



EXPLAINED:

MELTDOWN & SPECTRE





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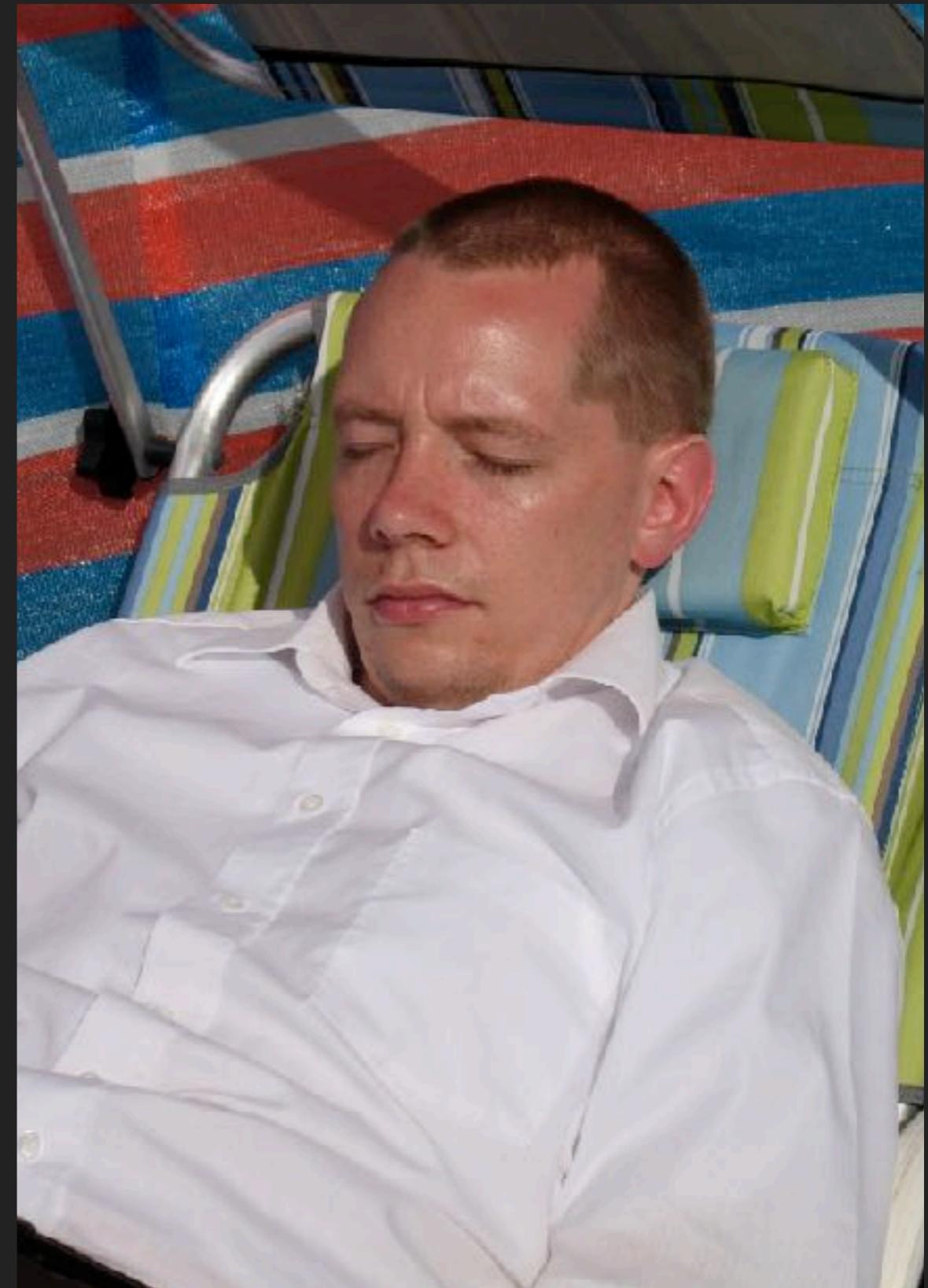
Entropia e.V.
CCC Karlsruhe

