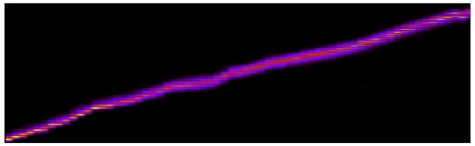
School of Computer Science & Engineering

COMP9242 Advanced Operating Systems



2020 T2 Week 07b

Security: Information Leakage

@GernotHeiser

Spectre/Meltdown material courtesy of
Yuval Yarom (UAde) & Daniel Genkin (UMI)

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Timing Channels

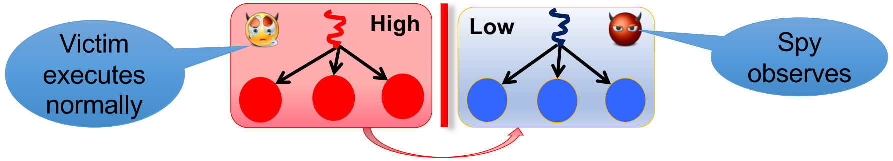
Principles

Refresh: Timing Channels

Information leakage through timing of events

- Typically by observing response latencies or own execution speed

Covert channel: Information flow that bypasses the security policy



Victim executes normally

High

Low

Spy observes

Side channel: Covert channel exploitable without insider help

Causes of Timing Channels

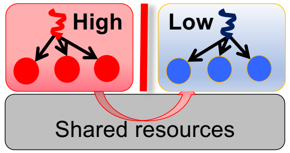
Algorithmic

```
if (secret) {
   short_operation(...);
} else {
   long_operation(...);
}
```

OS problem or not?

Resource Contention

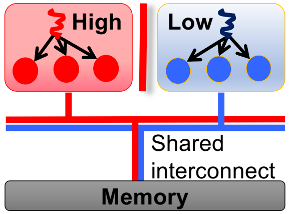
- Software resources
  - OS abstractions
  - buffer cache…
- Hardware resources
  - caches etc
  - not visible at ISA (HW-SW contract)



Affect execution speed

Micro-architectural timing channels

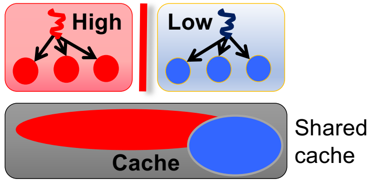
Shared Hardware: Stateless Interconnect



H/W is *bandwidth-limited*

- Interference during concurrent access
- Generally reveals no data or addresses
- Must encode info into access patterns
- *Only usable as covert channel, not side channel*

Shared Hardware: Stateful Resources



H/W is *capacity-limited*

- Interference during
  - concurrent access
  - time-shared access
- Collisions reveal addresses
- *Usable as side channel*

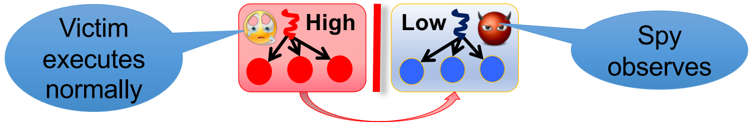
Can be any state-holding microarchitectural feature:

- CPU caches
- branch predictor
- pre-fetcher state machines

Timing Channels

Example: LLC Side Channel

Methodology: Prime and Probe



1. Fill cache with own data

2. Touch cache lines

Input Signal

3. Traverse cache, measure execution time

Output Signal

Challenge: Slow LLC Access Times

- L1 (32 KiB) probe:
  - 64 sets * 8 ways * 4 cycles = 2,048 cycles
- Small last-level cache (6 MiB):
  - 8,192 sets * 12 ways * ~30 cycles = ~3,000,000 cycles

Probing entire LLC is too slow, but single set is fast

Example: Look for square code in square-and-multiply exponentiation of GnuPG

- Approach:
  - *Probe one or a few cache sets at a time*
  - *Find “interesting” sets (“eviction set”) by looking for patterns*

Searching for square Code

Modular reduction: *r = b^e mod m*

```
long_int r (long_int b, m, e) {
  res = 1;
  for (i = n-1; i >= 0; i--) {
    if (e[i]) {
      r = mod (r * b, m);
    }
  }
  return res;
}
```

ith bit of e

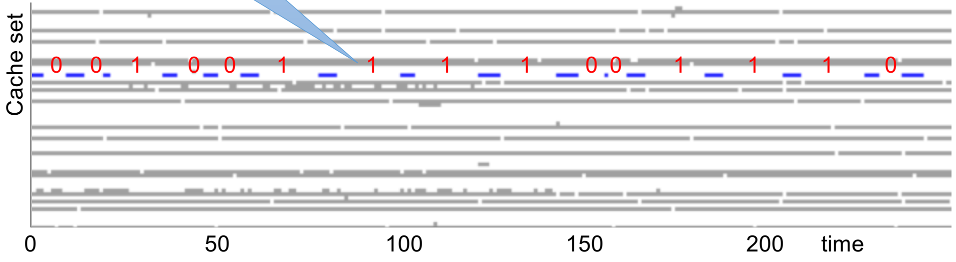
Long computation if bit is set

Expected pattern: Bursts of activity separated by longer or shorter intervals indicating modular reduction operation

