# Speculative Execution and Cache Attacks

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Hasso Plattner Institute, University of Potsdam, Germany

29 June – 3 July 2026

Cyber in Saint-Malo, France

# Computer Revolution

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|---|---|---|---|
| 1977 |  | 1 MHz | 500 ns |

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| 2020 |  | 20 × 3700 MHz | 50 ns |

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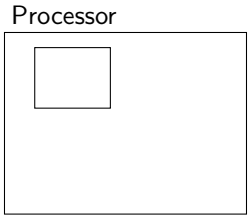


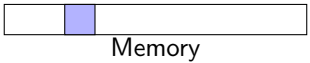

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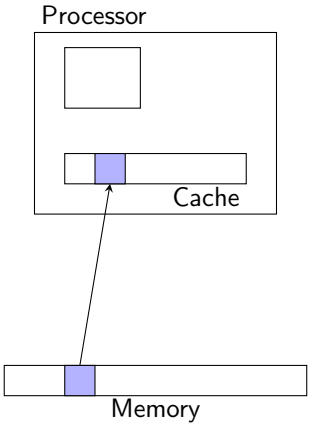

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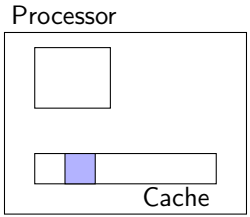


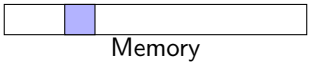

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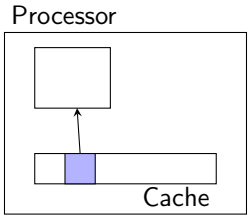


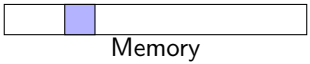

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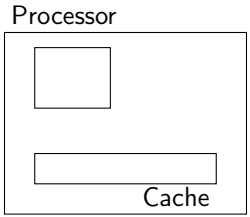


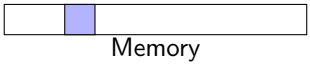

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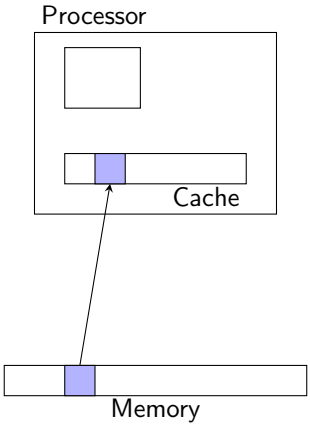

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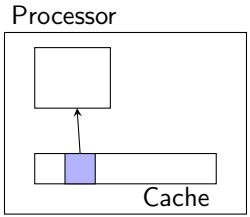


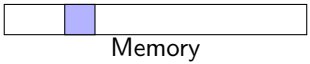

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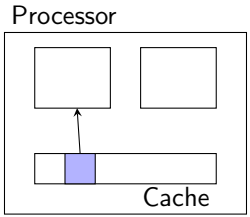


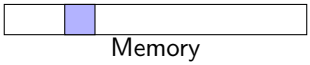

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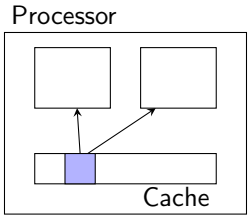


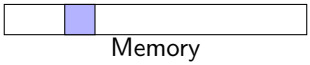

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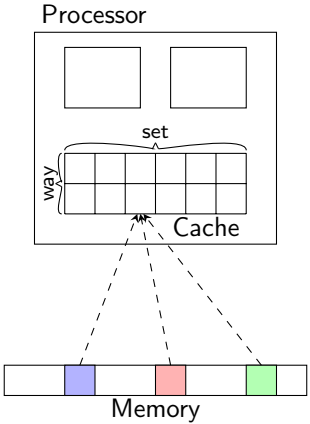

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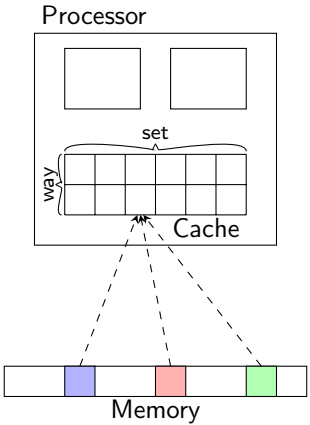

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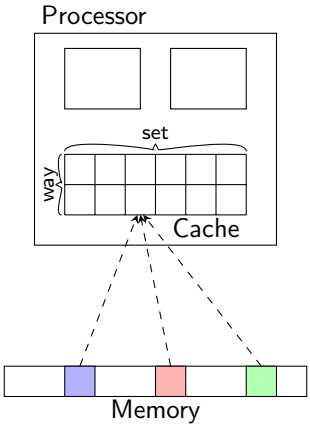