people
Jens Neuhalfen

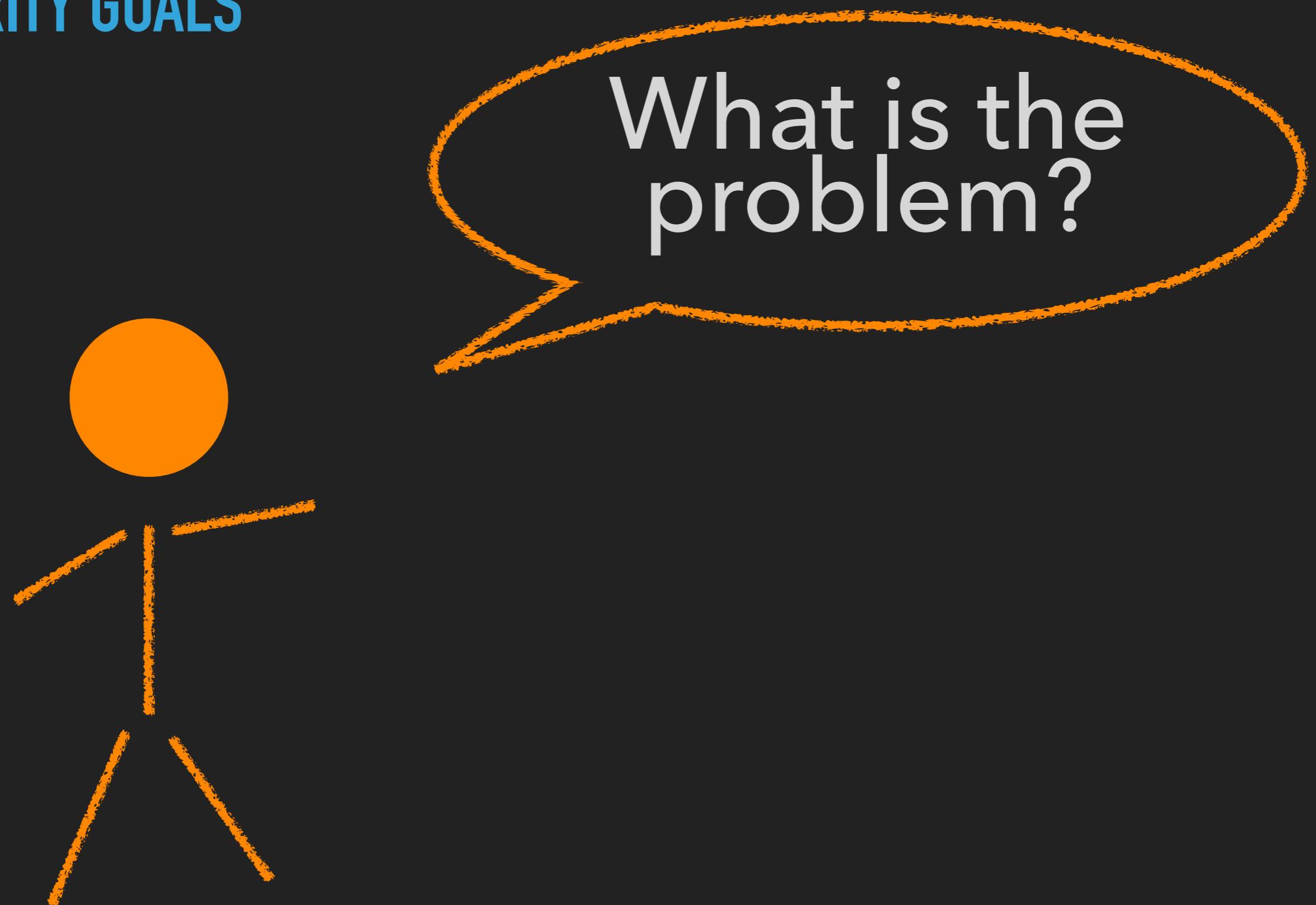


WHO AM I?

- ▶ Jens Neuhalfen
- ▶ Age: Forty something
- ▶ IT since: ever
- ▶ Skills: Bridge between IT and business, IT-Security Management, writing software
- ▶ <https://github.com/neuhalje>



SECURITY GOALS



A PROCESS MUST BE
ISOLATED (PROTECTED) FROM
OTHER PROCESSES!