Searching for square Code

Can read out bits of exponent! [Liu S&P’15]

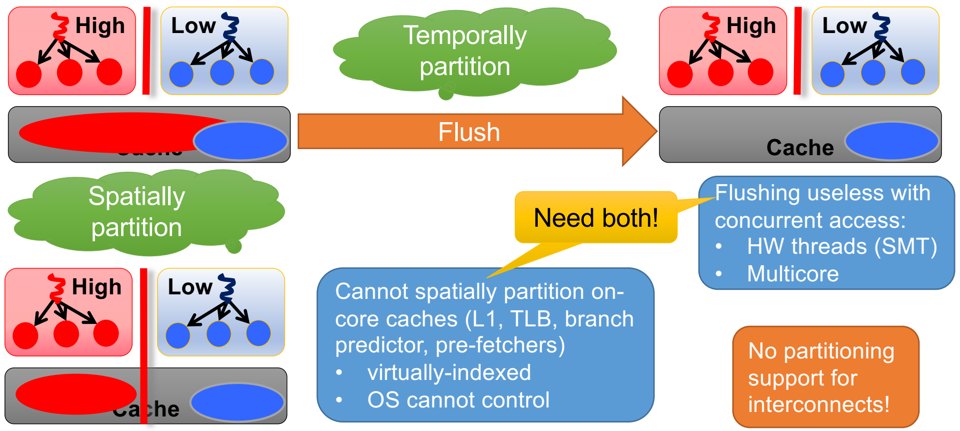
Expected pattern: Bursts of activity separated by longer or shorter intervals indicating modular reduction operation



Timing Channels

Evaluating Hardware

Timing-Channel Prevention: Partition HW



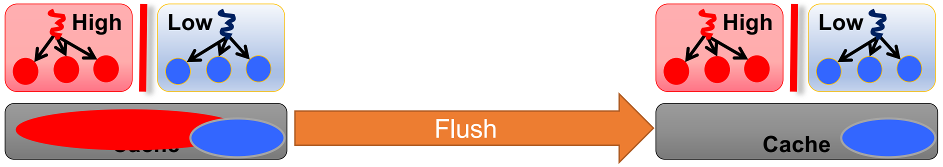
Need both!

Flushing useless with concurrent access:
- HW threads (SMT)
- Multicore

Cannot spatially partition on-core caches (L1, TLB, branch predictor, pre-fetchers)
- virtually-indexed
- OS cannot control

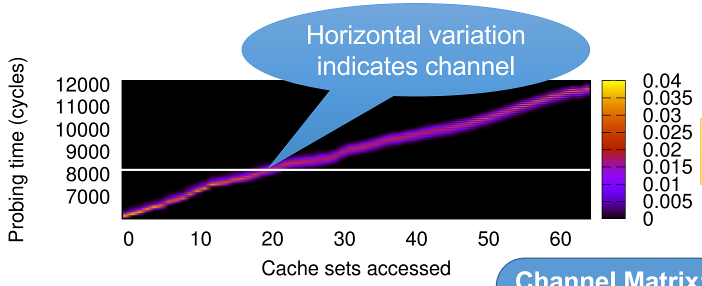
No partitioning support for interconnects!

Evaluating Intra-Core Channels



Methodology:
- Flush all caches on context switch
  - using all flush ops provided by HW
- Run prime&probe *covert channel* attack

Methodology: Channel Matrix

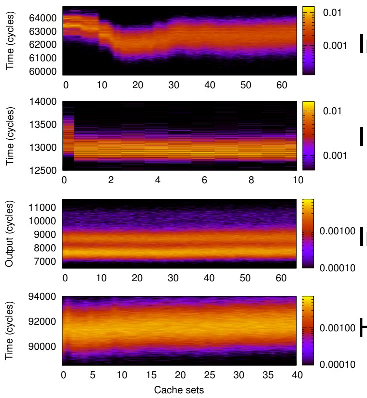


Horizontal variation indicates channel

Raw I-cache channel Intel Sandy Bridge

Channel Matrix:
- Conditional probability of observing time *t*, given input *n*.
- Represented as heat map: bright = high probability.

I-Cache Channel With Full State Flush



CHANNEL! Intel Sandy Bridge

CHANNEL! Intel Haswell

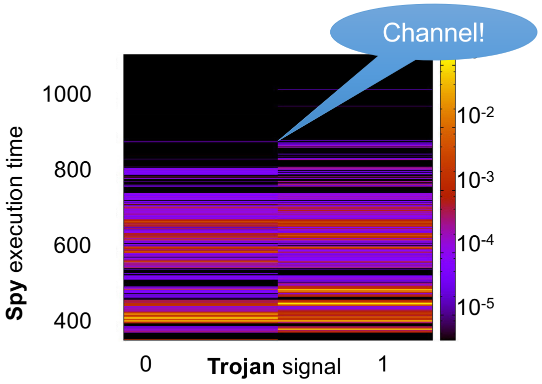
No evidence of channel — Intel Skylake

SMALL CHANNEL! HiSilicon A53

HiSilicon A53 Branch History Buffer

Branch history buffer (BHB)

