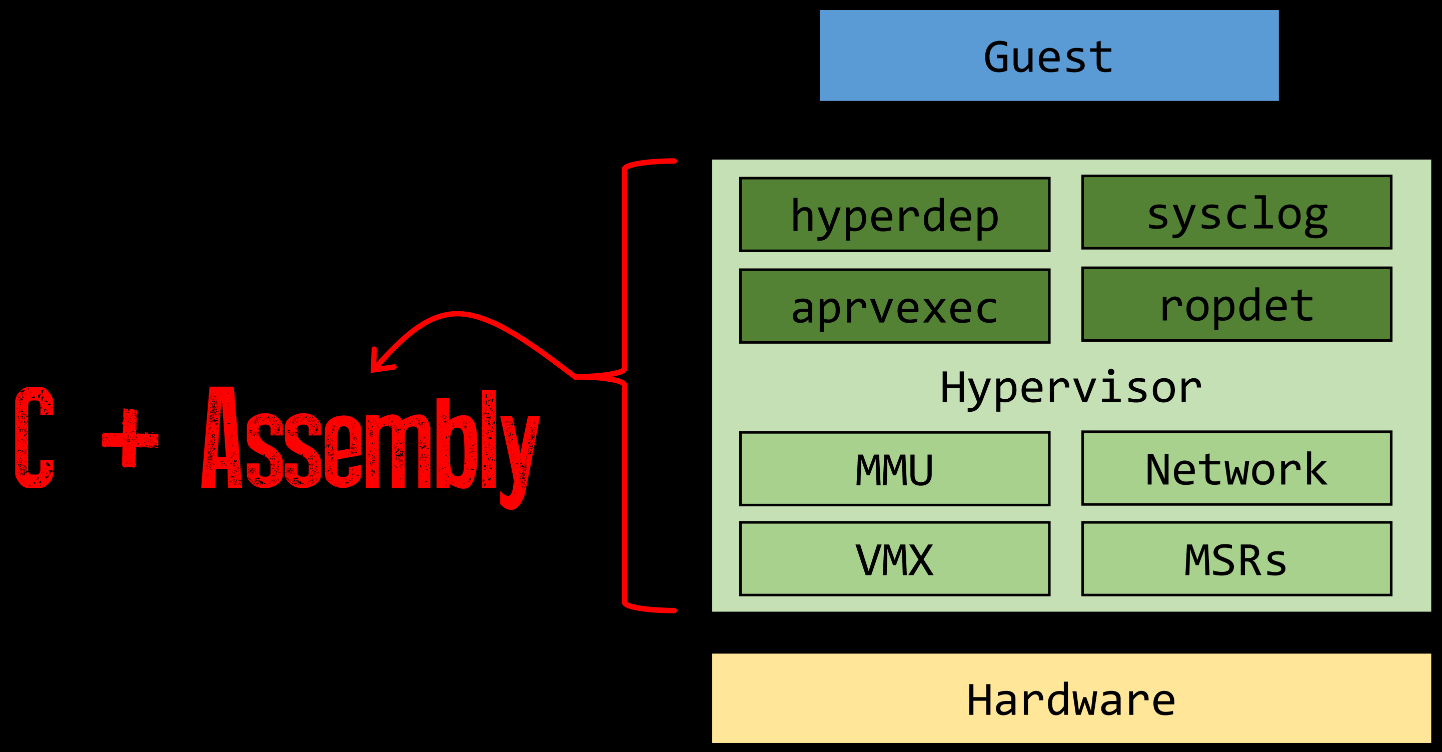
Commodity Compatibility

Performance

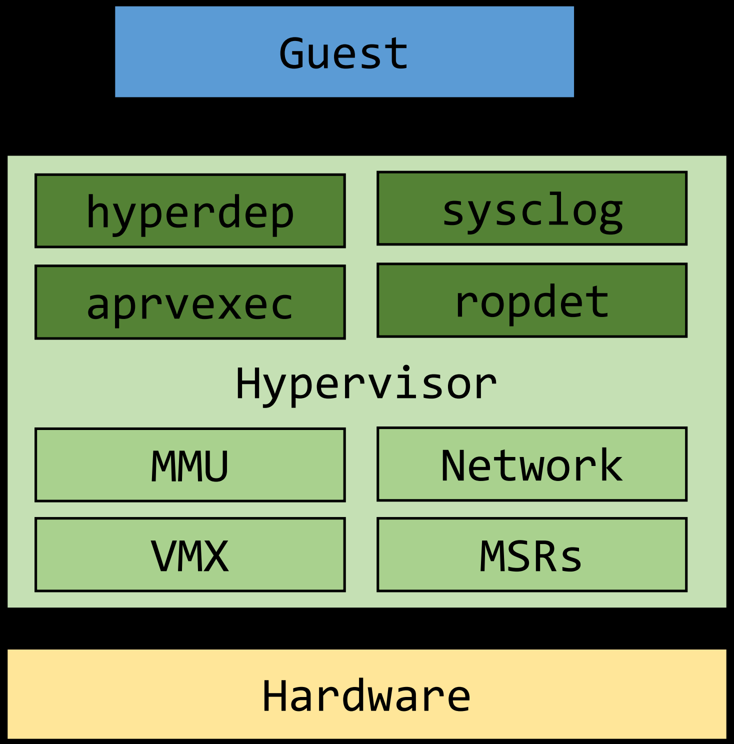
Why do this now?