You

SECURITY GOALS: APP ISOLATION

SECURITY GOALS: APP ISOLATION

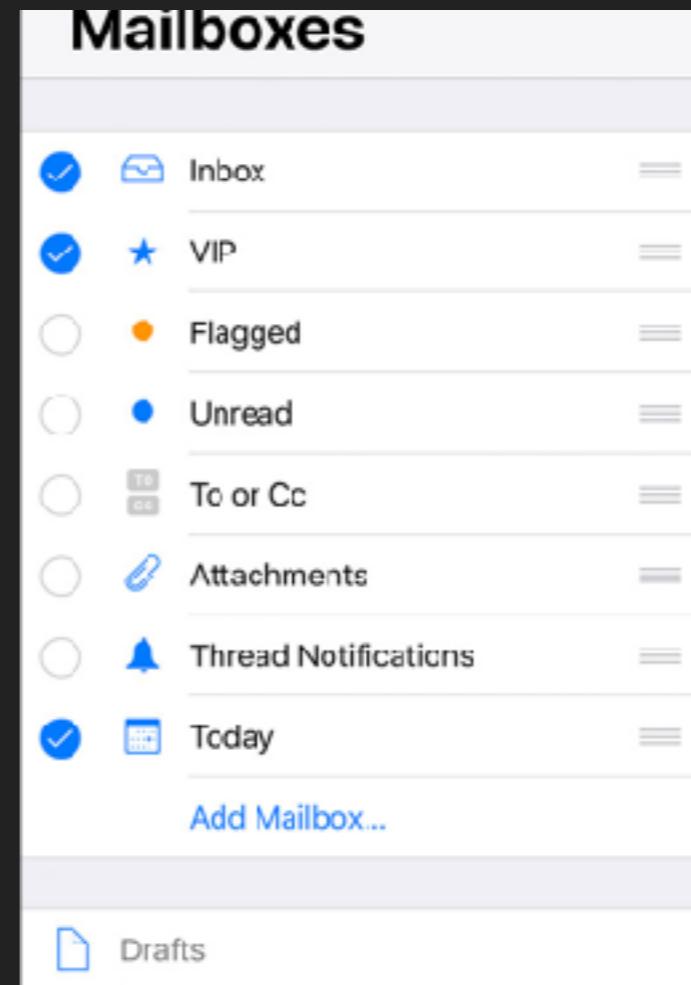


You don't want
this

SECURITY GOALS: APP ISOLATION



You don't want
this



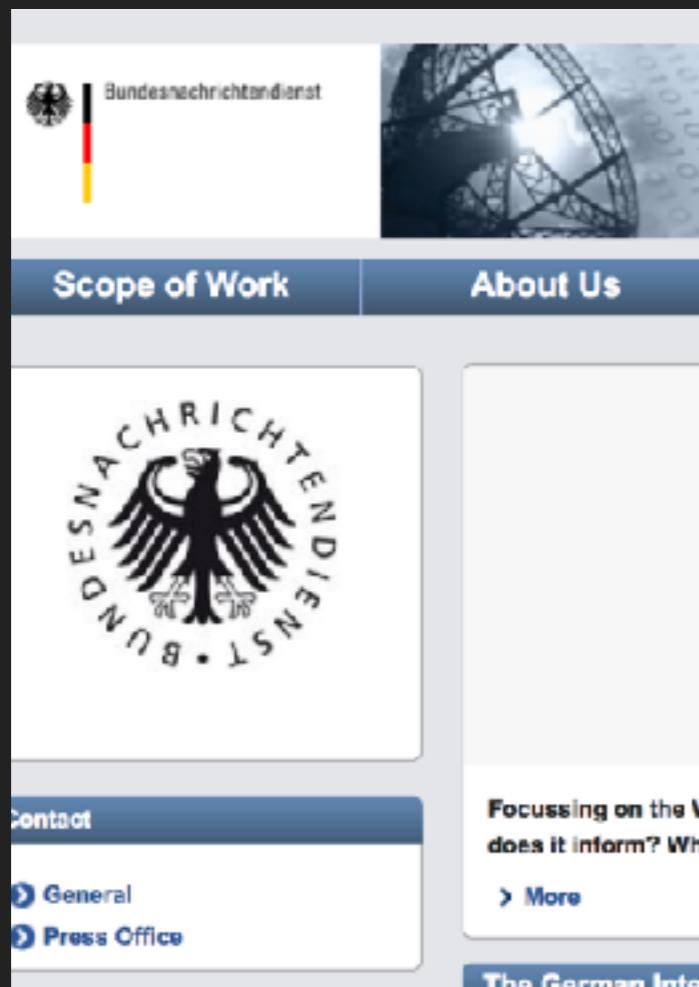
To read
that

SECURITY GOALS: BROWSER TAB ISOLATION

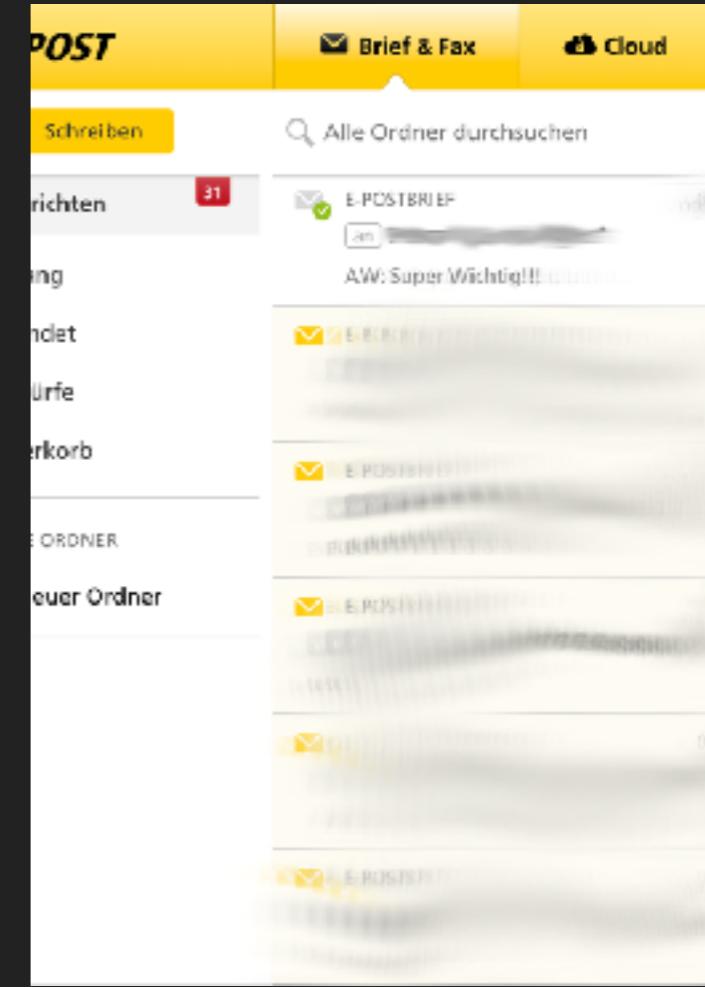


You don't want
this

SECURITY GOALS: BROWSER TAB ISOLATION



You don't want
this



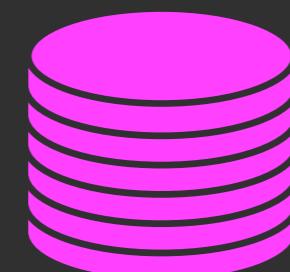
To read
that

SECURITY GOALS: CLOUD ISOLATION



You don't want
this

SECURITY GOALS: CLOUD ISOLATION



You don't want
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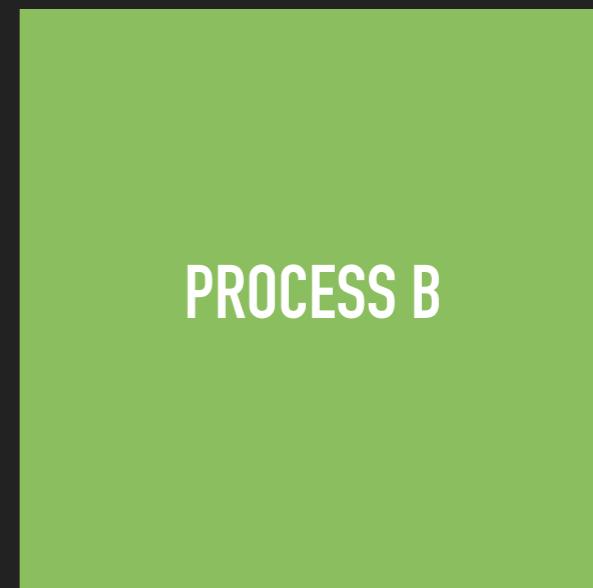
To read
that

SECURITY GOALS: MEMORY ISOLATION



You don't want
this

SECURITY GOALS: MEMORY ISOLATION



You don't want
this

To read
that

SECURITY GOALS: MEMORY ISOLATION

The more a system relies on process isolation to achieve its security goal, the more critical Meltdown and Spectre are.

PROCESS A

PROCESS B

You don't want
this

To read
that

SECURITY GOALS: MEMORY ISOLATION

The more a system relies on process isolation to achieve its security goal, the more critical Meltdown and Spectre are.