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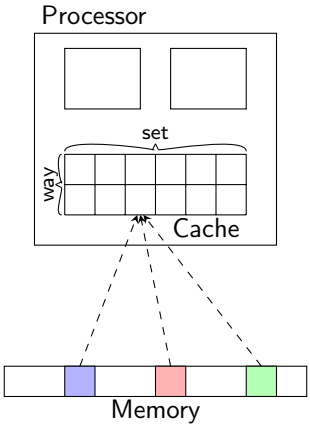

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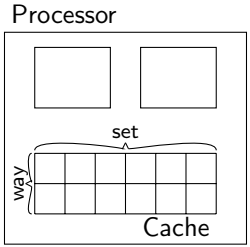


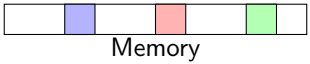

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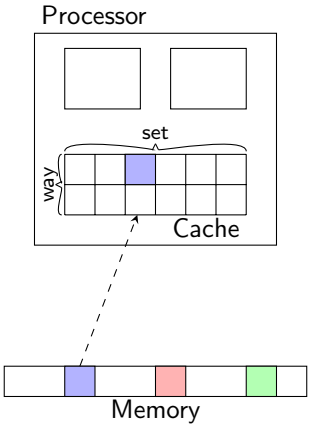

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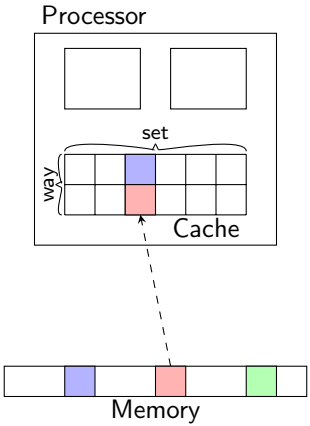

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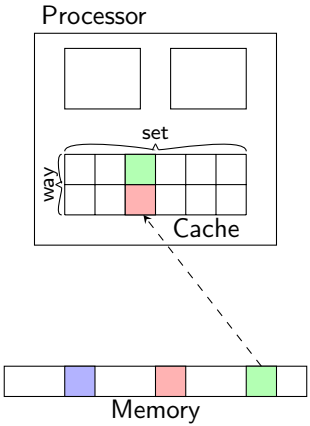

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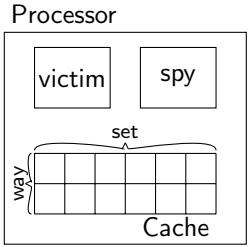


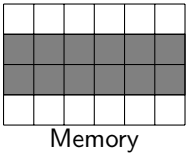

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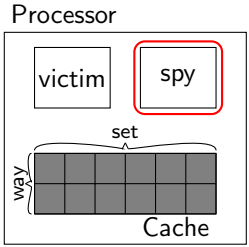


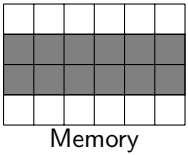

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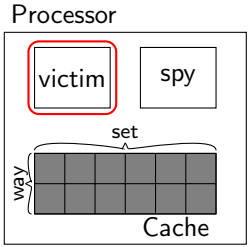


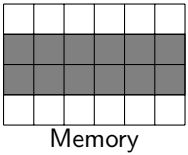

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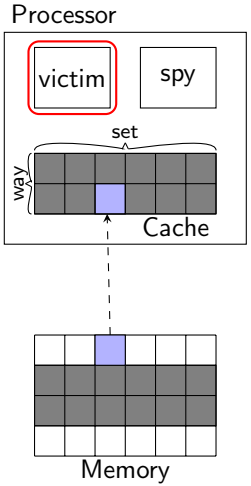

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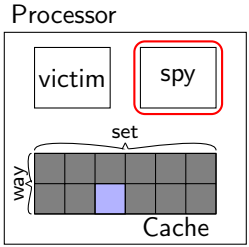


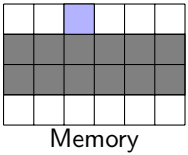

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- Measuring access time observes state (and set to TRUE)

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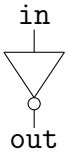
`out = NOT(in)`



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| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | |

# Other Functions

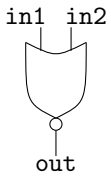
```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |



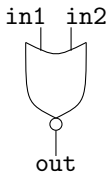

out = NOR(in1,in2)

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