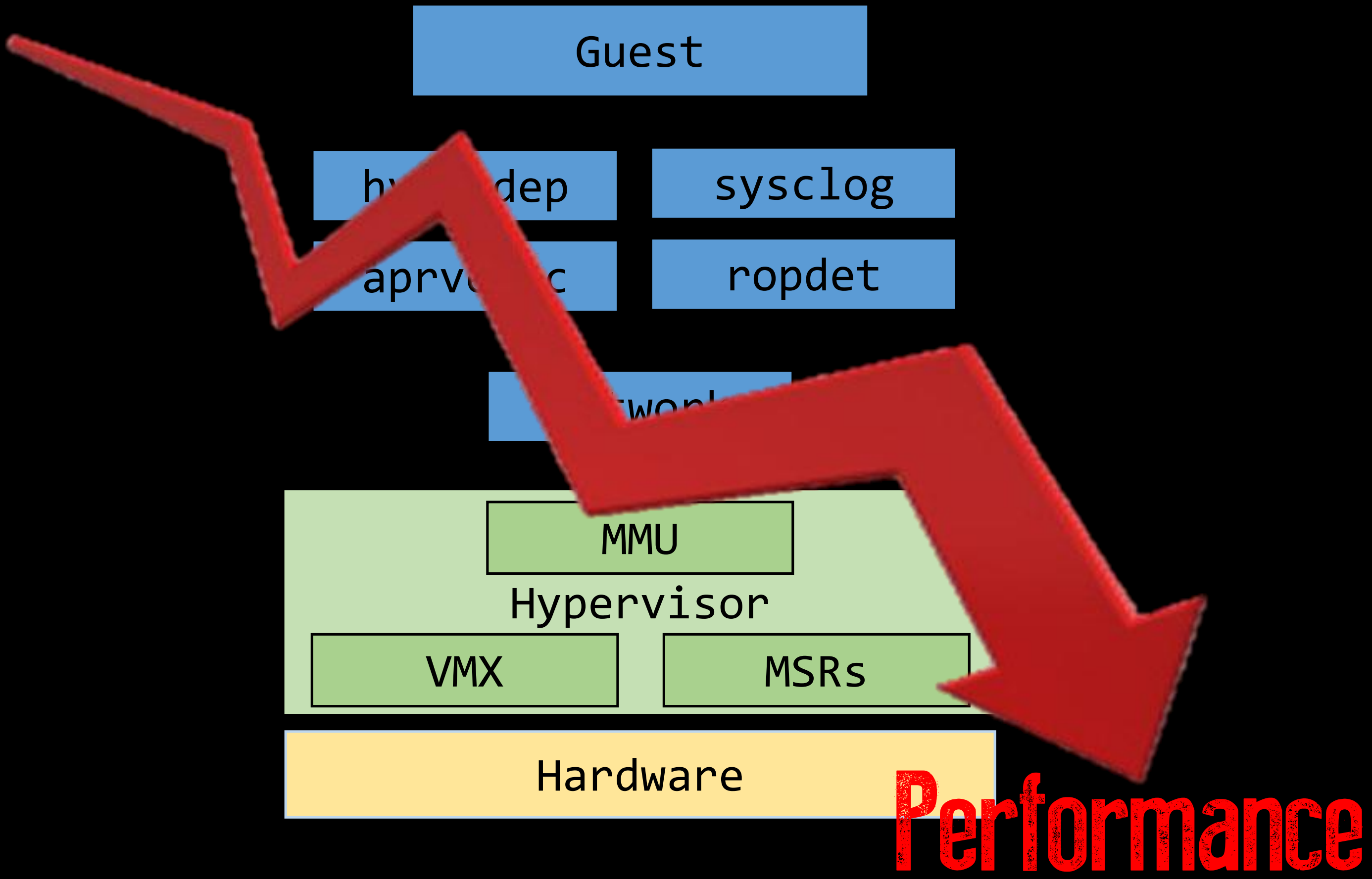
- Formal C static analysis tools are very practical [Frama-C]
- Certifiable compilation tools [Compcert] are practical for moderate module sizes
- It's trendy! [seL4, IronClad, IronFleet, FSCQ, mCertiKOS]