PROCESS A

PROCESS B

Fortunately an attacker must be able to execute his code on a system to exploit the Meltdown and Spectre attacks.

You don't
this
read
hat



MELTDOWN AND
SPECTRE

MANAGEMENT SUMMARY

MELTDOWN



- ▶ **Result:** Programs can read memory it should not
- ▶ **Affects:** All modern CPU/OS
- ▶ **Vector:** Uses *out of order execution* to read forbidden memory and *cache timing* as side channel to exfiltrate data
- ▶ **How bad:** Bad
- ▶ **Fixes:** Needs changes in CPU and/or OS patches. Modest (X%) to severe (XX%) performance impact, higher on older CPU. Performance impact varies and depends on CPU and workload type.

SPECTRE



- ▶ **Result:** Programs can read all memory
- ▶ **Affects:** All modern CPU/OS
- ▶ **Vector:** Uses *speculative execution* to read forbidden memory and *cache timing* to exfiltrate data
- ▶ **How bad:** Very bad
- ▶ **Fixes:** Needs changes in CPU and/or changes in programs. Performance impact varies and depends on CPU and workload type.

THREAT-O-METER

Threat - O - Meter

LOW RISK

Exploit unlikely or
running
untrusted code already
worst case

MEDIUM RISK

Exploit possible but
needs another
successful attack to run
attackers code

HIGH RISK

Exploit possible and
runs untrusted code "by
design"

THREAT-O-METER

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MELTDOWN & SPECTRE FOR NORMAL PEOPLE

THREAT-O-METER

Public clouds run code of many untrusted parties which makes them very vulnerable.



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THREAT-O-METER



**DATABASE
SERVER**



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THREAT-O-METER



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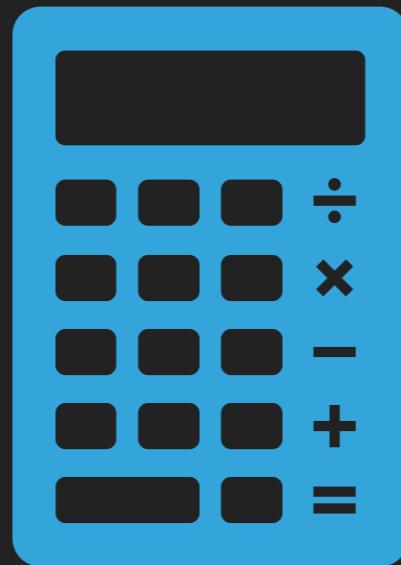
MEDIUM RISK

Exploit possible
needs another
successful attack
attackers co-

Databases are often protected from the internet and are accessed only by application servers.

Running untrusted code on a database is often already the worst case scenario. Patching against Meltdown/Spectre would only marginally increase security.

THREAT-O-METER



MAILSERVER



LOW RISK

Exploit unlikely or
running
untrusted code already
worst case

MEDIUM RISK

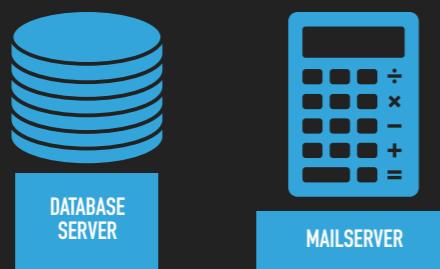
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THREAT-O-METER



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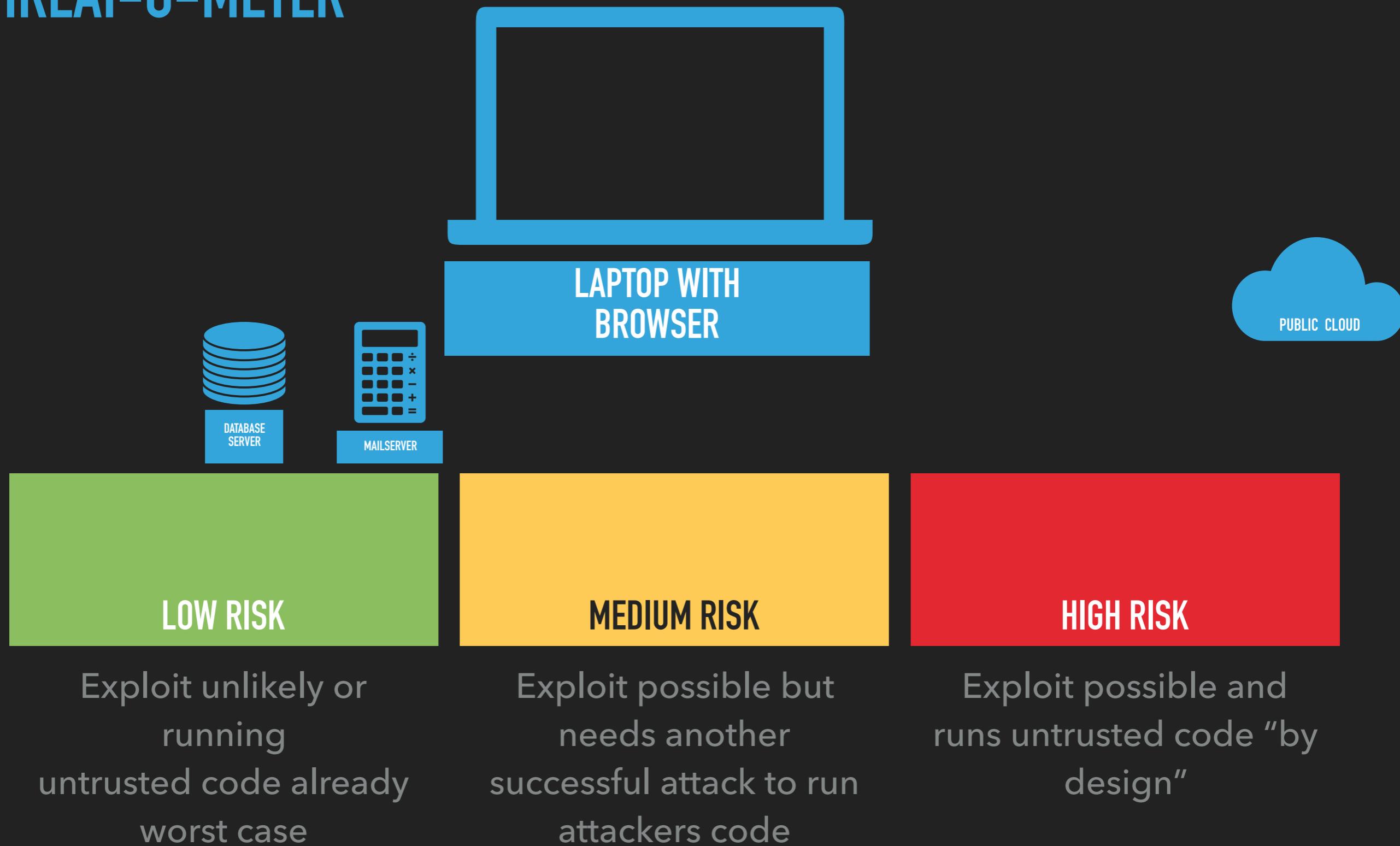
Mailserver are exposed to the internet but have been proven to be very robust to “remote code execution” attacks.