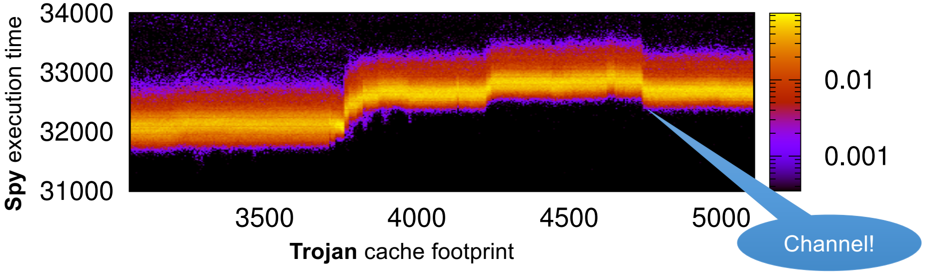
- Prediction of branch taken
- One-bit channel
- All reset operations applied



Intel Haswell Branch Target Buffer

Branch target buffer

- Prediction of branch destination
- All reset operations applied



Result Summary: Measured Capacities

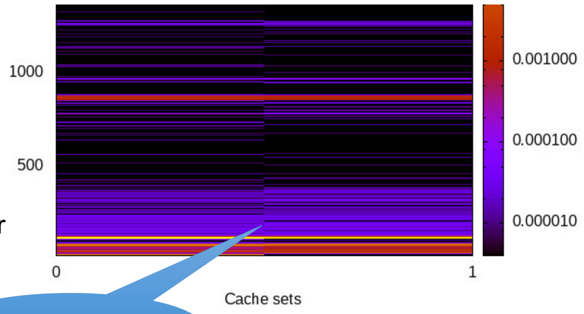
Channel	Sandy Bridge		Haswell		Skylake		ARM A9		ARM A53	
	raw	flush	raw	flush	raw	flush	raw	flush	raw	flush
L1 D-cache	4.0	0.04	4.7	0.43	3.3	0.18	5.0	0.11	2.8	0.15
L1 I-cache	3.7	0.85	0.46	0.36	0.37	0.18	4.0	1.0	4.5	0.5
TLB	3.2	0.47	3.2	0.18	2.5	0.11	0.33	0.16	3.4	0.14
BTB	2.0	1.7	4.1	1.6	1.8	1.9	1.1	0.07	1.3	0.64
BHB	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.01	1.0	0.5

Residual channels

Uncloseable channel on each processor studied!

Intel Spectre Defences

Intel added *indirect branch control* (IBC) feature, which closes most channels, but…



Intel Skylake
Branch history buffer

Small channel!

Speculating Desaster

Instruction Pipelining

- Nominally, the processor executes instructions one after the other
- Instruction execution consists of multiple steps
  - Each uses a different unit

Instruction Fetch	Instruction Decode	Argument Fetch	Execute	Write Back

Instruction Pipelining

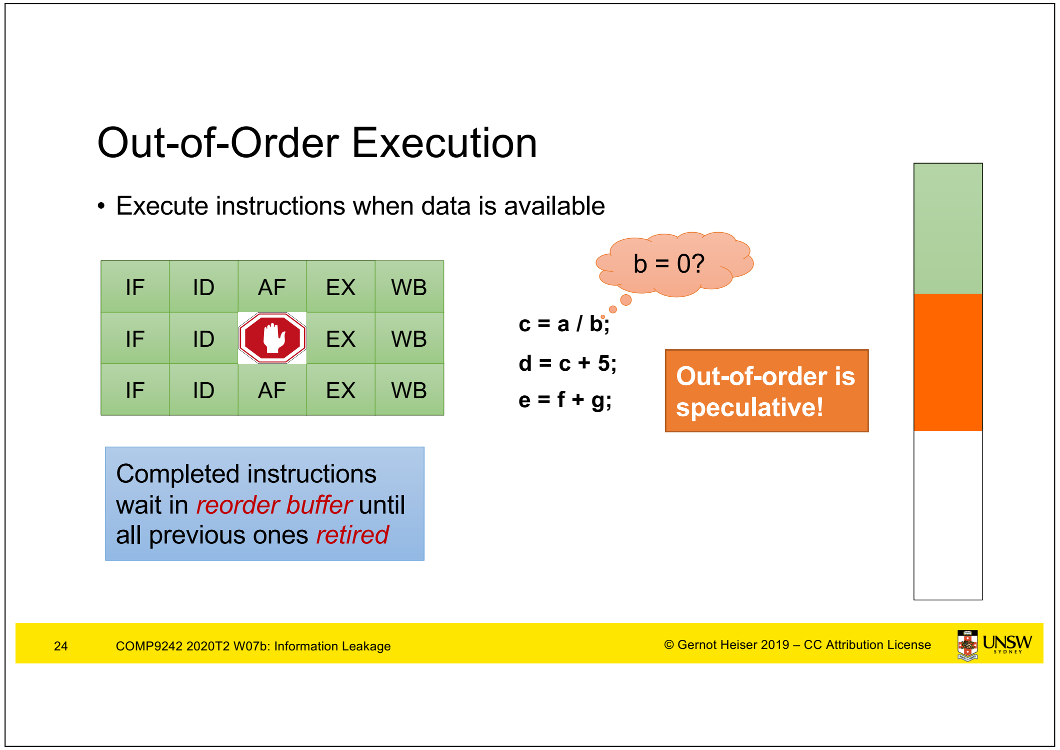
- Nominally, the processor executes instructions sequentially
- Instruction execution consists of multiple steps
  - Each uses a different unit
- Pipelining concurrently instruction execution

```
c = a / b;
d = c + 5;
```