An extensible hypervisor

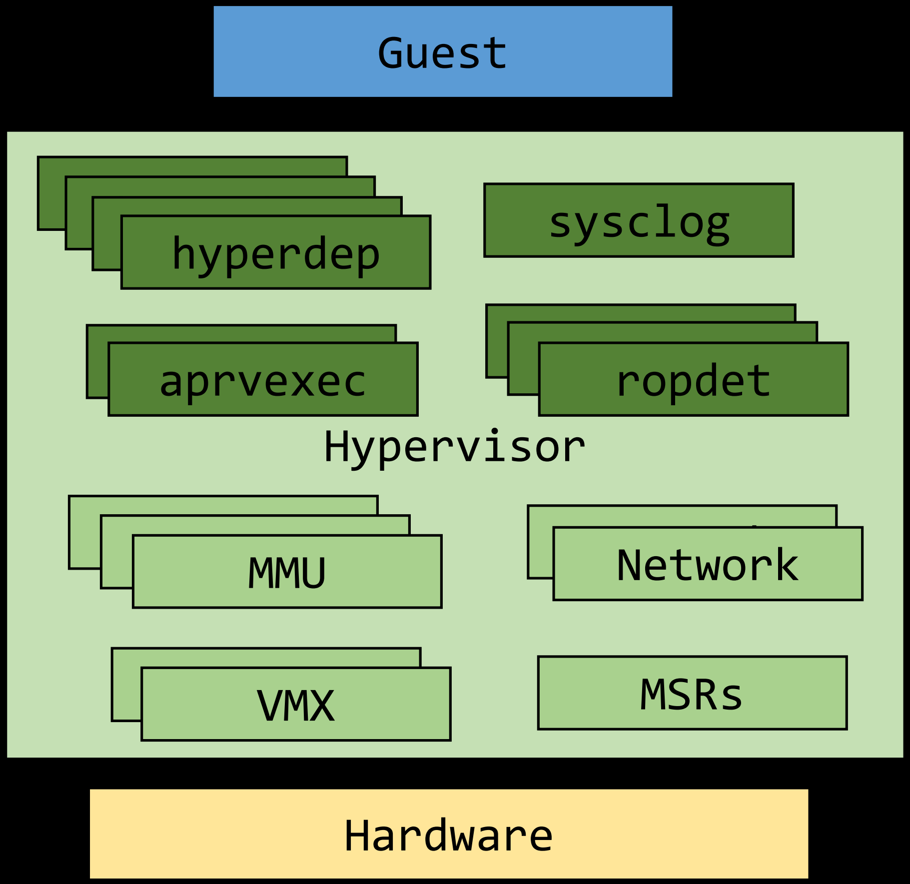


Challenge-1: Code size vs. HW de-privileging

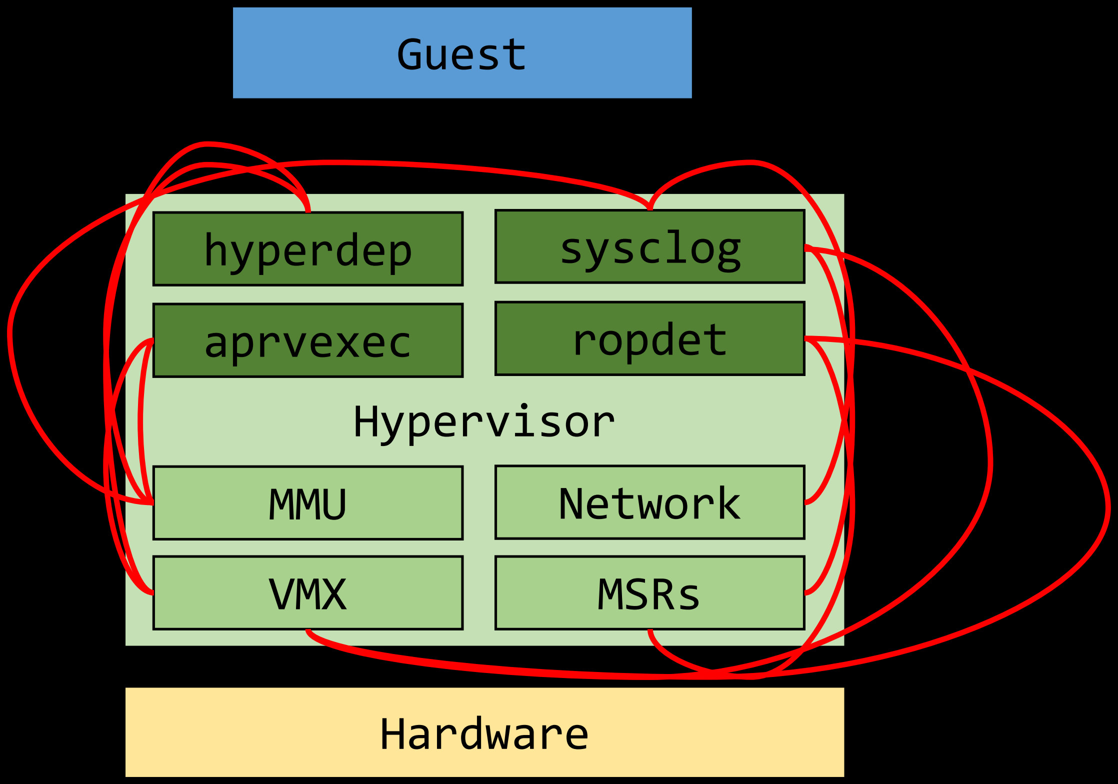




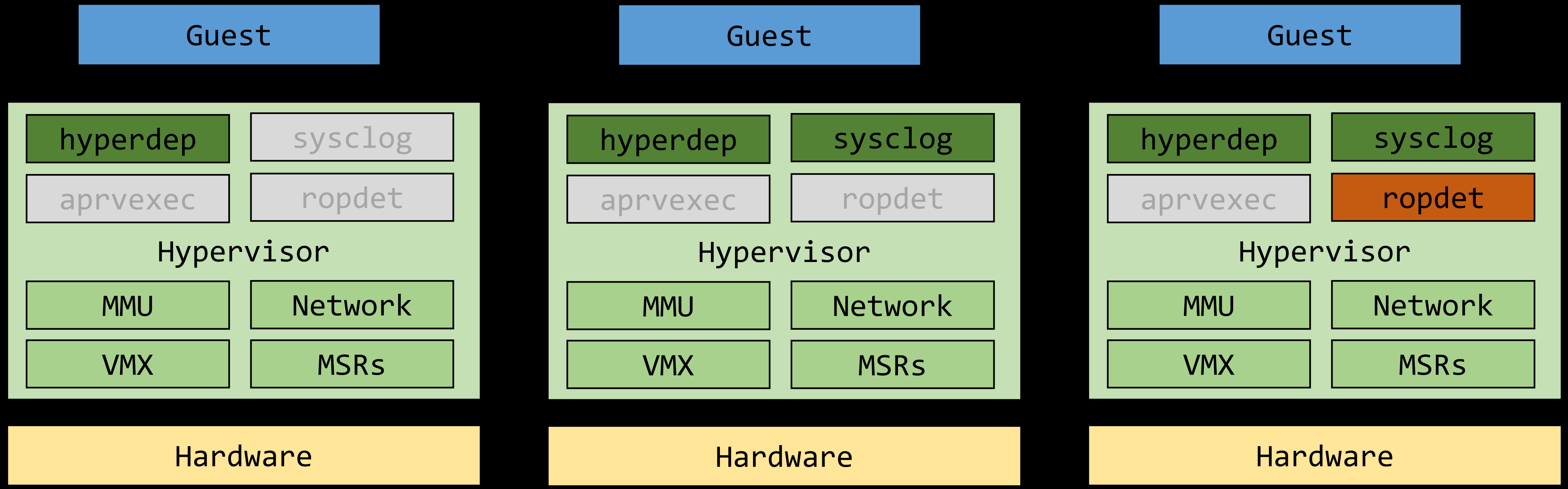
Challenge-2: Continuous Development