Also a code execution is already the worst case.

Arguably mail servers can be placed in “medium” due to their exposure to the internet.

“design”

THREAT-O-METER



THREAT-O-METER



LOW RISK

Exploit unlikely or
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MEDIUM RISK

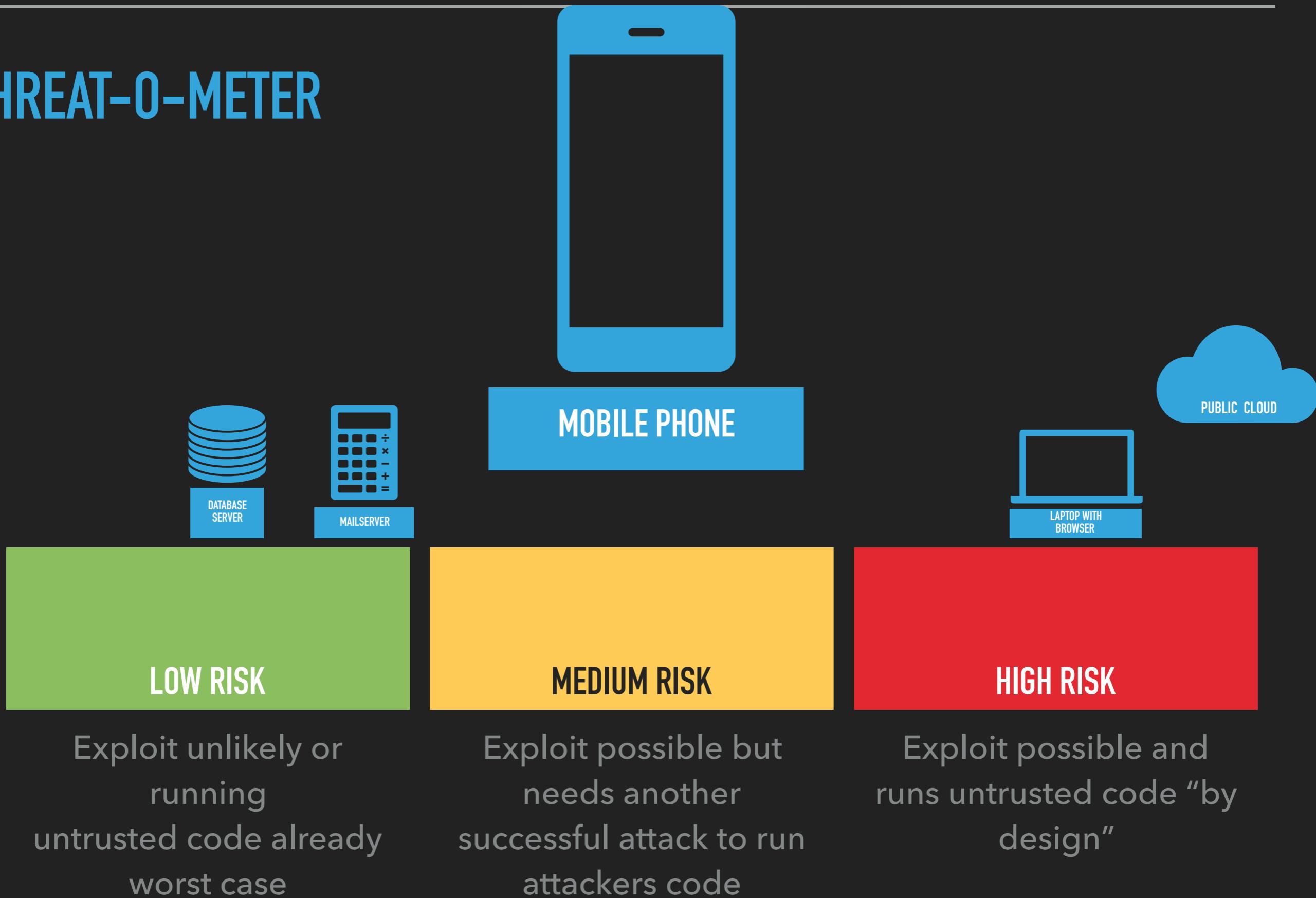
Exploit possible but
needs another
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HIGH RISK

Laptops/desktop systems with browsers are very vulnerable because they execute untrusted code in the form of JavaScript from websites.

