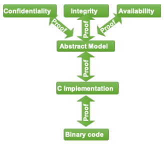
School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2019 T2 Week 09b

Local OS Research

@GernotHeiser



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Quantifying Security Impact of Operating-System Design

Quantifying OS-Design Security Impact

Approach:

- Examine all ***critical*** Linux CVEs (vulnerabilities & exploits database)
  - easy to exploit
  - high impact
  - no defence available
  - confirmed

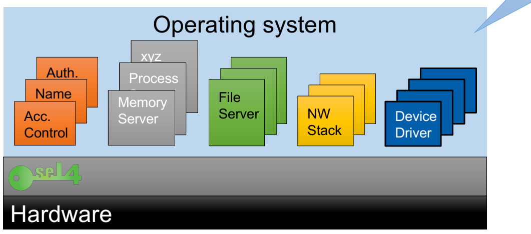
115 critical Linux CVEs to Nov'17

- For each establish how microkernel-based design would change impact

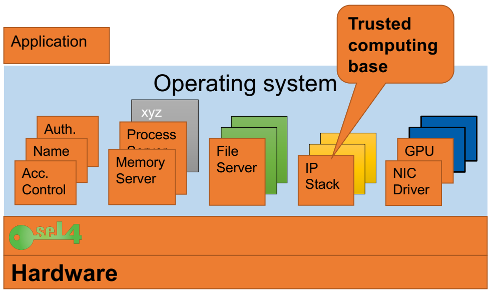
seL4 Hypothetical seL4-based OS

OS structured in *isolated* components, minimal inter-component dependencies, *least privilege*

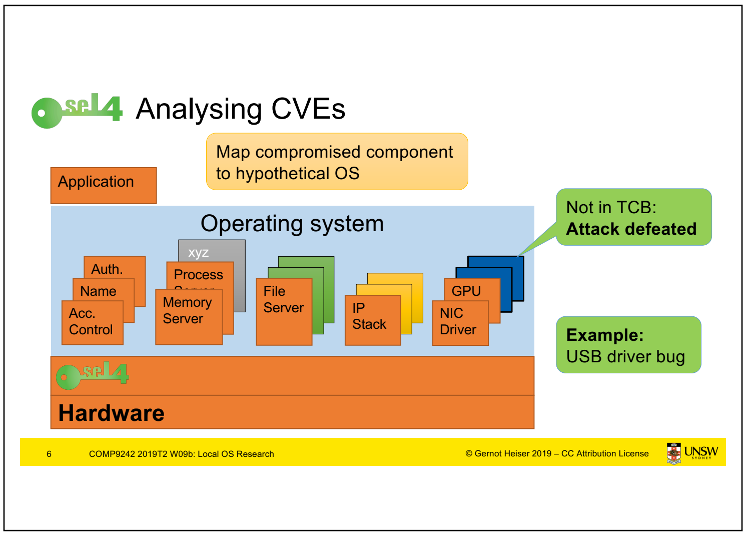
Functionality comparable to Linux



seL4 Hypothetical Security-Critical App



App requires:
- IP networking
- File storage
- Display output



Analysing CVEs

Map compromised component to hypothetical OS

Application

Operating system

Auth.
Name
Acc. Control

xyz
Process
Memory Server

File Server

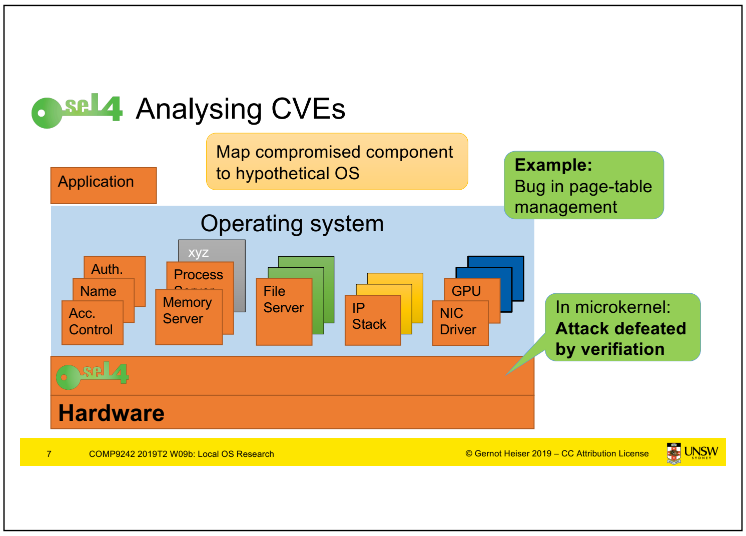
IP Stack

GPU
NIC Driver

Hardware

Not in TCB:
Attack defeated

Example:
USB driver bug



Analysing CVEs

Map compromised component to hypothetical OS

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Memory Server

File Server

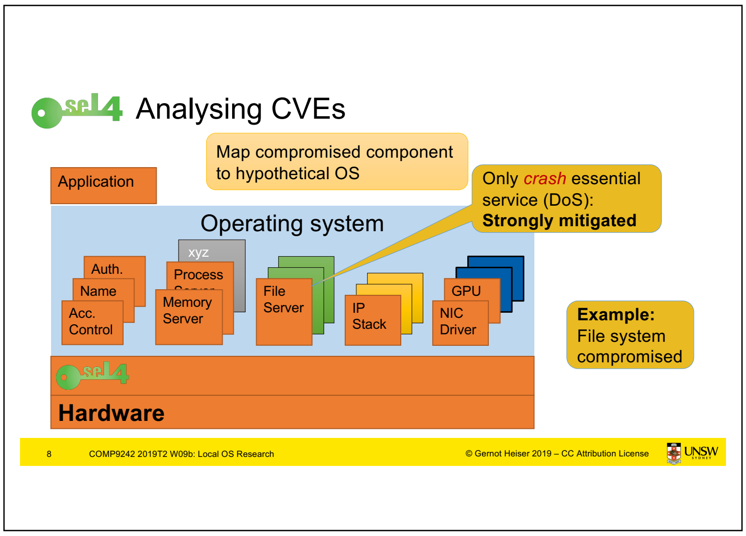
IP Stack

GPU
NIC Driver

Hardware

Example:
Bug in page-table management

In microkernel:
Attack defeated by verifiation



Analysing CVEs

Map compromised component to hypothetical OS

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Auth.
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Memory Server

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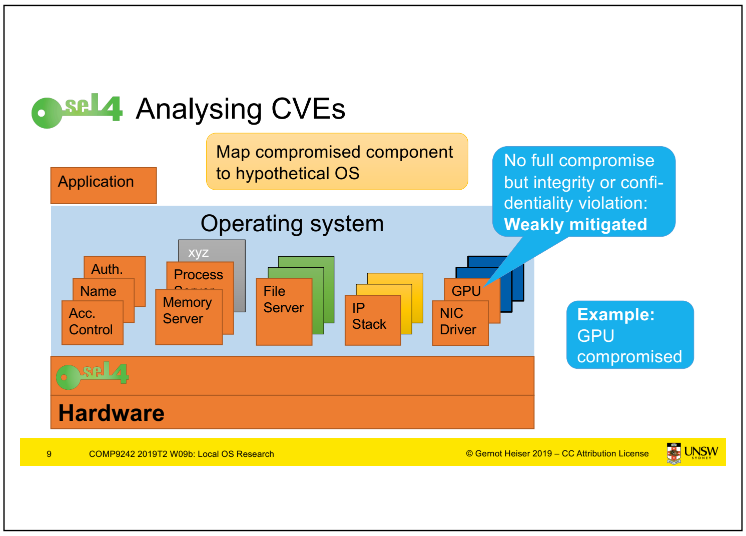
IP Stack