Problem: Dependencies

Inst fetch	Inst decode	Arg fetch	Execute	Write back
Inst fetch	Inst decode	Arg fetch	Execute	Write back
Inst fetch	Inst decode	Arg fetch	Execute	Write back
Inst fetch	Inst decode	Arg fetch	Execute	Write back
Inst fetch	Inst decode	Arg fetch	Execute	Write back

```
mulq $m0
add  %rax,$A[0]
mov  8*2($np),%rax
lea  32($tp),$tp
adc  \$0,%rdx
mov  %rdx,$A[1]
mulq $m1
add  %rax,$N[0]
mov  8($a,$j),%rax
adc  \$0,%rdx
add  $A[0],$N[0]
adc  \$0,%rdx
mov  $N[0],-24($tp)
mov  %rdx,$N[1]
mulq $m0
add  %rax,$A[1]
mov  8*1($np),%rax
adc  \$0,%rdx
mov  %rdx,$A[0]
mulq $m1
add  %rax,$N[1]
mov  ($a,$j),%rax
mov  8($a,$j),%rax
adc  \$0,%rdx
```



Out-of-Order Execution

- Execute instructions when data is available

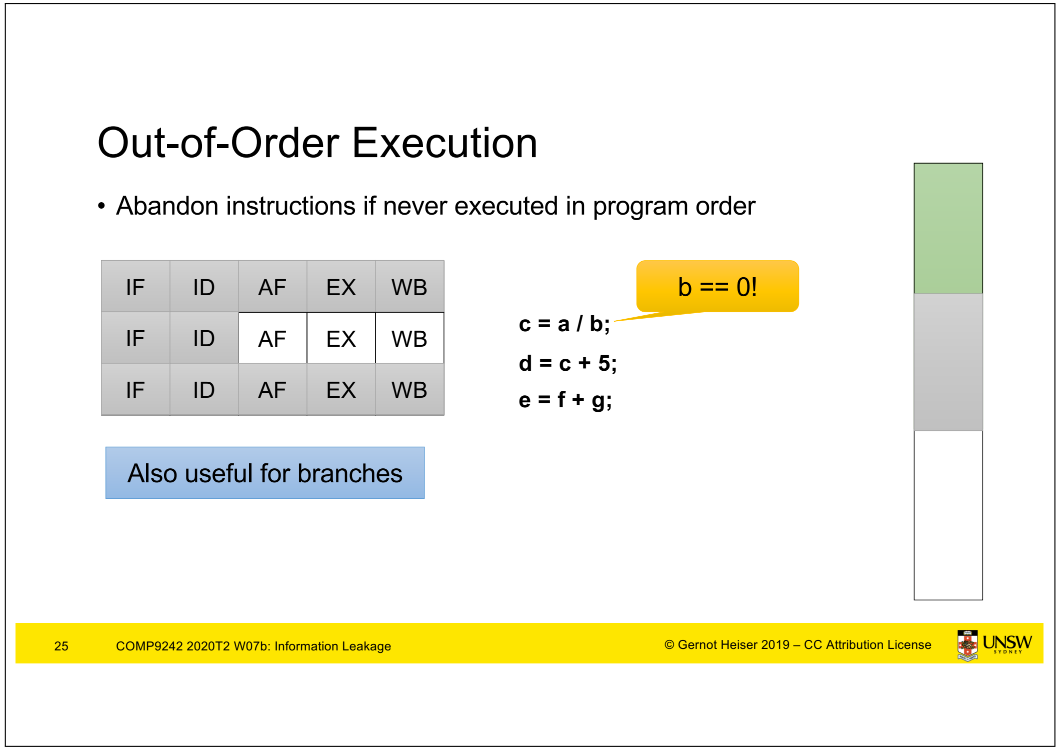
IF	ID	AF	EX	WB
IF	ID	🛑	EX	WB
IF	ID	AF	EX	WB

b = 0?

c = a / b;
d = c + 5;
e = f + g;

Out-of-order is speculative!

Completed instructions wait in *reorder buffer* until all previous ones *retired*