```
if (*in1 + *in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |



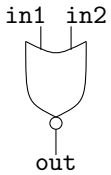

out = **NOR**(in1,in2)

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

```
if (*in1 + *in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |




| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | |
| FALSE | TRUE | |
| TRUE | FALSE | |
| TRUE | TRUE | |

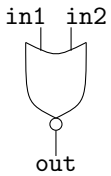
out = **NOR**(in1,in2)

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

```
if (*in1 + *in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |




| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | |
| TRUE | FALSE | |
| TRUE | TRUE | |

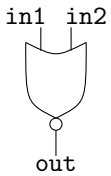
out = **NOR**(in1,in2)

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

```
if (*in1 + *in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |




| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | TRUE |
| TRUE | FALSE | |
| TRUE | TRUE | |

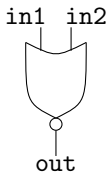
out = NOR(in1,in2)

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

```
if (*in1 + *in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |




out = NOR(in1,in2)

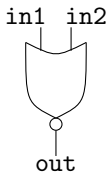
| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | TRUE |
| TRUE | FALSE | TRUE |
| TRUE | TRUE | |

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

```
if (*in1 + *in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |



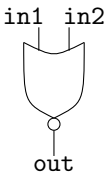

out = NOR(in1,in2)

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | TRUE |
| TRUE | FALSE | TRUE |
| TRUE | TRUE | FALSE |

# Other Functions

```
if (*in1 == 99)
  return
if (*in2 == 99)
  return
a = *out
```

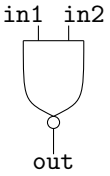
| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | FALSE |
| TRUE | FALSE | FALSE |
| TRUE | TRUE | FALSE |




out = **NOR**(in1,in2)

```
if (*in1 + *in2 == 99)
  return
a = *out
```

| *in1 | *in2 | *out |
|---|---|---|
| FALSE | FALSE | TRUE |
| FALSE | TRUE | TRUE |
| TRUE | FALSE | TRUE |
| TRUE | TRUE | FALSE |




out = **NAND**(in1,in2)

# Quiz Time

```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

# Quiz Time

```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | |
| FALSE | FALSE | TRUE | |
| FALSE | TRUE | FALSE | |
| FALSE | TRUE | TRUE | |
| TRUE | FALSE | FALSE | |
| TRUE | FALSE | TRUE | |
| TRUE | TRUE | FALSE | |
| TRUE | TRUE | TRUE | |

# Quiz Time

```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | |
| FALSE | TRUE | FALSE | |
| FALSE | TRUE | TRUE | |
| TRUE | FALSE | FALSE | |
| TRUE | FALSE | TRUE | |
| TRUE | TRUE | FALSE | |
| TRUE | TRUE | TRUE | |

# Quiz Time

```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | |
| FALSE | TRUE | TRUE | |
| TRUE | FALSE | FALSE | |
| TRUE | FALSE | TRUE | |
| TRUE | TRUE | FALSE | |
| TRUE | TRUE | TRUE | |

# Quiz Time

```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | TRUE |
| FALSE | TRUE | TRUE | |
| TRUE | FALSE | FALSE | |
| TRUE | FALSE | TRUE | |
| TRUE | TRUE | FALSE | |
| TRUE | TRUE | TRUE | |

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```
if (*in1 + *in2 == 99)
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if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | TRUE |
| FALSE | TRUE | TRUE | FALSE |
| TRUE | FALSE | FALSE | |
| TRUE | FALSE | TRUE | |
| TRUE | TRUE | FALSE | |
| TRUE | TRUE | TRUE | |

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```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | TRUE |
| FALSE | TRUE | TRUE | FALSE |
| TRUE | FALSE | FALSE | TRUE |
| TRUE | FALSE | TRUE | |
| TRUE | TRUE | FALSE | |
| TRUE | TRUE | TRUE | |

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```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | TRUE |
| FALSE | TRUE | TRUE | FALSE |
| TRUE | FALSE | FALSE | TRUE |
| TRUE | FALSE | TRUE | FALSE |
| TRUE | TRUE | FALSE | |
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if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | TRUE |
| FALSE | TRUE | TRUE | FALSE |
| TRUE | FALSE | FALSE | TRUE |
| TRUE | FALSE | TRUE | FALSE |
| TRUE | TRUE | FALSE | FALSE |
| TRUE | TRUE | TRUE | |

# Quiz Time

```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | TRUE |
| FALSE | TRUE | TRUE | FALSE |
| TRUE | FALSE | FALSE | TRUE |
| TRUE | FALSE | TRUE | FALSE |
| TRUE | TRUE | FALSE | FALSE |
| TRUE | TRUE | TRUE | FALSE |

# Quiz Time