GPU
NIC Driver

Hardware

Only *crash* essential service (DoS):
Strongly mitigated

Example:
File system compromised



Analysing CVEs

Map compromised component to hypothetical OS

Application

Operating system

Auth.
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xyz
Process
Memory Server

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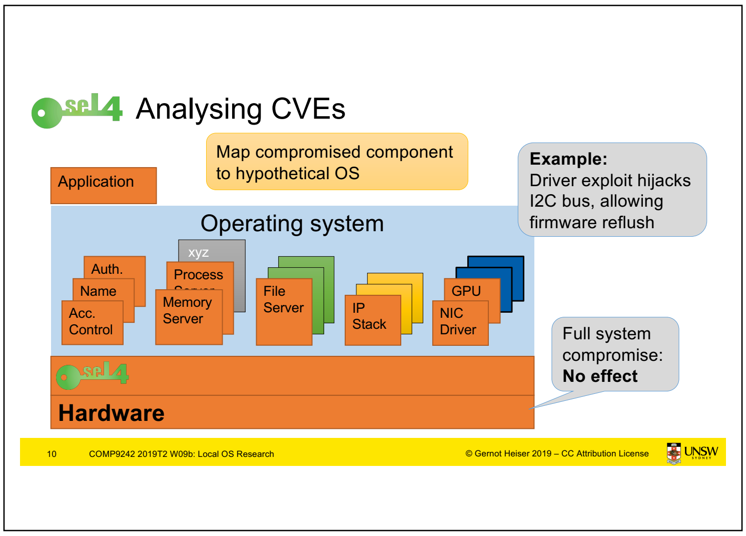
IP Stack

GPU
NIC Driver

Hardware

No full compromise but integrity or confidentiality violation:
Weakly mitigated

Example:
GPU compromised



Analysing CVEs

Map compromised component to hypothetical OS

Application

Operating system

Auth.
Name
Acc. Control

xyz
Process
Memory Server

File Server

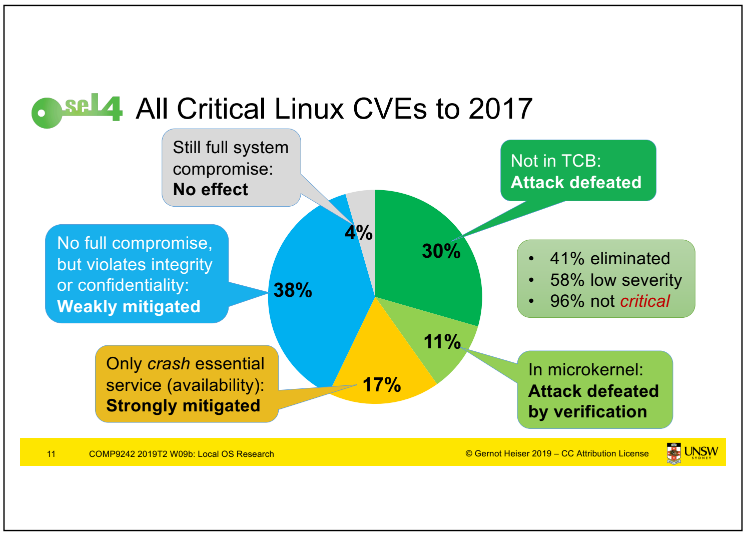
IP Stack

GPU
NIC Driver

Hardware

Example:
Driver exploit hijacks I2C bus, allowing firmware reflush

Full system compromise:
No effect



All Critical Linux CVEs to 2017

Still full system compromise:
No effect

4%

Not in TCB:
Attack defeated

30%

No full compromise, but violates integrity or confidentiality:
Weakly mitigated

38%

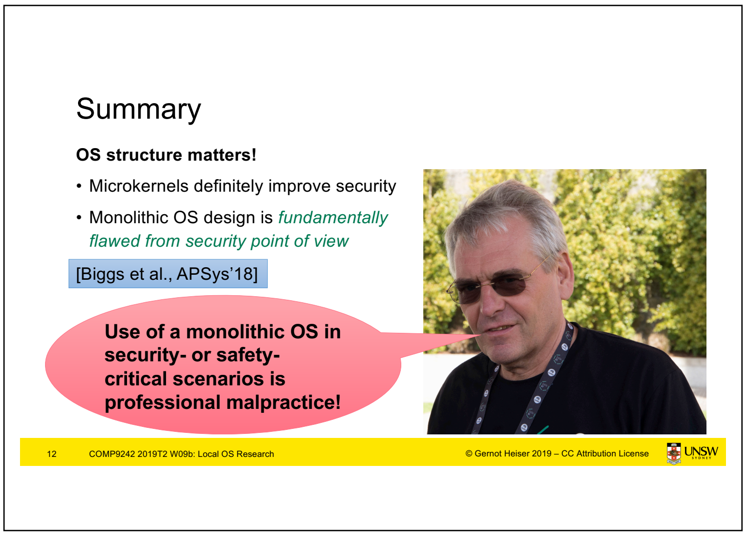
- 41% eliminated
- 58% low severity
- 96% not *critical*

11%

In microkernel:
Attack defeated by verification

Only *crash* essential service (availability):
Strongly mitigated

17%



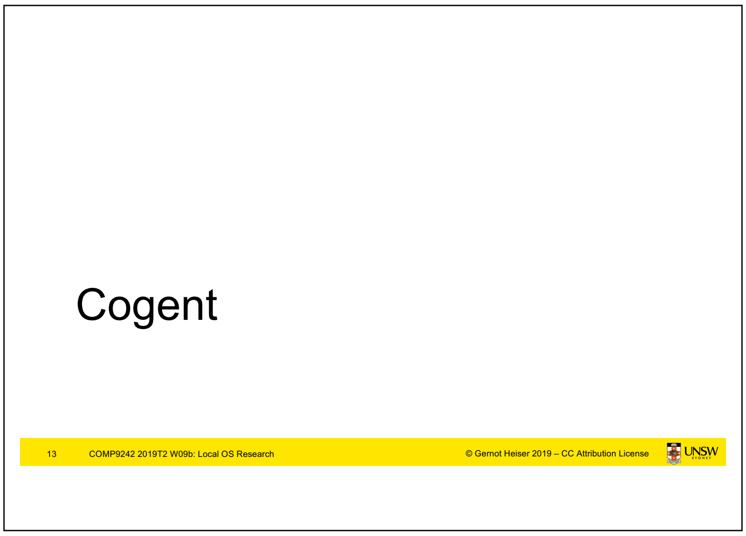
Summary

OS structure matters!