Out-of-Order Execution

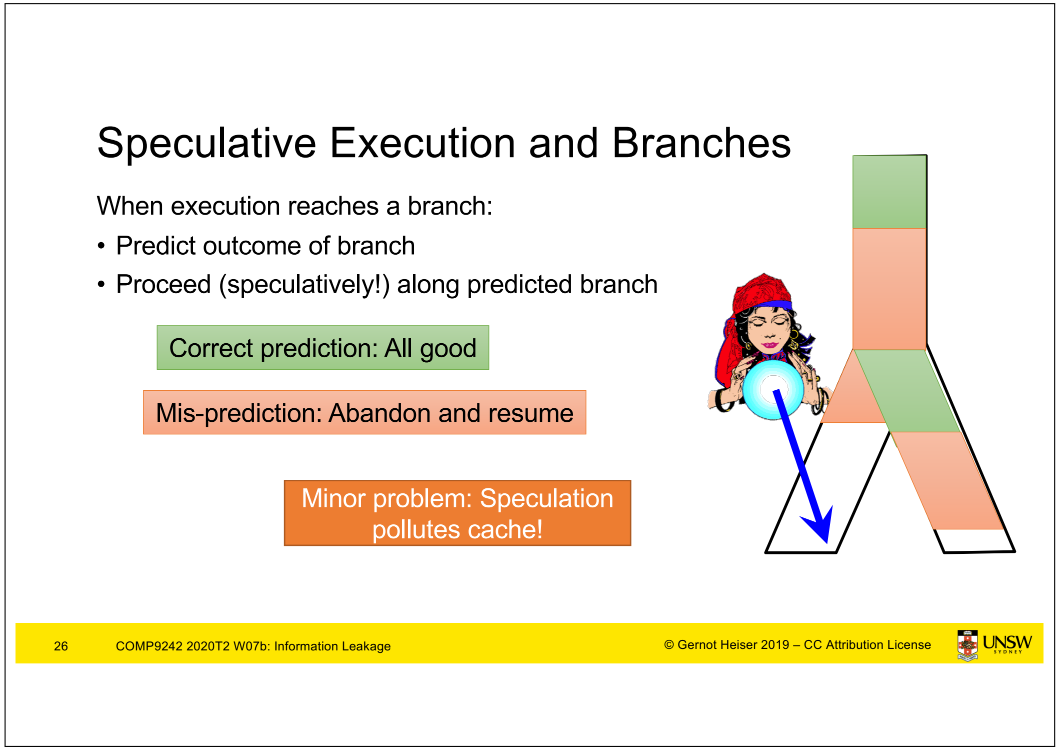
- Abandon instructions if never executed in program order

IF	ID	AF	EX	WB
IF	ID	AF	EX	WB
IF	ID	AF	EX	WB

b == 0!

c = a / b;
d = c + 5;
e = f + g;

Also useful for branches



Speculative Execution and Branches

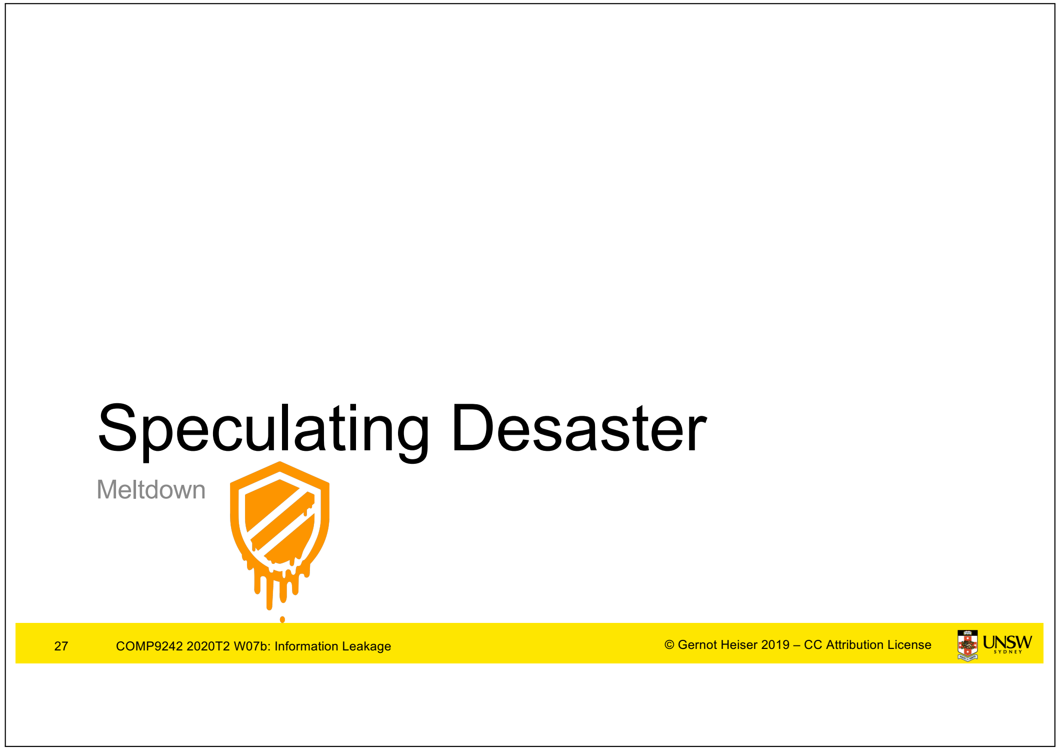
When execution reaches a branch:

- Predict outcome of branch
- Proceed (speculatively!) along predicted branch

Correct prediction: All good

Mis-prediction: Abandon and resume

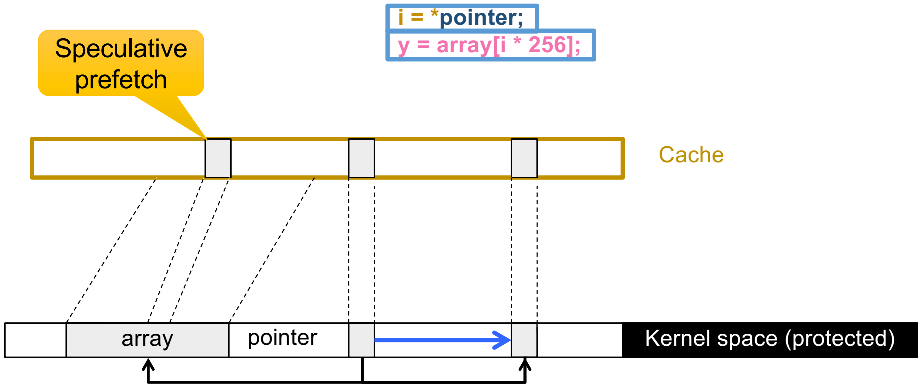
Minor problem: Speculation pollutes cache!