Challenge-3: Shared Resources

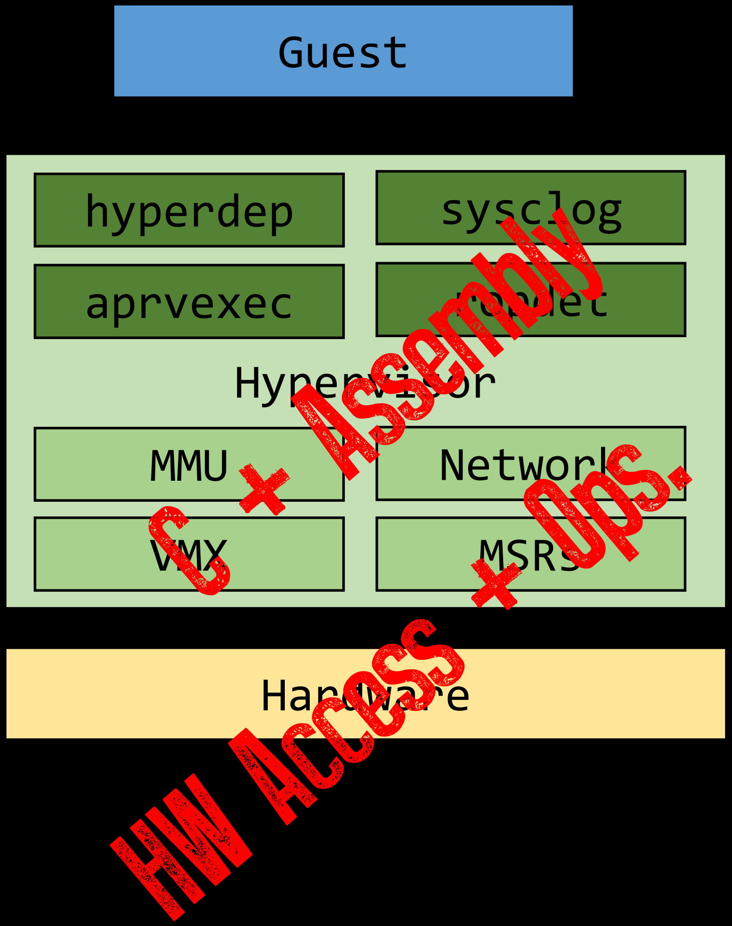


Challenge-4: Different Configurations



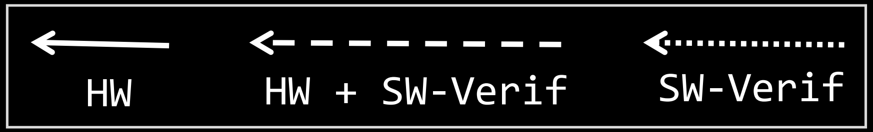
Challenge-5: Verification vs. Programming Paradigm