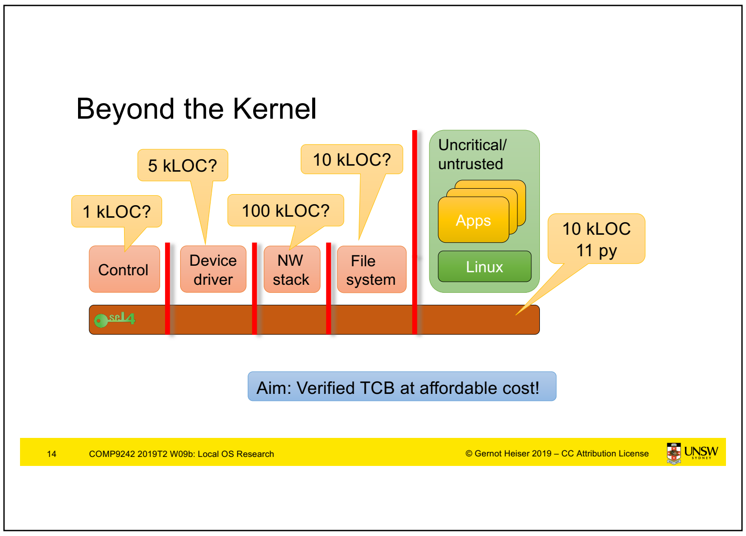
- Microkernels definitely improve security
- Monolithic OS design is *fundamentally flawed from security point of view*

[Biggs et al., APSys'18]

Use of a monolithic OS in security- or safety-critical scenarios is professional malpractice!

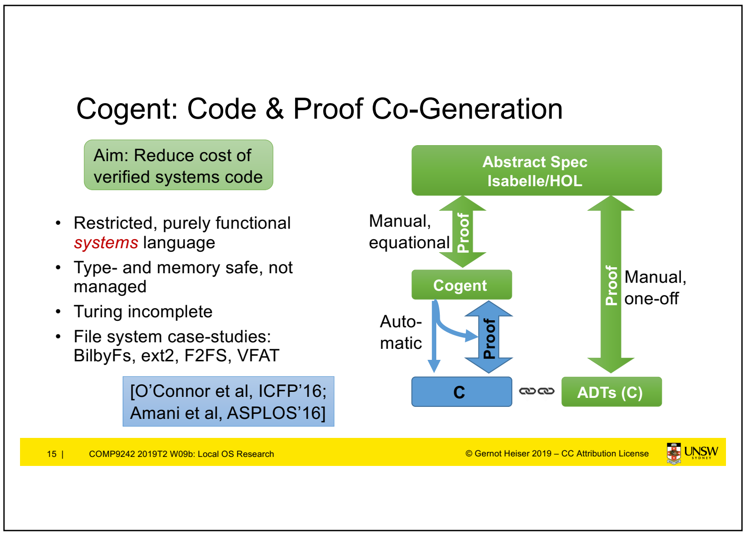


Cogent



Beyond the Kernel

Aim: Verified TCB at affordable cost!

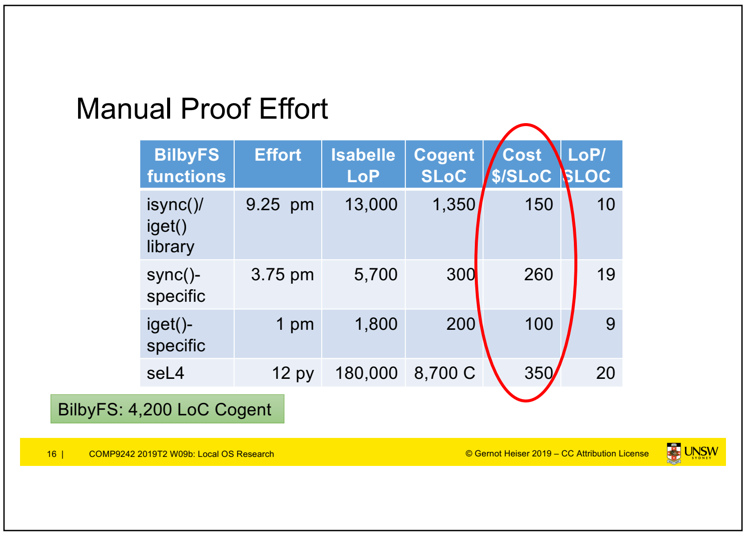


Cogent: Code & Proof Co-Generation

Aim: Reduce cost of verified systems code

- Restricted, purely functional *systems* language
- Type- and memory safe, not managed
- Turing incomplete
- File system case-studies: BilbyFs, ext2, F2FS, VFAT

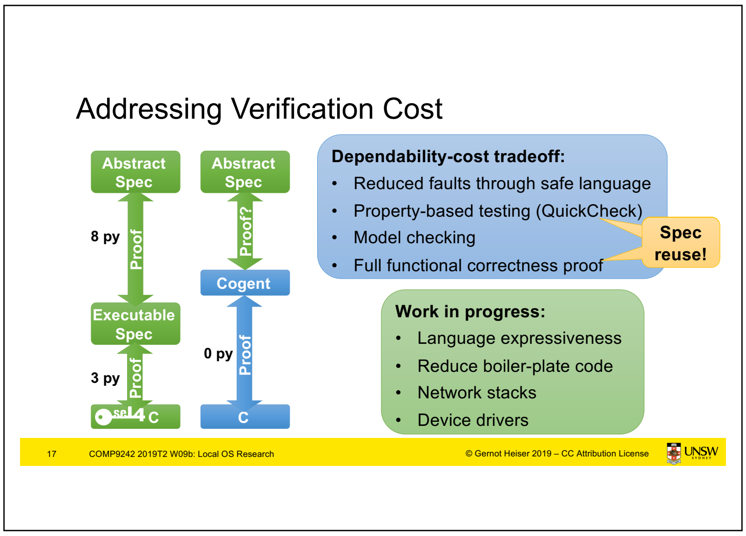
[O'Connor et al, ICFP'16; Amani et al, ASPLOS'16]



Manual Proof Effort

BilbyFS functions	Effort	Isabelle LoP	Cogent SLoC	Cost $/SLoC	LoP/ SLOC
isync()/ iget() library	9.25 pm	13,000	1,350	150	10
sync()-specific	3.75 pm	5,700	300	260	19
iget()-specific	1 pm	1,800	200	100	9
seL4	12 py	180,000	8,700 C	350	20

BilbyFS: 4,200 LoC Cogent



Addressing Verification Cost

Dependability-cost tradeoff:

- Reduced faults through safe language
- Property-based testing (QuickCheck)
- Model checking
- Full functional correctness proof

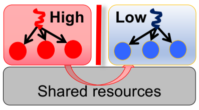
Spec reuse!