Speculating Desaster

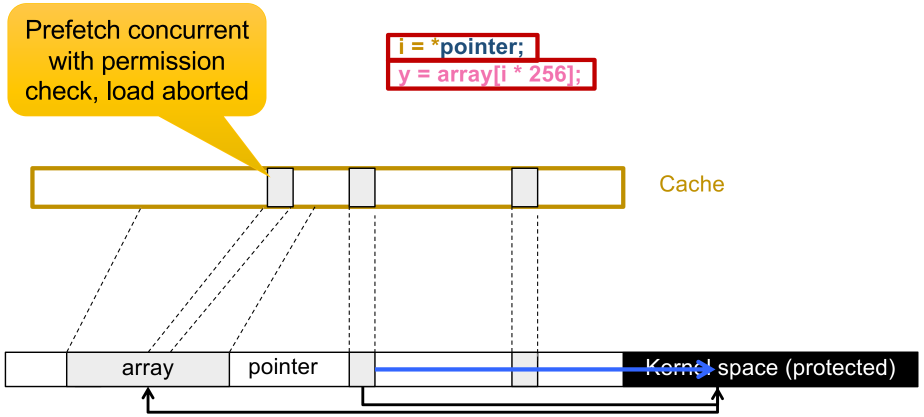
Meltdown

Meltdown: Speculative Load



i = *pointer;
y = array[i * 256];

Meltdown: Speculative Loads



i = *pointer;
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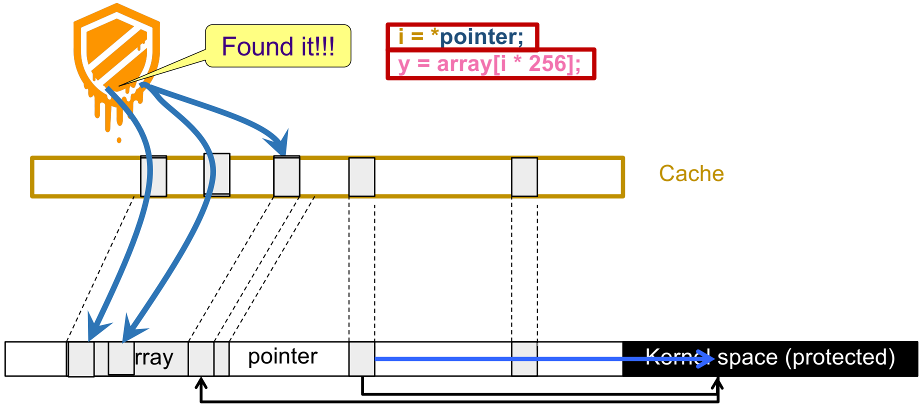
Meltdown: Cache-Channel to Read