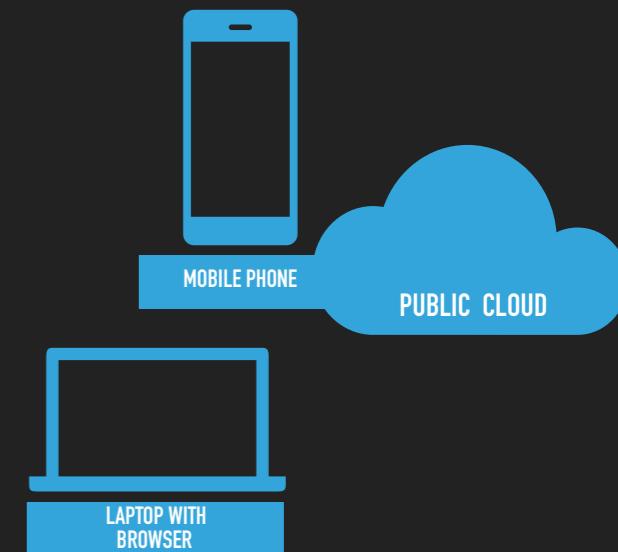
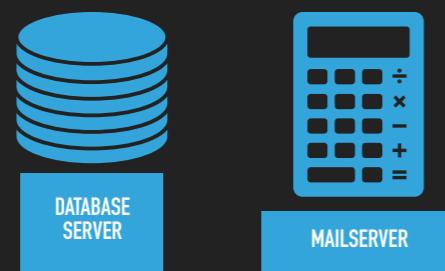


THREAT-O-METER



THREAT-O-METER

Mobile phones run apps and websites (JavaScript).



LOW RISK

Exploit unlikely or running untrusted code already worst case

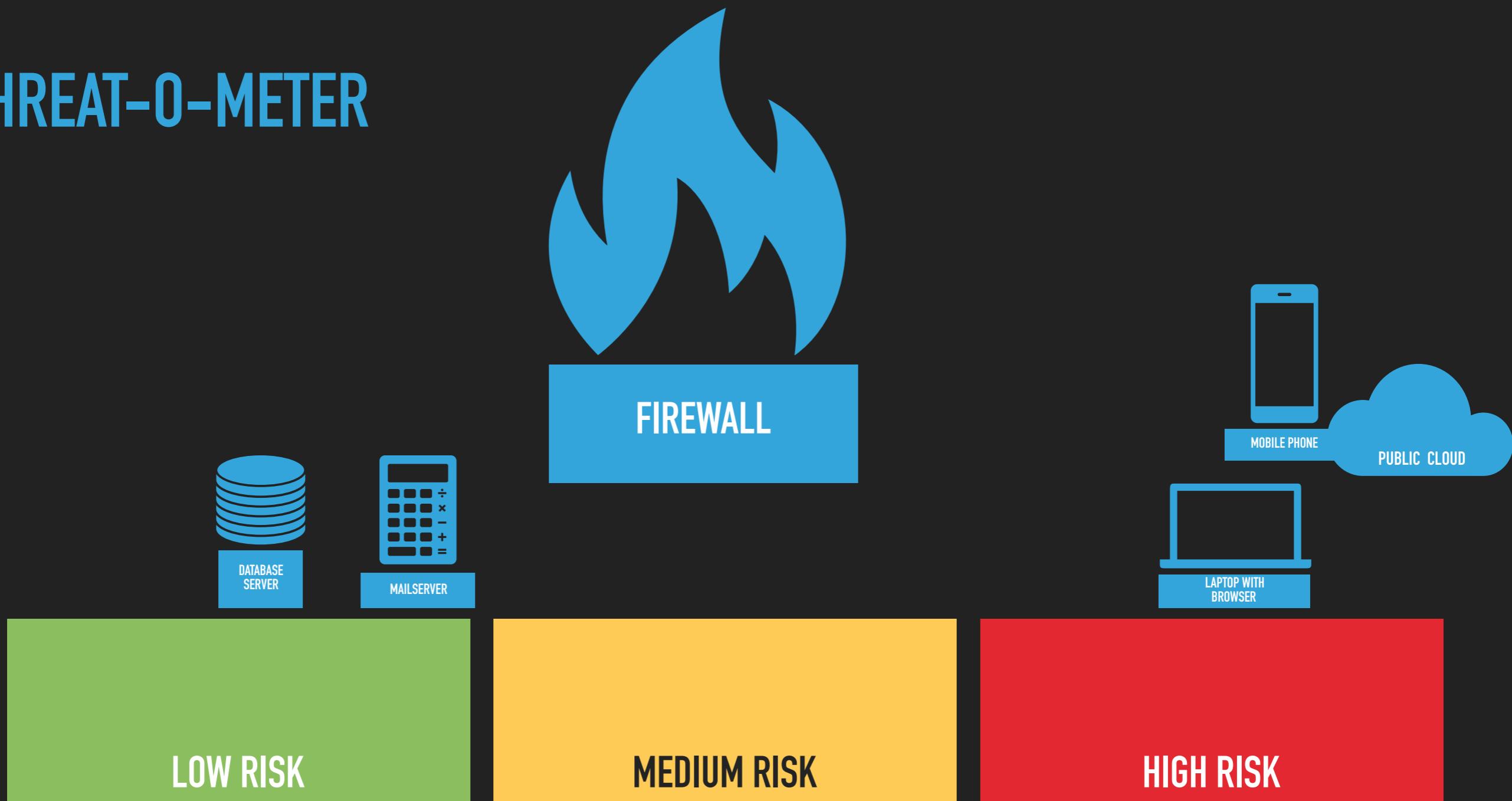
MEDIUM RISK

Exploit possible but needs another successful attack to run attackers code

HIGH RISK

Exploit possible and runs untrusted code "by design"