```
if (*in1 + *in2 == 99)
  return
if (*in2 + *in3 == 99)
  return
if (*in1 + *in3 == 99)
  return
a = *out
```

| *in1 | *in2 | *in3 | *out |
|---|---|---|---|
| FALSE | FALSE | FALSE | TRUE |
| FALSE | FALSE | TRUE | TRUE |
| FALSE | TRUE | FALSE | TRUE |
| FALSE | TRUE | TRUE | FALSE |
| TRUE | FALSE | FALSE | TRUE |
| TRUE | FALSE | TRUE | FALSE |
| TRUE | TRUE | FALSE | FALSE |
| TRUE | TRUE | TRUE | FALSE |

`out = NOT(major(in1,in2,in3))`

# Multiple Outputs

# Multiple Outputs

- Needed because gates destroy their inputs

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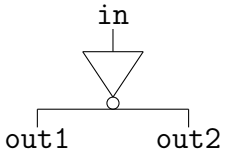
- Needed because gates destroy their inputs

```
if (*in == 99)
  return
a = *out1 + *out2
```

# Multiple Outputs

- Needed because gates destroy their inputs

```
if (*in == 99)
  return
a = *out1 + *out2
```



# Circuits

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- 4-bit ALU
  - 1 258 gates, 84-95% accuracy

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- SHA-1
  - one round: 2 208 gates, 95% accuracy

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  - 1 258 gates, 84-95% accuracy
- SHA-1
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- Game of Life
  - 7 807 gates, 73% accuracy for one generation

# Circuits

- 4-bit ALU
  - 1 258 gates, 84-95% accuracy
- SHA-1
  - one round: 2 208 gates, 95% accuracy
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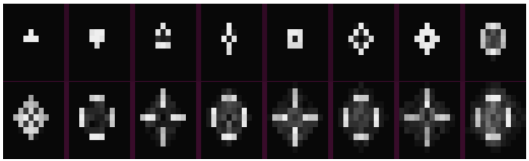
  - 7 807 gates, 73% accuracy for one generation



# Amplification

- NOT gate with large fan-out

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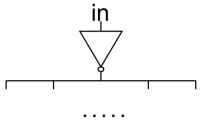
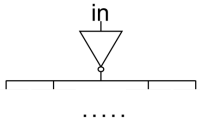
- NOT gate with large fan-out (e.g., Y = 8)



# Amplification

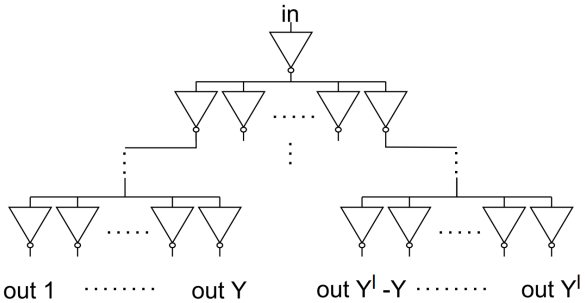
- NOT gate with large fan-out (e.g., Y = 8)




```
if (*in == 99)
  return
a = *out1 + *out2 + *out3 + *out4+ *out5 + *out6 + *out7 + *out8
```

# Amplification

- NOT gate with large fan-out (e.g., $Y = 8$)
  - $l = 2$ layers: 64
  - $l = 3$ layers: 512
  - $l = 4$ layers: 4 096