Work in progress:

- Language expressiveness
- Reduce boiler-plate code
- Network stacks
- Device drivers

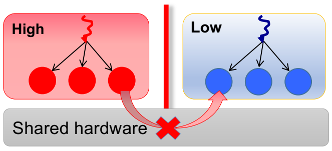
Time Protection

Refresh: Microarchitectural Timing Channels



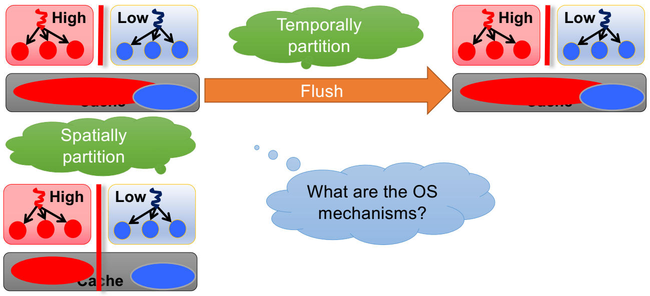
Contention for shared hardware resources affects execution speed, leading to timing channels

OS Must Enforce *Time Protection*



Preventing interference is core duty of the OS!
- *Memory protection* is well established
- *Time protection* is completely absent

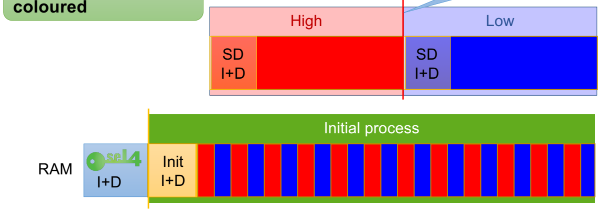
Time Protection: No Sharing of HW State



seL4 Spatial Partitioning: Cache Colouring

Partitions restricted to coloured memory

System permanently coloured



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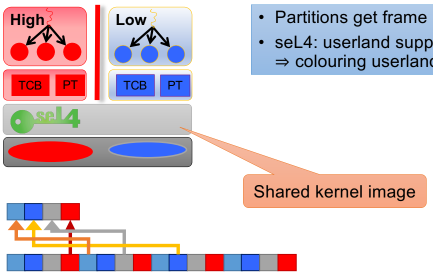
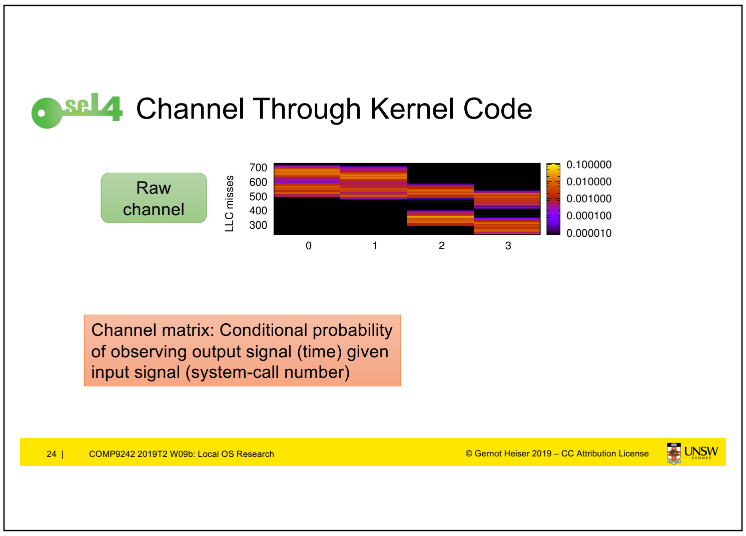


- Partitions get frame pools of disjoint colours
- seL4: userland supplies kernel memory ⇒ colouring userland colours kernel memory

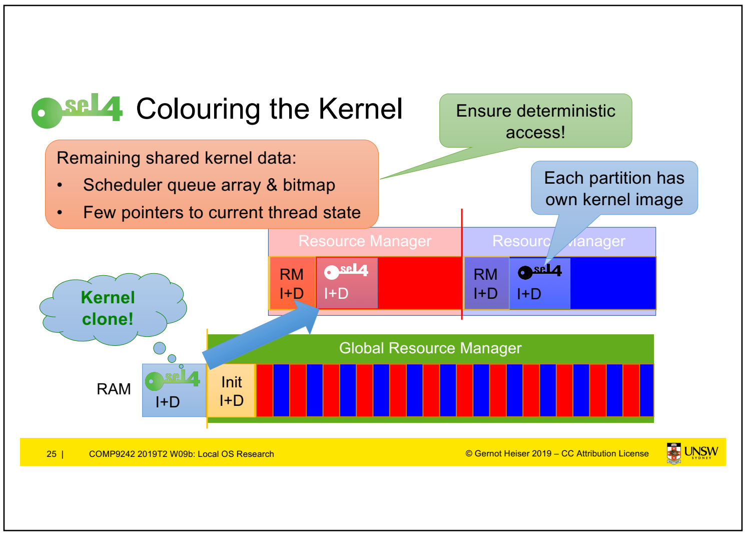
Shared kernel image



Channel Through Kernel Code

Raw channel

Channel matrix: Conditional probability of observing output signal (time) given input signal (system-call number)



Colouring the Kernel

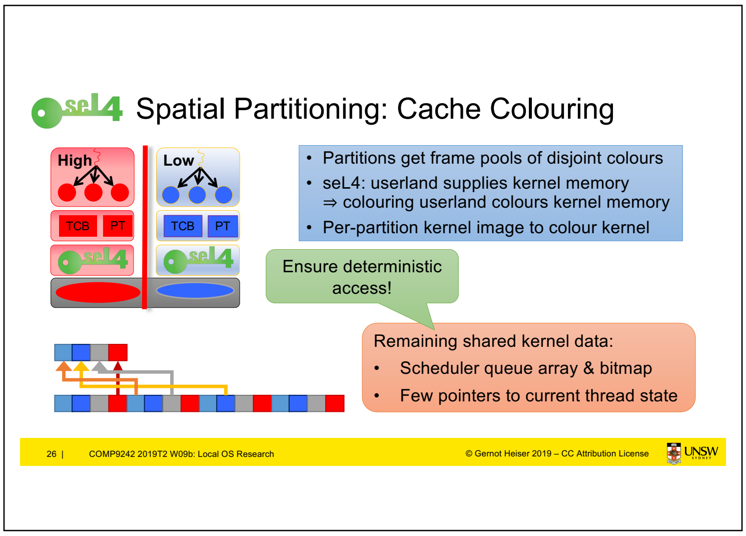
Ensure deterministic access!

Remaining shared kernel data:

- Scheduler queue array & bitmap
- Few pointers to current thread state

Each partition has own kernel image

Kernel clone!



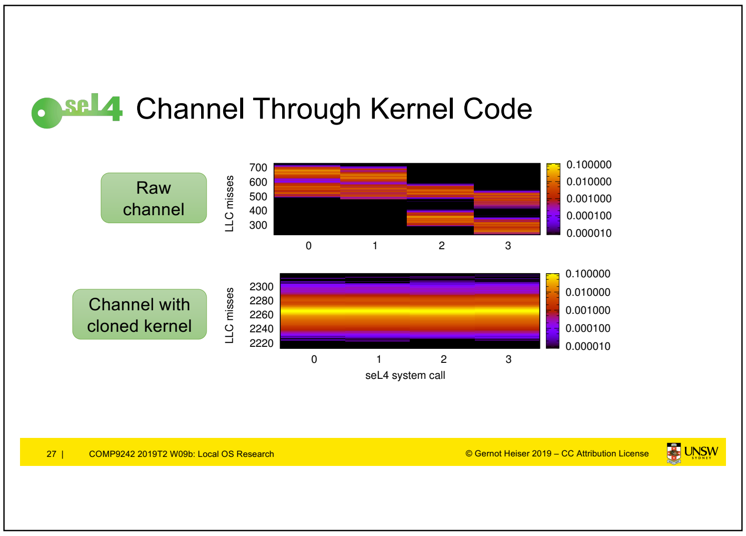
Spatial Partitioning: Cache Colouring

- Partitions get frame pools of disjoint colours
- seL4: userland supplies kernel memory ⇒ colouring userland colours kernel memory
- Per-partition kernel image to colour kernel

Ensure deterministic access!