- Programming Paradigm
  - C + Assembly is de-facto
  - C + Assembly can clobber stuff! [stack, registers, MSRs etc.]
  - HW access and ops. with multi-core
- State-of-the-art Verification Tools
  - Often impose use of “developer-unwieldy” high-level languages with steep learning curve [Coq, Haskell, Dafny]
  - Largely lack support for Assembly
  - Mainly target sequential code
  - Largely lack support for HW integration



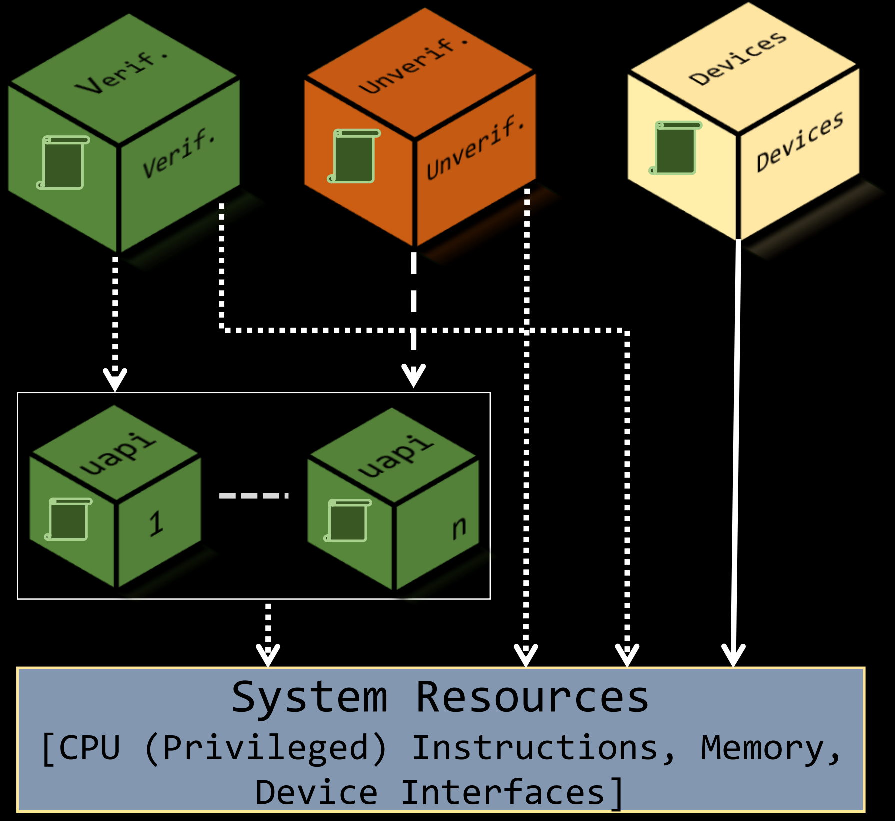
überSpark from above

- Goals
  - Compositionality
  - Commodity Compatibility
  - Performance
- Verifiable Object Abstraction (uberObject)
  - Security invariants
  - Commodity HW + Software Verification

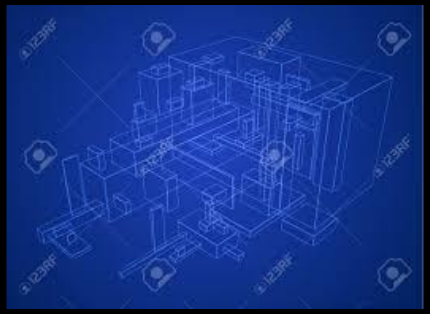


ÜberObjects

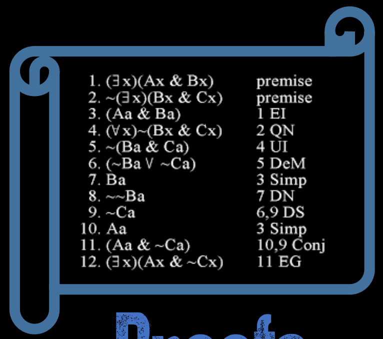
[C + Assembly + ACSL]