```
if (*in == 99)
  return
a = *out1 + *out2 + *out3 + *out4+ *out5 + *out6 + *out7 + *out8
```

# Prime+Store: High-Resolution Prime+Probe

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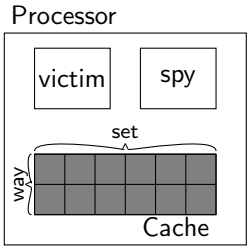
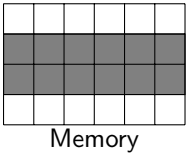
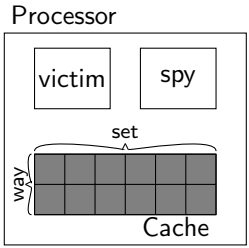
- Prime as in Prime+Probe

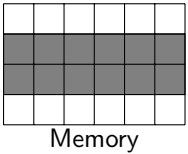


# Prime+Store: High-Resolution Prime+Probe

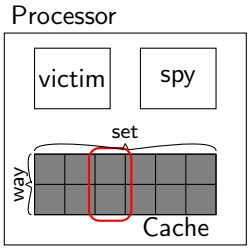
- Prime as in Prime+Probe
- Probe is basically a NAND gate

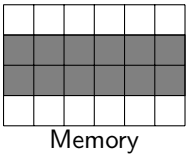


# Prime+Store: High-Resolution Prime+Probe

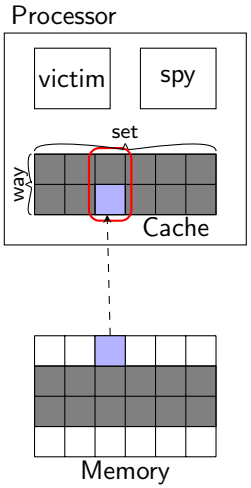
- Prime as in Prime+Probe
- Probe is basically a NAND gate
  - FALSE if all are cached



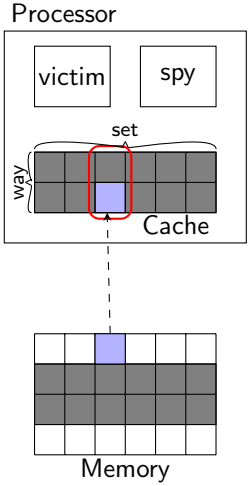
# Prime+Store: High-Resolution Prime+Probe

- Prime as in Prime+Probe
- Probe is basically a NAND gate
  - FALSE if all are cached
  - TRUE if some are not cached