Remaining shared kernel data:

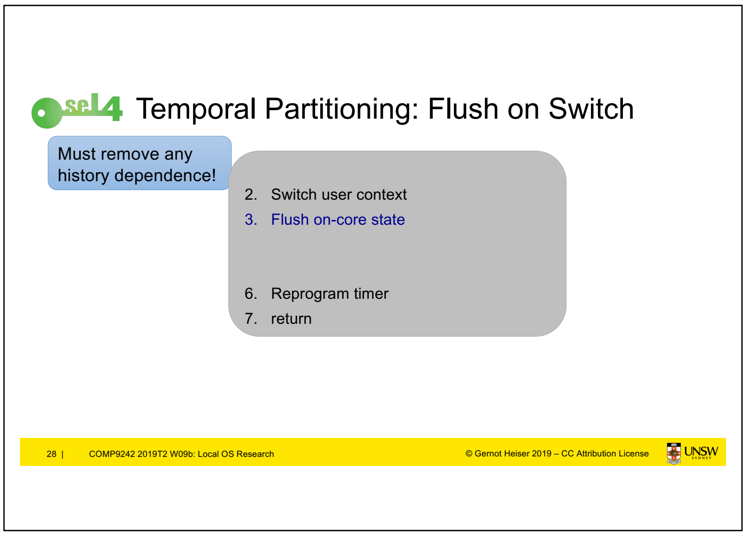
- Scheduler queue array & bitmap
- Few pointers to current thread state



Channel Through Kernel Code

Raw channel

Channel with cloned kernel

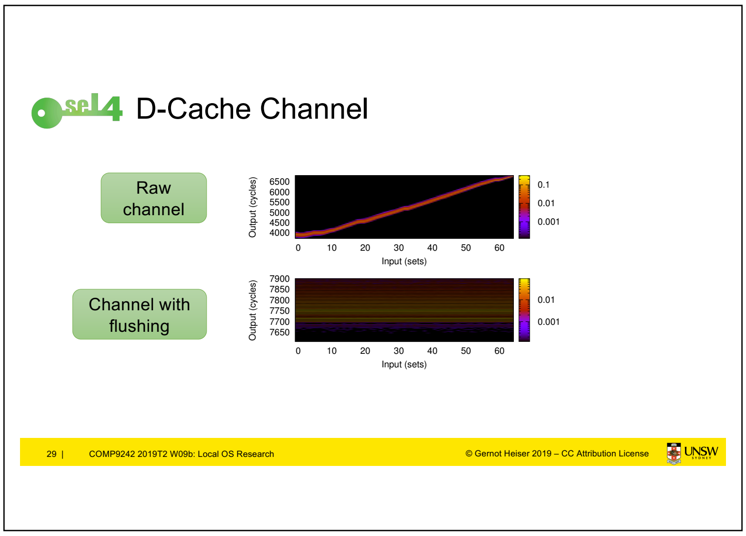


Temporal Partitioning: Flush on Switch

Must remove any history dependence!

2. Switch user context
3. Flush on-core state

6. Reprogram timer
7. return



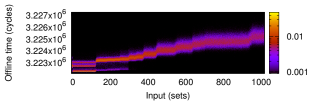
D-Cache Channel

Raw channel

Channel with flushing

Flush-Time Channel

Raw channel



Temporal Partitioning: Flush on Switch

Must remove any history dependence!

1. T_0 = current_time()
2. Switch user context
3. Flush on-core state
4. Touch all shared data needed for return
5. while (T_0+WCET < current_time()) ;
6. Reprogram timer
7. return

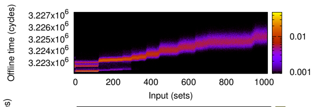
Latency depends on prior execution!

Time padding to remove dependency

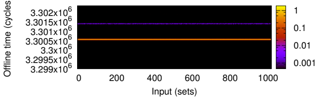
Ensure deterministic execution

Flush-Time Channel

Raw channel

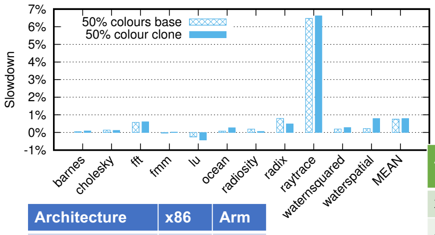


Channel with deterministic flushing



Performance Impact of Colouring

Splash-2 benchmarks on Arm A9



Architecture	x86	Arm
Mean slowdown	3.4%	1.1%

- Overhead mostly low
- Not evaluated is cost of not using super pages

[Ge et al., EuroSys'19]

Arch	seL4 clone	Linux fork+exec
x86	79 µs	257 µs
Arm	608 µs	4,300 µs

A New HW/SW Contract

For all shared microarchitectural resources:

aISA: augmented ISA

1. Resource must be spatially partitionable or flushable
2. Concurrently shared resources must be spatially partitioned
3. Resource accessed solely by virtual address must be flushed and not concurrently accessed
4. Mechanisms must be sufficiently specified for OS to partition or reset
5. Mechanisms must be constant time, or of specified, bounded latency
6. Desirable: OS should know if resettable state is derived from data, instructions, data addresses or instruction addresses

Cannot share HW threads across security domains!

[Ge et al., APSys'18]

Can Time Protection Be Verified?

1. Correct treatment of spatially partitioned state:
   - Need hardware model that identifies all such state (augmented ISA)
   - To prove:
     No two domains can access the same physical state

Functional property!

Transforms timing channels into storage channels!

2. Correct flushing of time-shared state
   - Not trivial: eg proving all cleanup code/data are forced into cache after flush
     - Needs an actual cache model
   - Even trickier: need to prove padding is correct
     - … without explicitly reasoning about time!