ÜBlueprint



+

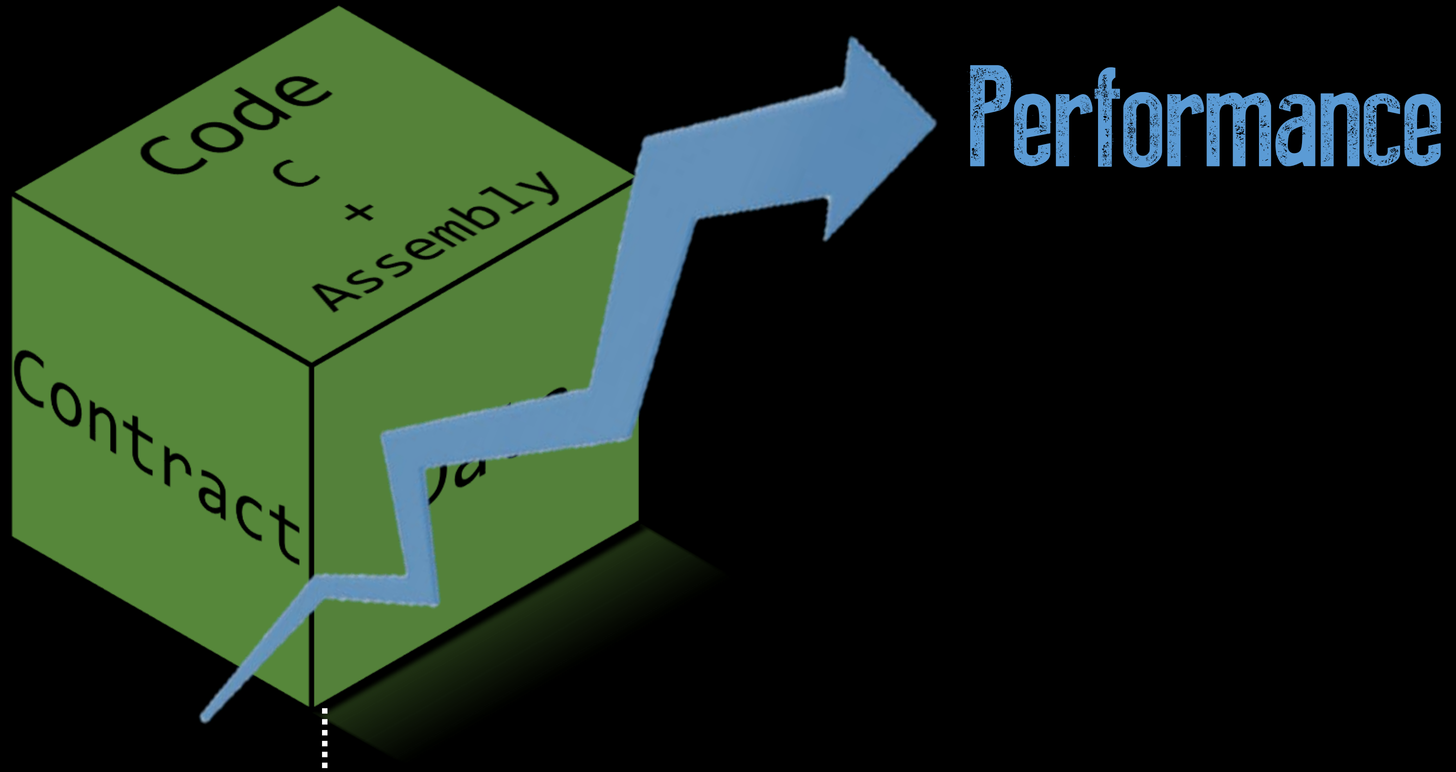


Proofs

The überObject

Contract

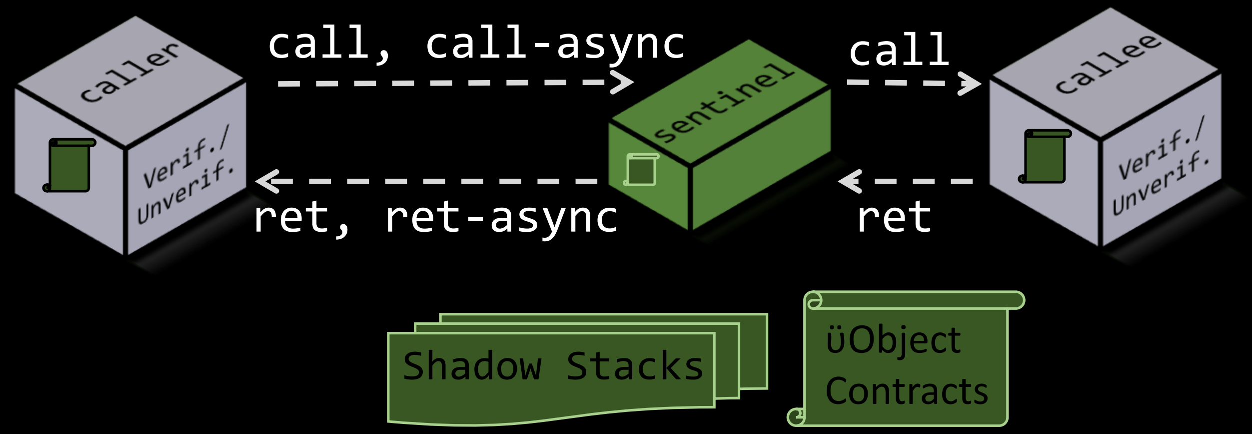
Use Manifest
+
Behavior Specifications in C-like language