# Prime+Store: High-Resolution Prime+Probe

- Prime as in Prime+Probe
- Probe is basically a NAND gate
  - FALSE if all are cached
  - TRUE if some are not cached
- Do multiple probes of the same cache set and store results.



# Prime+Store: High-Resolution Prime+Probe (cont.)

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- Decouple probe from time measurement

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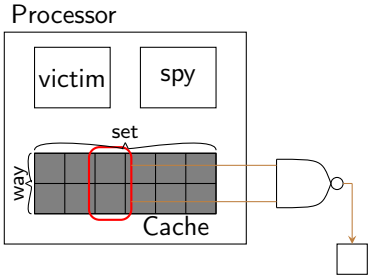
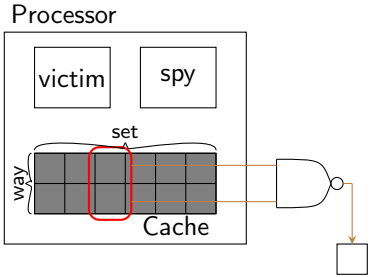


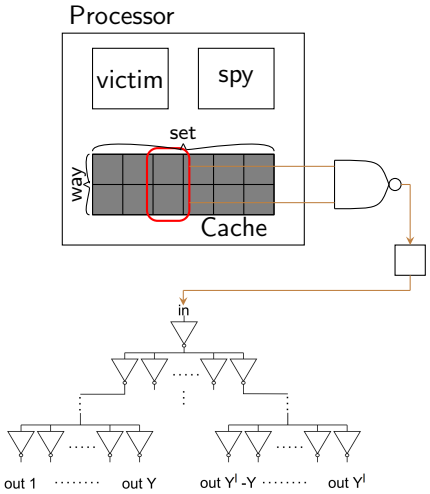
# Prime+Store: High-Resolution Prime+Probe (cont.)

- Decouple probe from time measurement
- Measure time with amplification tree



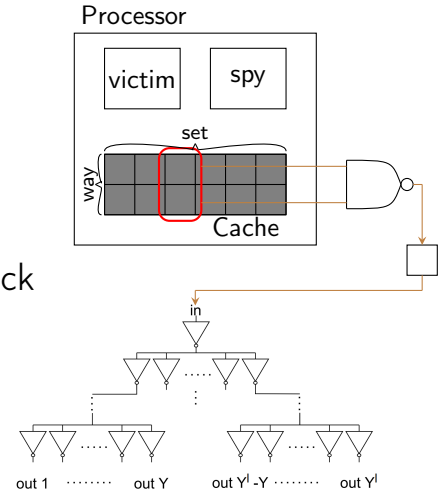
# Prime+Store: High-Resolution Prime+Probe (cont.)

- Decouple probe from time measurement
- Measure time with amplification tree



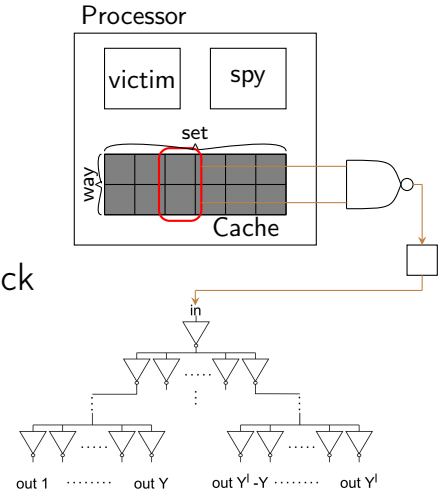
# Prime+Store: High-Resolution Prime+Probe (cont.)

- Decouple probe from time measurement