THREAT-O-METER

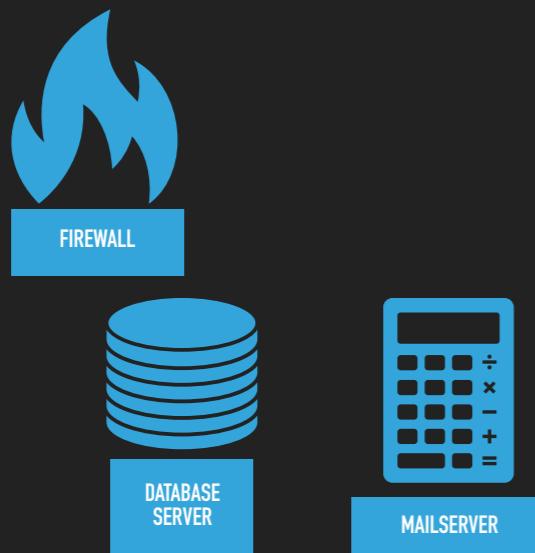


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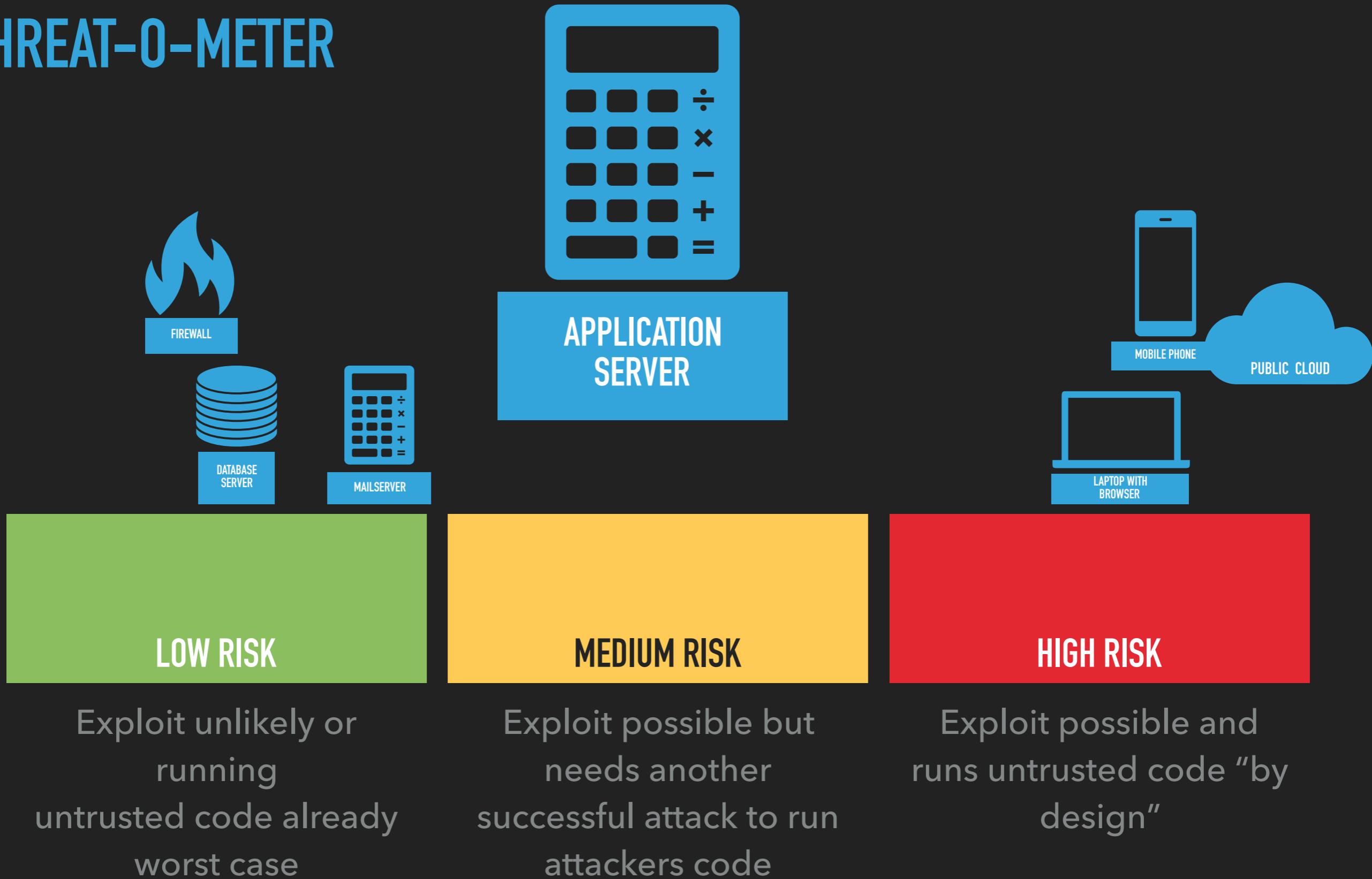
Firewalls and switches
(normally) do not expose
an attackable surface to
the external network.

This greatly reduces the
likelihood of attacks.

A code execution is
already the worst case.

VPN gateways expose a
complex interface and
are more likely to be
attacked.

THREAT-O-METER



THREAT-O-METER

Application servers only run trusted code but attacks can lead to code execution.

How many Java (node, Ruby,...) libraries does your software use? And transitively? Who audits all these?