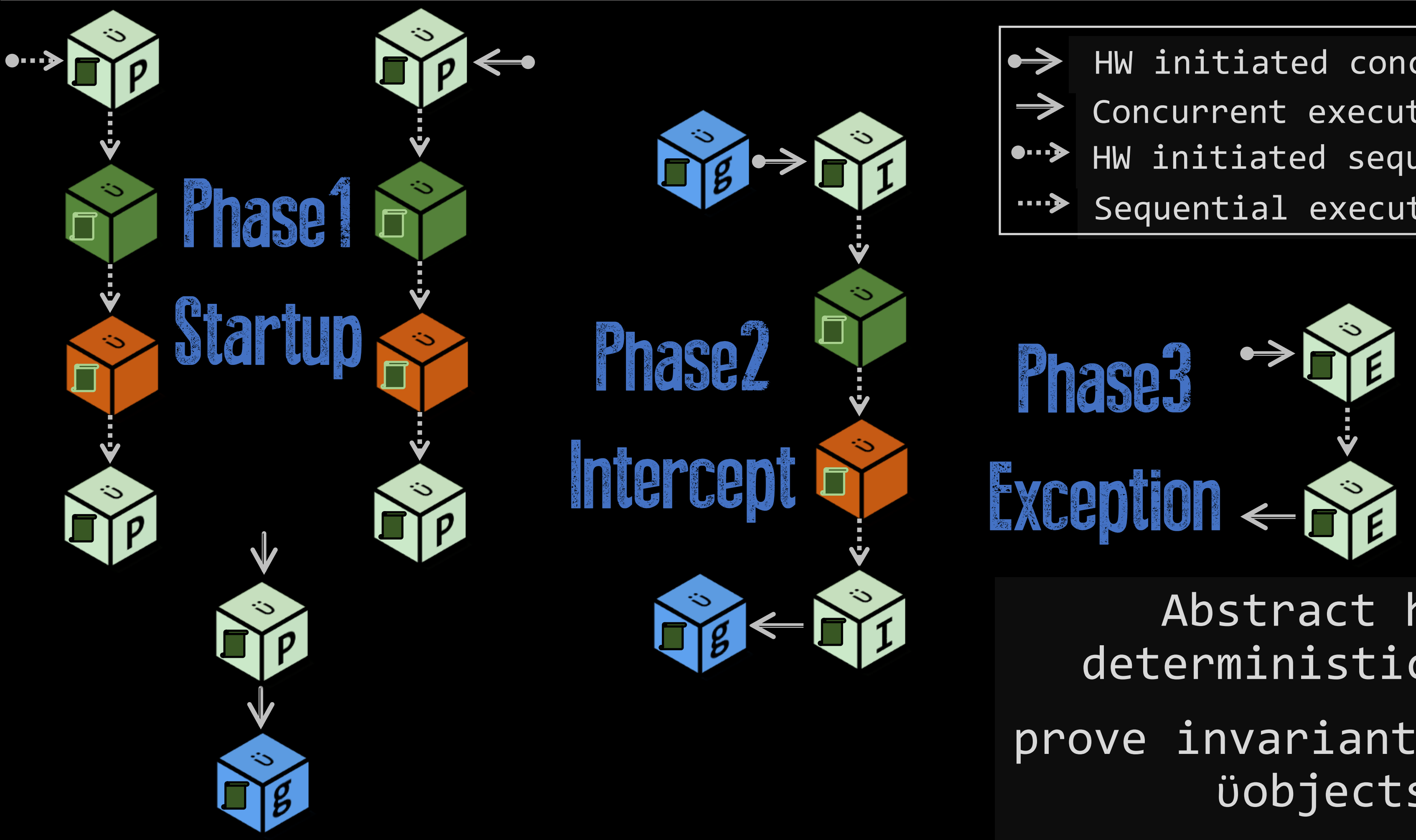
System Resources
[CPU (Privileged) Instructions, Memory, Device Interfaces]

überObject: Sentinel

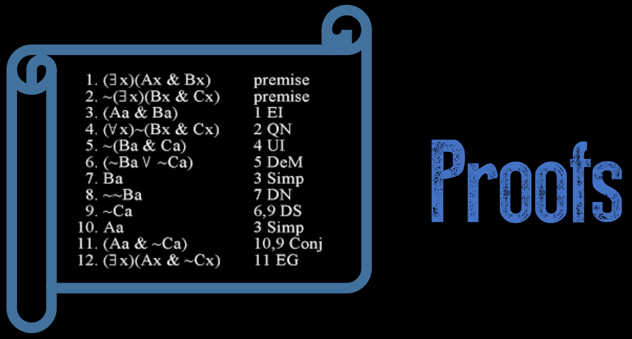
- Sentinel
  - Establishes “call-ret” semantics
  - Object to object control-flow enforcer
- überObjects verified not to write on other stack frames
- Enables sound application of sequential source code verification to verify invariants over sequential überobject invocations



überBlueprint & Concurrency



- HW initiated concurrent execution
- Concurrent execution
- HW initiated sequential execution
- Sequential execution



Abstract hypervisor as a non-deterministic sequential program ➔

prove invariant properties of individual üobjects and compose them

überObject: CASM Functions & HW Model

- CASM Functions
  - C functions composed solely of Assembly
  - (Any) Assembly instruction as macro
- HW model specifies semantics
- Custom Frama-C verification plugins
  - Inline C99 semantics to verify
  - Inline Assembly to compile down

```
void gp_setup_vhmempgtbl(void){
  u32 i, spatype, slabid=XMHF_SLAB_PRIME;
  u64 flags; ...
void casm_writecr3(u32 value){
  ci_movl_mesp_eax(0x4);
  ci_movl_eax_cr3();
  ci_ret();
}
    vhpgtbl1t[i] = pae_make_pte((i*SZB_4K),flags);
  } ...
  casm_writecr3(vhsmpgtbl4t[0]);
}
```