- Measure time with amplification tree
- Attack square-and-multiply with slow clock



# Prime+Store: High-Resolution Prime+Probe (cont.)

- Decouple probe from time measurement
- Measure time with amplification tree
- Attack square-and-multiply with slow clock
- Bypass countermeasure of reducing timer resolution



# Challenges in Finding Eviction Sets

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- Cache replacement policies

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  - e.g., LRU, pseudo-LRU, FIFO

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- Cache hierarchies

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- Cache replacement policies
  - e.g., LRU, pseudo-LRU, FIFO
- Cache hierarchies
  - e.g., inclusive, non-inclusive

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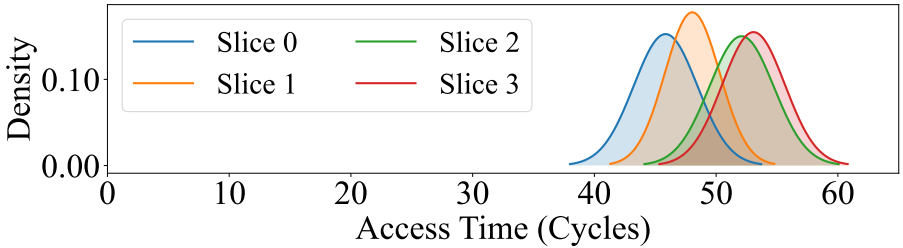

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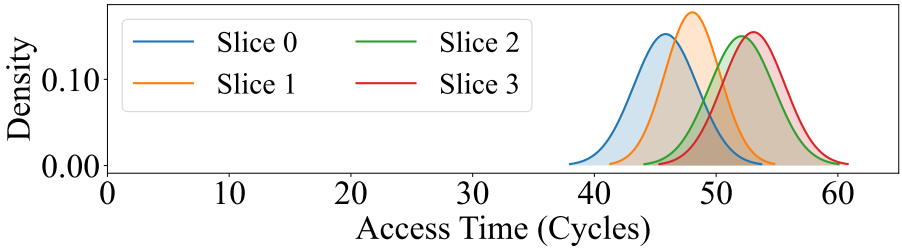