i = *pointer;
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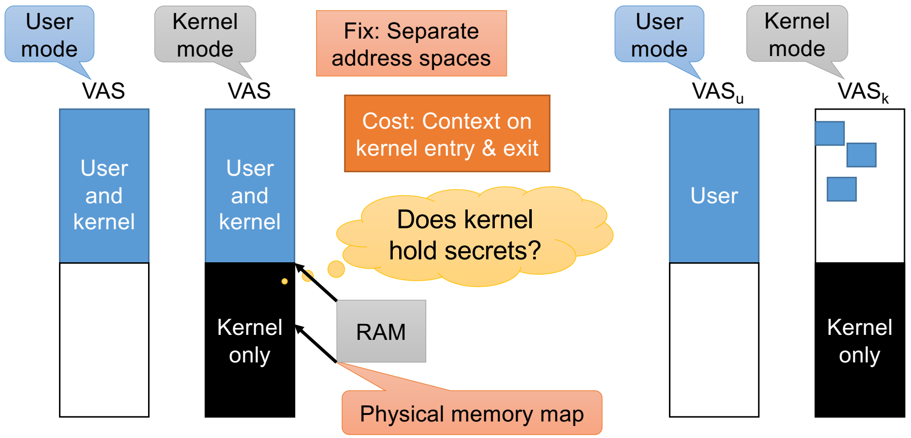
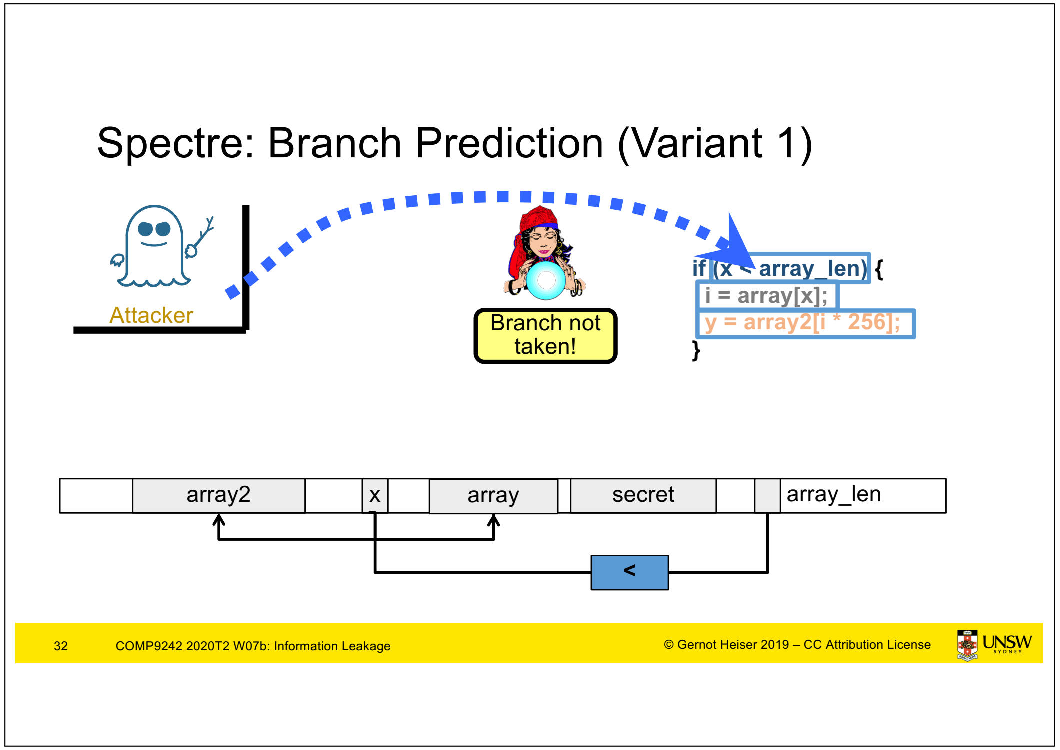
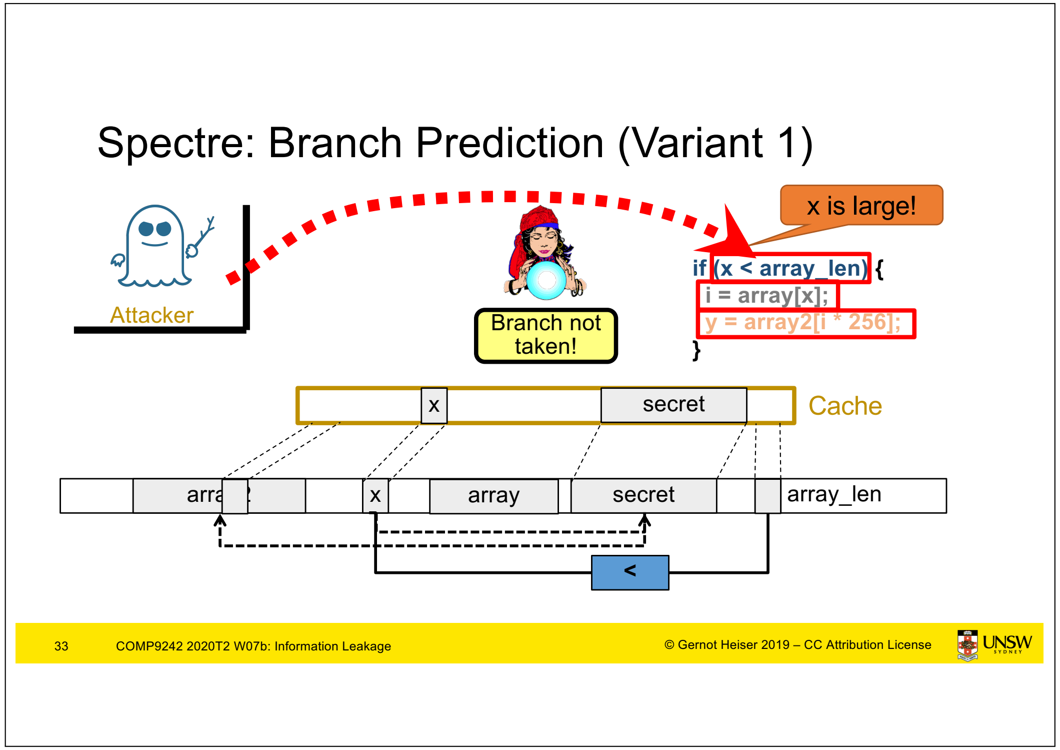
Meltdown: Full Kernel Memory Disclosure





Spectre: Branch Prediction (Variant 1)

```
if (x < array_len) {
  i = array[x];
  y = array2[i * 256];
}
```