Functional property!

seL4 Verifying Time Padding

- Idea: Minimal formalisation of hardware clocks (abstract time)
  - Monotonically-increasing counter
  - Can add constants to time values
  - Can compare time values

To prove: padding loop terminates as soon as timer value ≥ T_0+WCET

Functional property

[Heiser et al., HotOS'19]

Making COTS Hardware Dependable

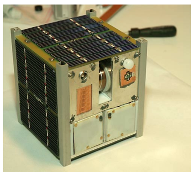
Satellites: SWaP vs Dependability

Space is becoming commodisized:

- many, small (micro-) satellites
- increasing cost pressure

Harsh evironment for electronics:

- temperature fluctuations
- ionising radiation

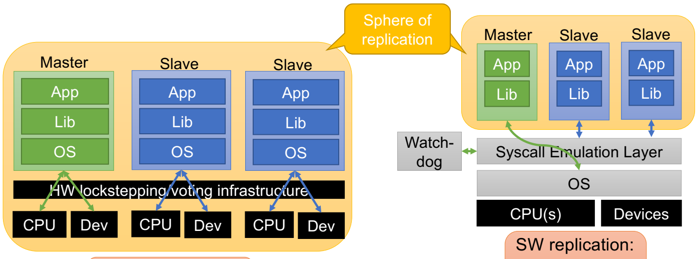


NCUBE2 by Bjørn Pedersen, NTNU (CC BY 1.0)

Radiation-hardened processors are slow, bulky and expensive

Use redundancy of cheap COTS multicores

Traditional Redundancy Approaches



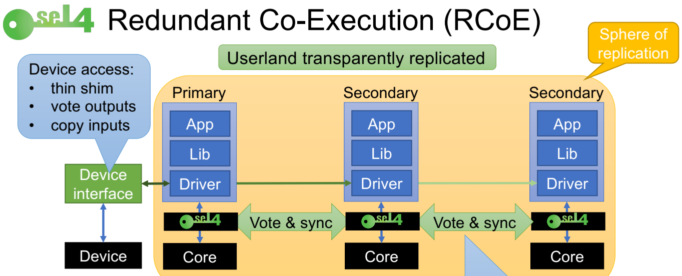
Fault-tolerant HW:

- expensive

SW replication:

- cheap
- incomplete

seL4 Redundant Co-Execution (RCoE)



Device access:

- thin shim
- vote outputs
- copy inputs

No master-slave, but peer-to-peer

- Vote on checksums of arguments & state
- Logical time for sync

RCoE: Two Variants

Loosely-coupled RCoE

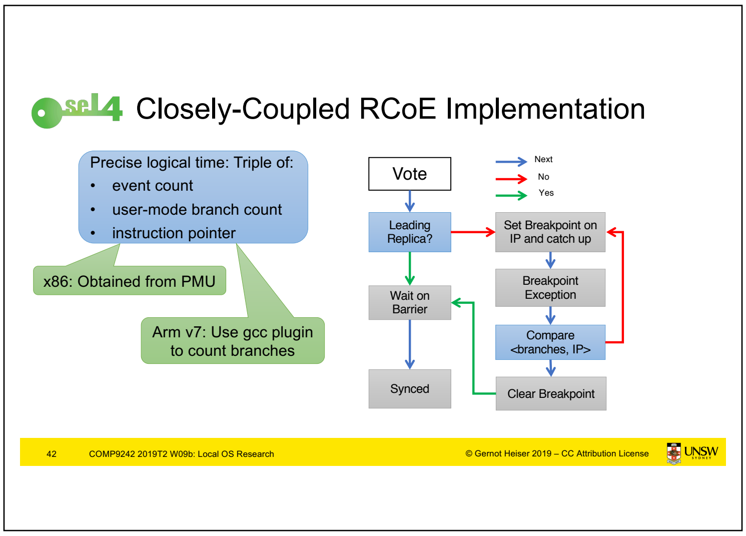
- Sync on syscalls & exceptions
- Preemptions in usermode not further synchronised (imprecise)

- Low overhead
- Cannot support racy apps, threads, virtual machines

Closely-coupled RCoE

- Sync on instruction
- Precise preemptions

- High overhead
- Supports all apps
- May need re-compile

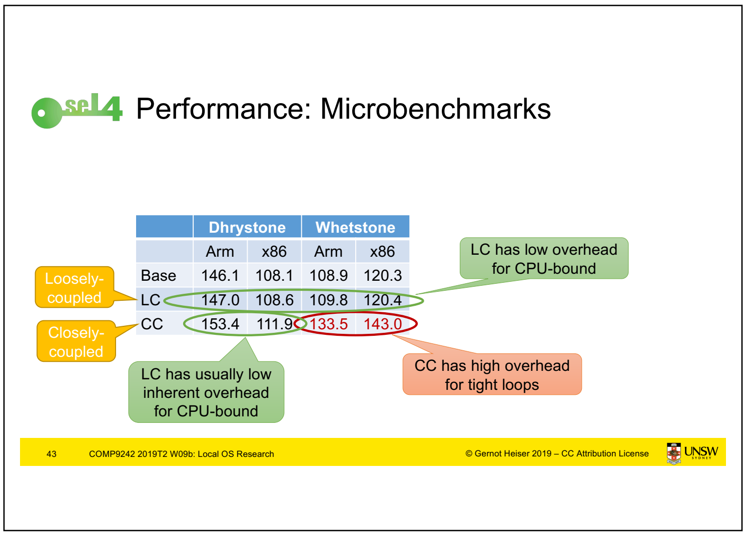


Closely-Coupled RCoE Implementation

Precise logical time: Triple of:
- event count
- user-mode branch count
- instruction pointer

x86: Obtained from PMU

Arm v7: Use gcc plugin to count branches



Performance: Microbenchmarks

	Dhrystone		Whetstone	
	Arm	x86	Arm	x86
Base	146.1	108.1	108.9	120.3
LC	147.0	108.6	109.8	120.4
CC	153.4	111.9	133.5	143.0