CASM Instructions

CASM Function

überObject: Coding and Behavior Specification

- C99 + CASM (principled Assembly)
- ANSI C Specification Language (ACSL)
  - requires/assigns/ensures
- Hoare triple proven automatically via Frama-C
  - deductive verification plugins
  - ensemble of SMT solvers

```
//@ghost u64 gflags[SZ_PDPT*SZ_PDT*SZ_PT];
/*@ ...
  requires \valid(vhpgtbl1t[0..(SZ_PDPT*SZ_PDT*SZ_PT)-1]); ...
  assigns vhpgtbl1t[0..(SZ_PDPT*SZ_PDT*SZ_PT)-1]; ...
  ensures (\forall u32 x;  0 <= x < SZ_PDPT*SZ_PDT*SZ_PT ==>
          ((u64)vhpgtbl1t[x] == (((u64)(x*SZB_4K)
          &  0x7FFFFFFFFFFFF000ULL) | (u64)(gflags[x]))));
@*/
void gp_setup_vhmempgtbl(void){
  u32 i, spatype, slabid=XMHF_SLAB_PRIME;
  u64 flags; ...
  /*@ loop invariant 0 <= i <= (SZ_PDPT*SZ_PDT*SZ_PT); ... @*/
  for(i=0; I < (SZ_PDPT*SZ_PDT*SZ_PT); ++i){
    spatype=_gp_getspatype(slabid, (u32)(i*SZB_4K));
    flags=_gp_getptflags(slabid, (u32)(i*SZB_4K),spatype);
    //@ghost gflags[i] = flags;
    vhpgtbl1t[i] = pae_make_pte((i*SZB_4K),flags);
    /*@assert vhpgtbl1t[i] == (((u64)(i*SZB_4K)
       & 0x7FFFFFFFFFFFF000ULL) | (u64)(gflags[i]))); @*/
  } ...
  casm_writecr3(vhsmpgtbl4t[0]);   } CASM function
}
```

überObject: Resource Interface Confinement

- überAPI überobjects
  - Wrap a reference monitor around (shared) resource
  - MMU, IOMMU, CRs, MSRs, Devices
- Client object manifests how it will use a (shared) resource
  - Verified on client via assertions
- During integration
  - Use manifests combined into one formula
  - SMT solvers check composability

überObject: Summary

- C99 + CASM + ACSL behavior specifications and behavior restrictions
- Object invariants including basic memory safety and control-flow integrity and other properties that can be formulated as invariants
- Architecture ensures invariant composition
- **Mind-Blow #1: Only need to worry about object behavior now – not implementation**
- **Mind-Blow #2: A compositionally verifiable C + Assembly system without hardware de-privileging**

An über Micro-Hypervisor (üXMHF)

- XMHF micro-hypervisor (http://xmhf.org)
  - Core hypervisor + single extension (hypapp)
  - Ubuntu 12.04 32-bit SMP on Intel VT-x/AMD
  - Various hypapps
    - tracing, attestation, app-level integrity, trusted path etc.
- üXMHF
  - Multiple extensions
  - Ubuntu 12.04 32-bit SMP on Intel VT-x
  - 11 überobjects, 7001 SLoC including prime and sentinel
  - Took ~3 person months for refactoring

üXMHF Verification Results

- Verification Tools TCB
  - Frama-C, uberSpark Plugins (1021 SLoC), SMT Solvers (Z3, CVC3, Alt-ergo), HW Model (2079 SLoC)
- Security Invariants in core Hypervisor and Extensions
  - memory-safety, control-flow integrity, no direct writes to hypervisor memory by guest, DEP, guest syscalls n/w logging etc.
- Verification Metrics
  - 11 überobjects, 5544 SLoC total ACSL annotations
  - Annotation to code ratio 0.2:1 to 1.6:1
  - überobject verification times from 48s to 23 min; cumulative ~1hr
  - Took ~9 person months

üXMHF: Micro & Application Benchmarks

- Sentinel transfer cost

Verified-Verified	Verified-Unverified / Uverified-Verified			
	SEG	CR3	TSK	HVM
2x	37x	48x	70x	278x

- üXMHF vs. vanilla XMHF
  - Verified hypapps (2% avg. overhead)
  - Unverified hypapps (10% avg. overhead)
  - I/O and normal Guest performance unaffected!

So, what do we have here?

- Can prove behavior one object at a time (trace properties)
- Can compose modules and behaviors cheaply
- Can write system code in "basically" C and Assembly and behavior specifications in C-like specification language
- Can integrate HW accesses and states into verification
- Can execute with good runtime performance

Goals

- Compositionality
- Commodity Compatibility
- Performance

So, what don't we have, yet?

- Not "exactly" C99 + Assembly; no cowboy control flow craziness
  - God forbid no C++
- Compcert + CASM proofs
  - Semantic compatibility between Frama-C, Compcert and CASM
- HW Model to Assembly instructions refinement
- Full functional correctness
- Concurrent verification
- Broader applicability
  - Other hypervisors (Xen, KVM), BIOS, Device firmware, OS Kernel and Drivers, User-space Applications and Browser Extensions

Questions?

überSpark

http://uberspark.org

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