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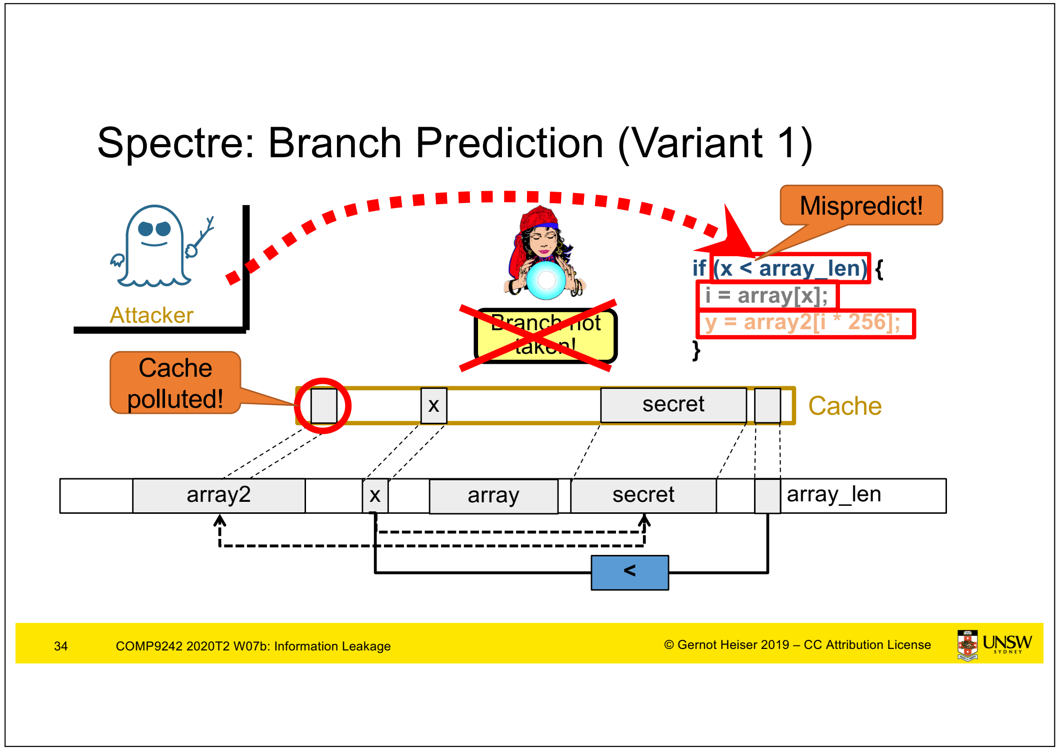

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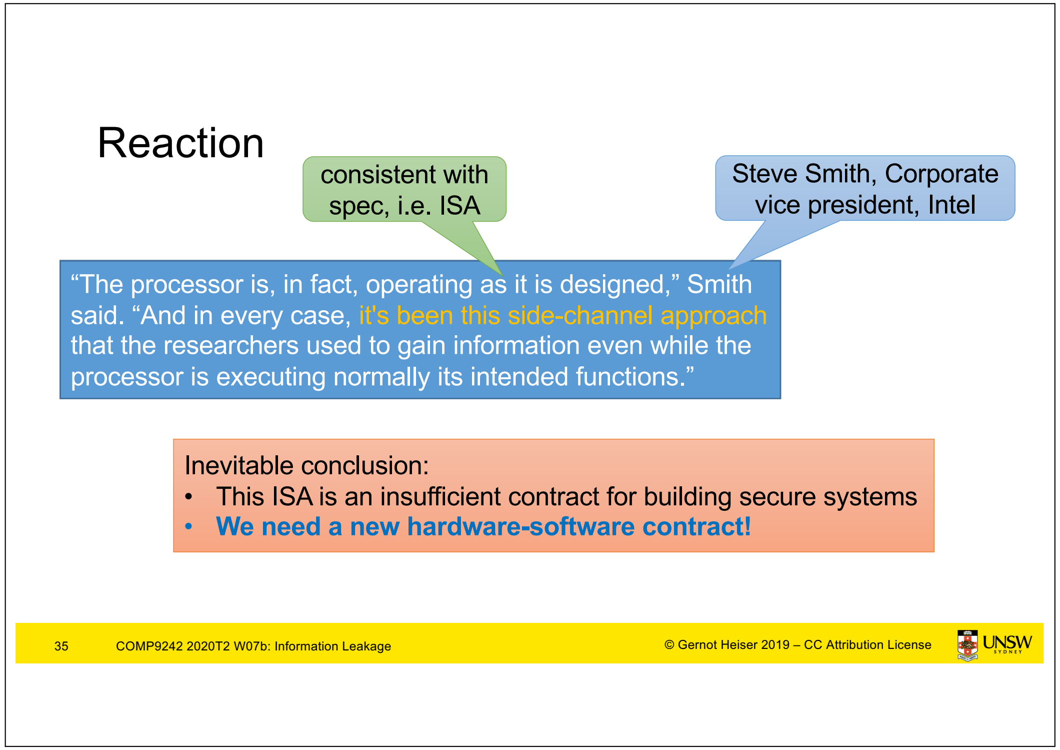

Reaction

consistent with spec, i.e. ISA

Steve Smith, Corporate vice president, Intel

"The processor is, in fact, operating as it is designed," Smith said. "And in every case, it's been this side-channel approach that the researchers used to gain information even while the processor is executing normally its intended functions."

Inevitable conclusion:

- This ISA is an insufficient contract for building secure systems
- **We need a new hardware-software contract!**