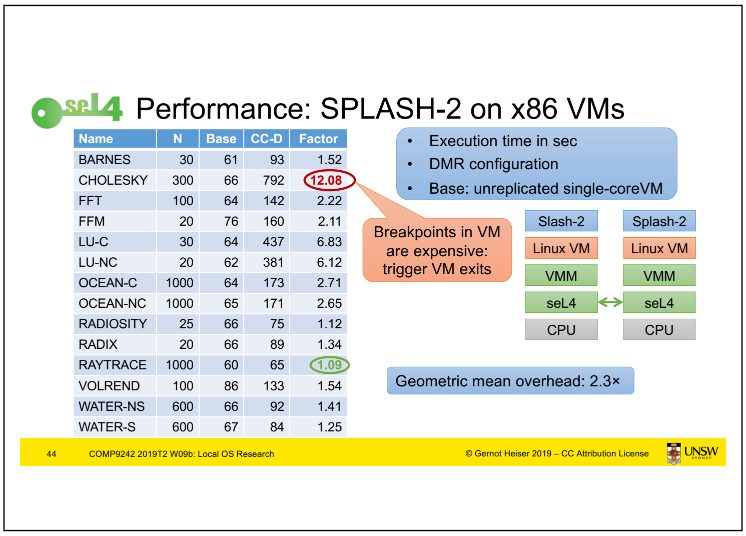
Loosely-coupled

Closely-coupled

LC has low overhead for CPU-bound

LC has usually low inherent overhead for CPU-bound

CC has high overhead for tight loops



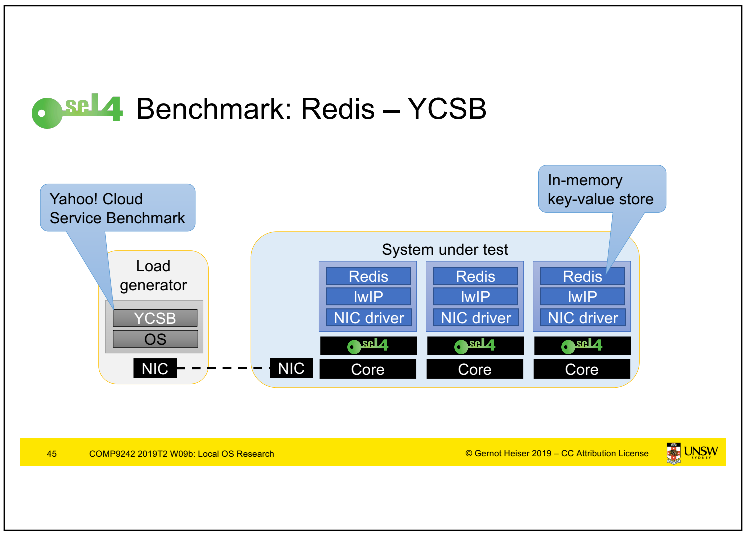
Performance: SPLASH-2 on x86 VMs

Name	N	Base	CC-D	Factor
BARNES	30	61	93	1.52
CHOLESKY	300	66	792	12.08
FFT	100	64	142	2.22
FFM	20	76	160	2.11
LU-C	30	64	437	6.83
LU-NC	20	62	381	6.12
OCEAN-C	1000	64	173	2.71
OCEAN-NC	1000	65	171	2.65
RADIOSITY	25	66	75	1.12
RADIX	20	66	89	1.34
RAYTRACE	1000	60	65	1.09
VOLREND	100	86	133	1.54
WATER-NS	600	66	92	1.41
WATER-S	600	67	84	1.25

- Execution time in sec
- DMR configuration
- Base: unreplicated single-coreVM

Breakpoints in VM are expensive: trigger VM exits

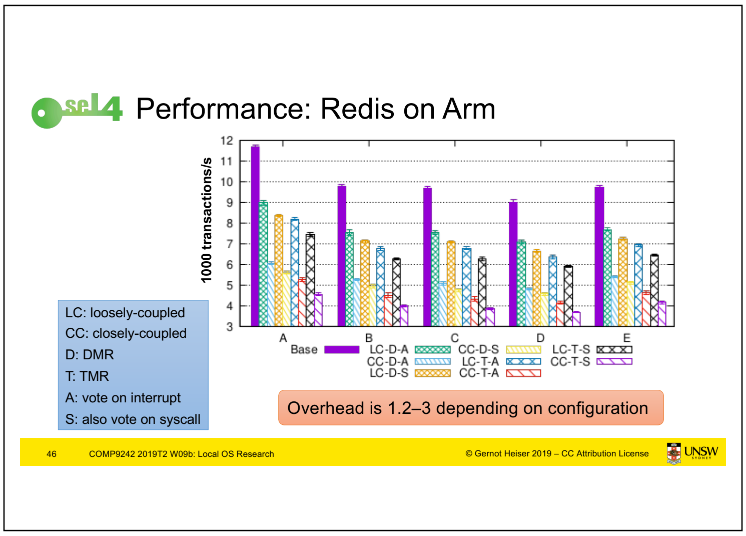
Geometric mean overhead: 2.3×



Benchmark: Redis – YCSB

Yahoo! Cloud Service Benchmark

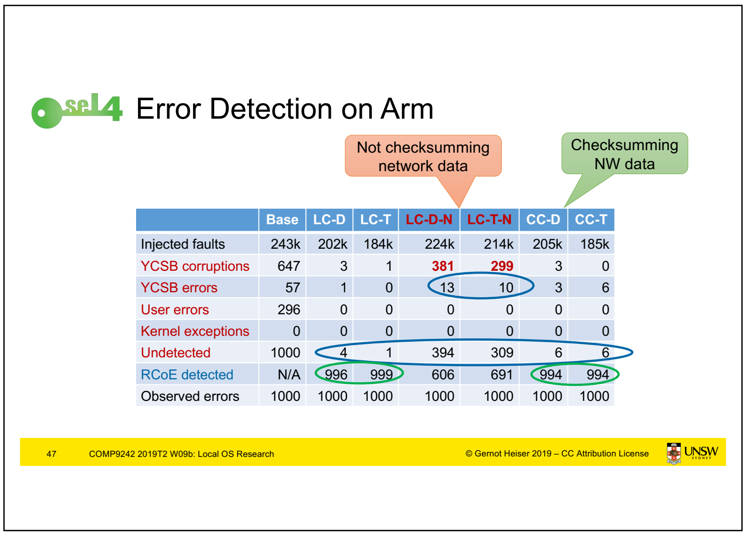
In-memory key-value store



Performance: Redis on Arm

LC: loosely-coupled
CC: closely-coupled
D: DMR
T: TMR
A: vote on interrupt
S: also vote on syscall

Overhead is 1.2–3 depending on configuration



Error Detection on Arm

Not checksumming network data

Checksumming NW data

	Base	LC-D	LC-T	LC-D-N	LC-T-N	CC-D	CC-T
Injected faults	243k	202k	184k	224k	214k	205k	185k
YCSB corruptions	647	3	1	**381**	**299**	3	0
YCSB errors	57	1	0	13	10	3	6
User errors	296	0	0	0	0	0	0
Kernel exceptions	0	0	0	0	0	0	0
Undetected	1000	4	1	394	309	6	6
RCoE detected	N/A	996	999	606	691	994	994
Observed errors	1000	1000	1000	1000	1000	1000	1000

Comparison to Rad-Hardened Processor

	Sabre Lite	RAD750
Cores @ clock	4 @ 800 MHz	1 @ 133 MHz
Performance	4 × 2,000 DMIPS	240 DMIPS
Power	< 5 W	< 6 W
Energy Efficiency	200 DMIPS/W	40 DMIPS/W
Cost	$200	$200,000
Perf/Cost	5 DMIPS/$	0.0002 DMIPS/$

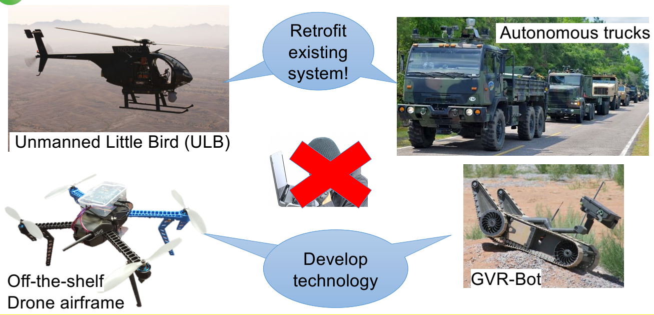
2002 price

Assuming 2× overhead, TMR

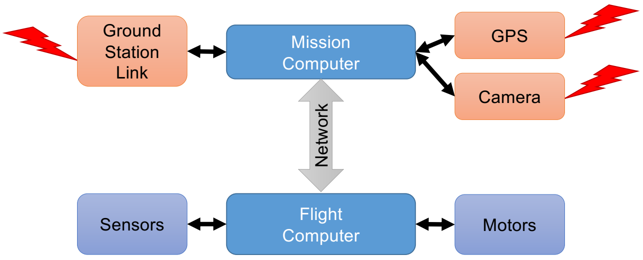
[Shen et al., DSN'19]