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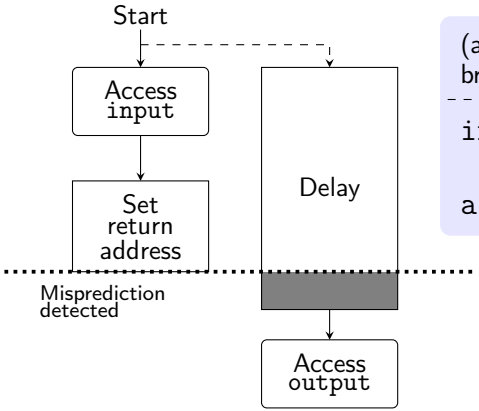


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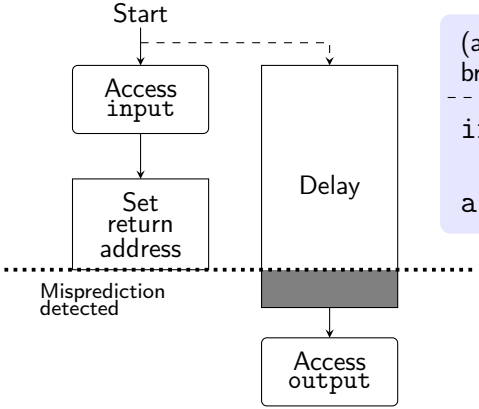


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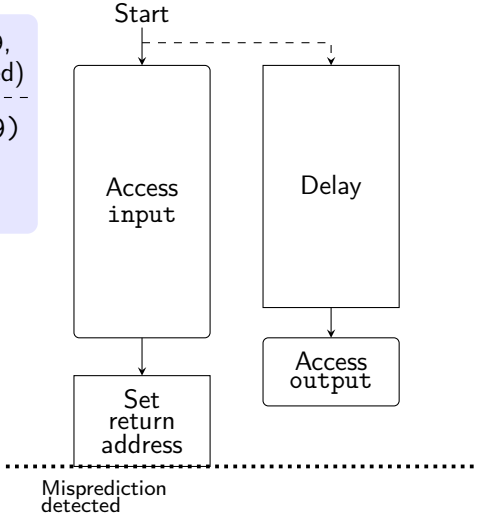

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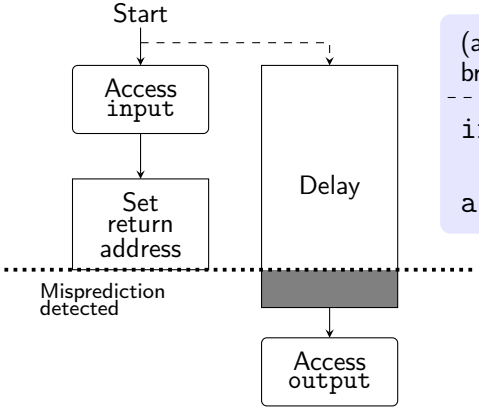


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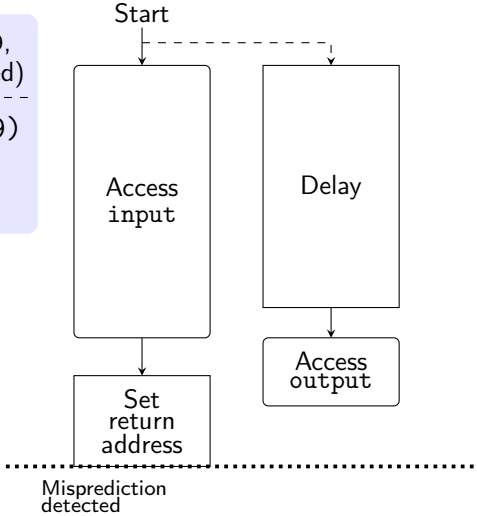
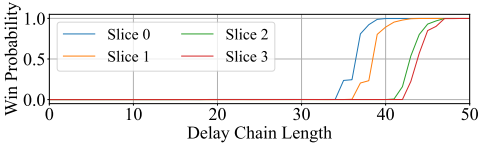
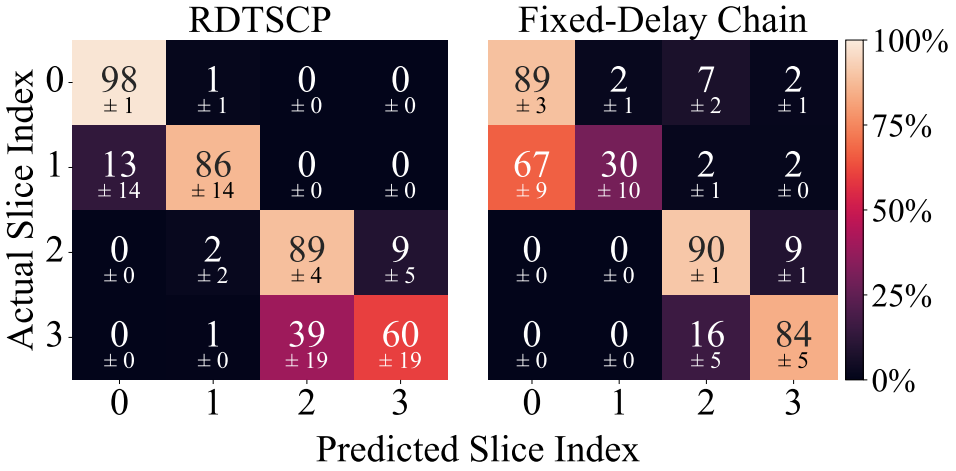


# Slice Classification: quiet system



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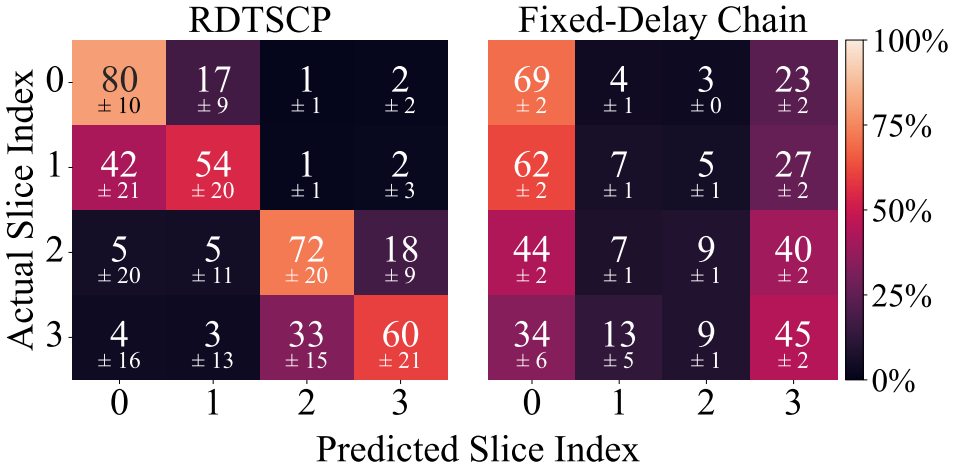
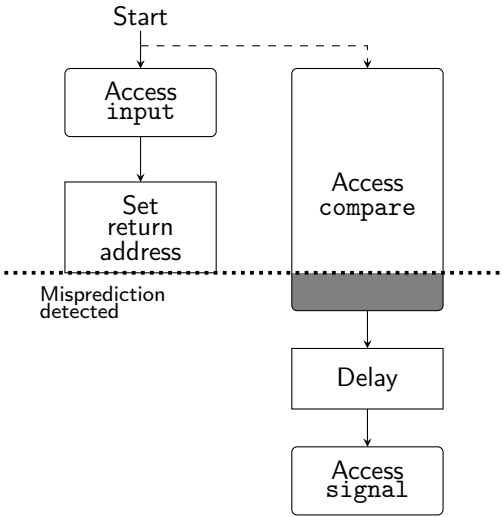
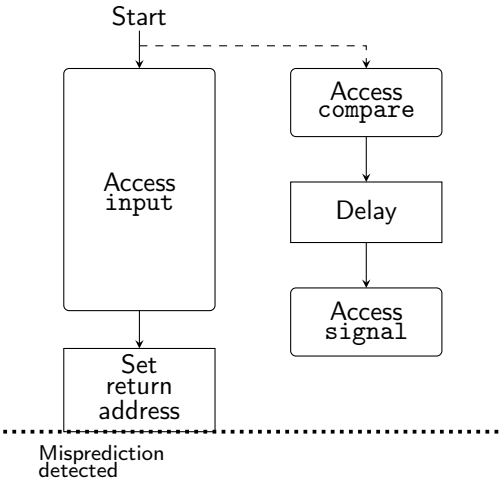
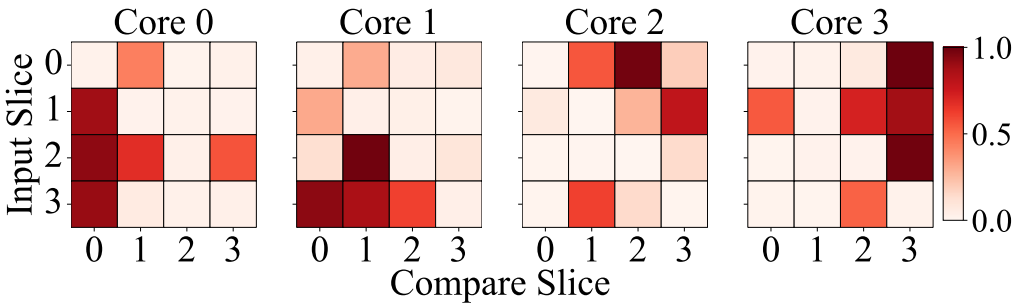


# Comparator Gate

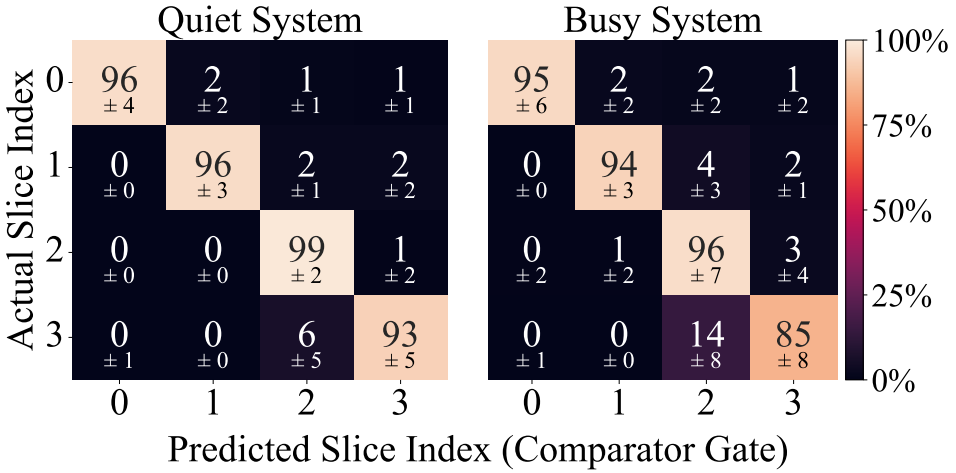


# Comparator Gate: signal access



# Slice Classification with Comparator Gate



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