Real-World Use

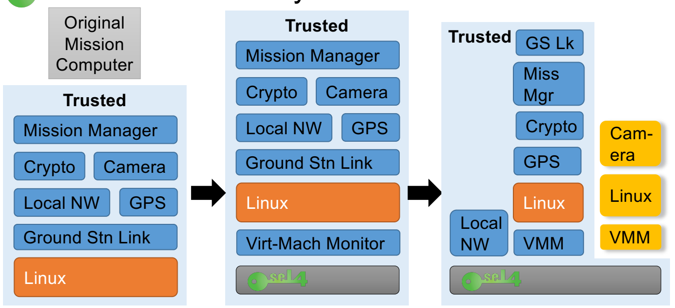
DARPA HACMS


Unmanned Little Bird (ULB)
Retrofit existing system!
Autonomous trucks
Off-the-shelf Drone airframe
Develop technology
GVR-Bot

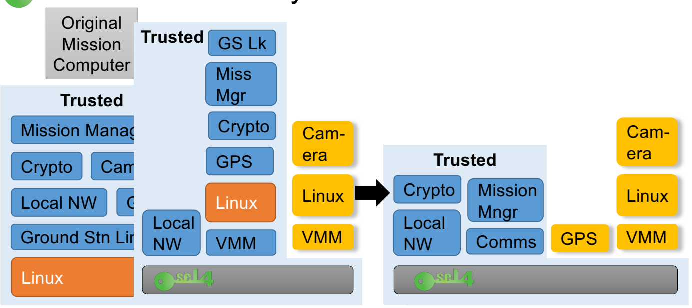
ULB Architecture



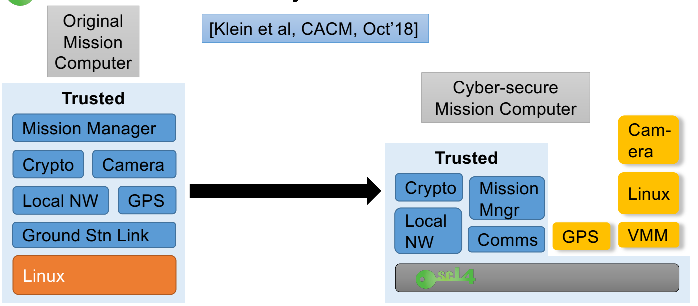
Incremental Cyber Retrofit



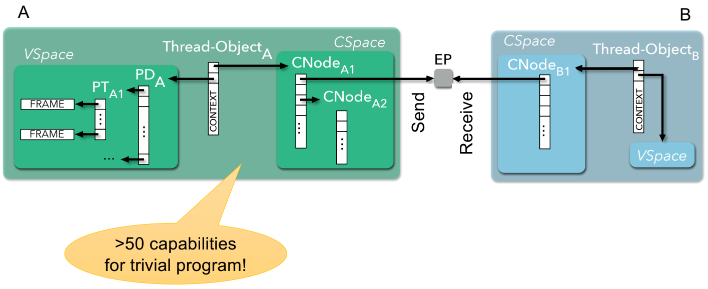
Incremental Cyber Retrofit



Incremental Cyber Retrofit

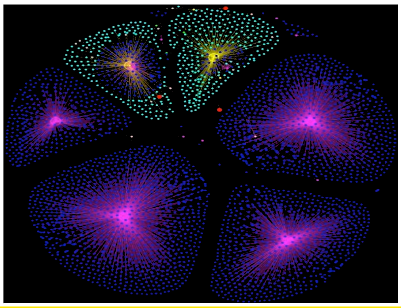

[Klein et al, CACM, Oct'18]

Issue: Capabilities are Low-Level



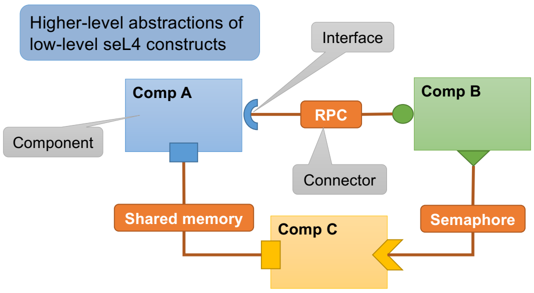
>50 capabilities
for trivial program!

Simple But Non-Trivial System



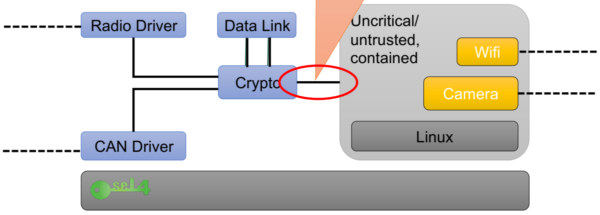
Component Middleware: CAmkES

Higher-level abstractions of
low-level seL4 constructs

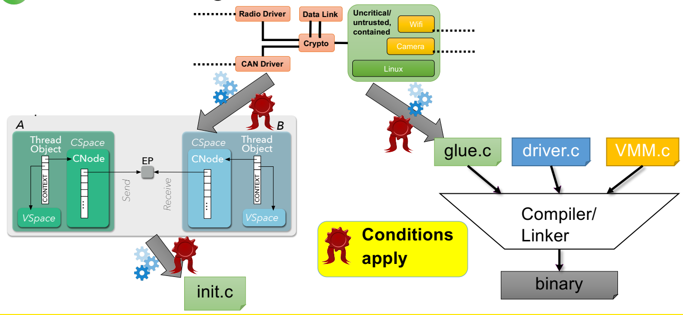


HACMS UAV Architecture

Security enforcement:
Linux only sees
encrypted data

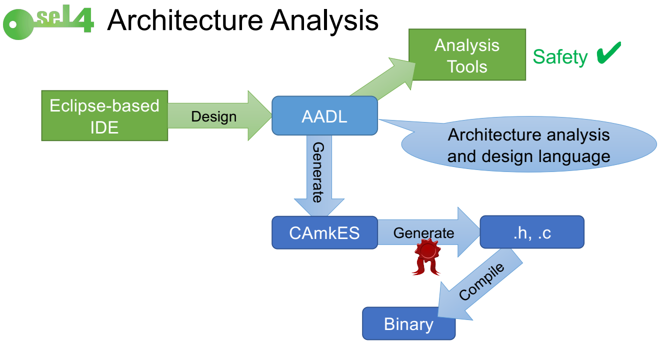


Enforcing the Architecture



Conditions
apply

seL4 Architecture Analysis



Analysis Tools

Safety ✔

Eclipse-based IDE

Design

AADL

Architecture analysis and design language

Generate

CAmkES

Generate

.h, .c

Compile

Binary

seL4 Military-Grade Security

Cross-Domain Desktop Compositor

Multi-level secure terminal

- Successful defence trial in AU
- Evaluated in US, UK, CA
- Formal security evaluation soon

Pen10.com.au crypto communication device in use in AU, UK defence

seL4 Real-World Use

Courtesy Boeing, DARPA