FIREWALL



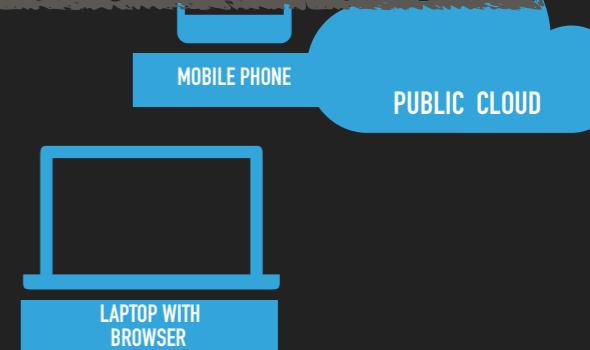
DATABASE SERVER



MAILSERVER



APPLICATION SERVER



MOBILE PHONE

PUBLIC CLOUD



LAPTOP WITH
BROWSER

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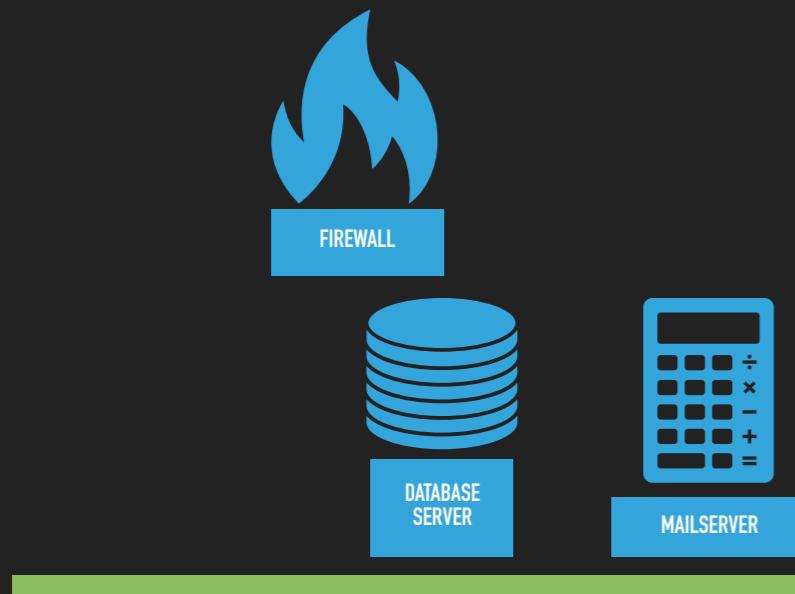
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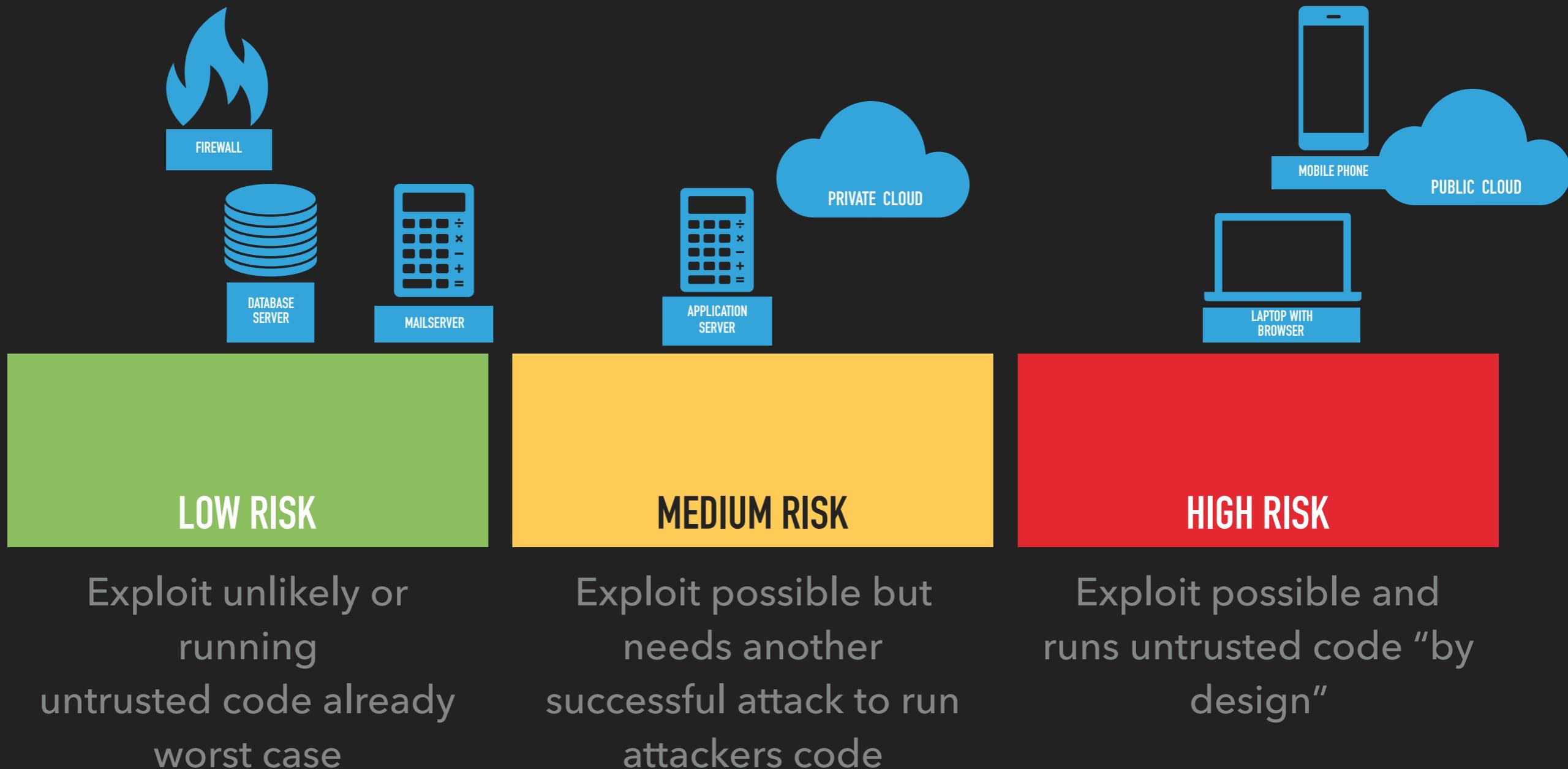
HIGH RISK

Exploit possible and
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Private clouds run many
different workloads but
they are all trusted.

An attacker only needs
to hack one application
running in the cloud to
run a Spectre attack.

THREAT-O-METER



THREAT-O-METER

Given the patches are risky w. regards to performance and availability.

What would be your patching strategy for each risk class?



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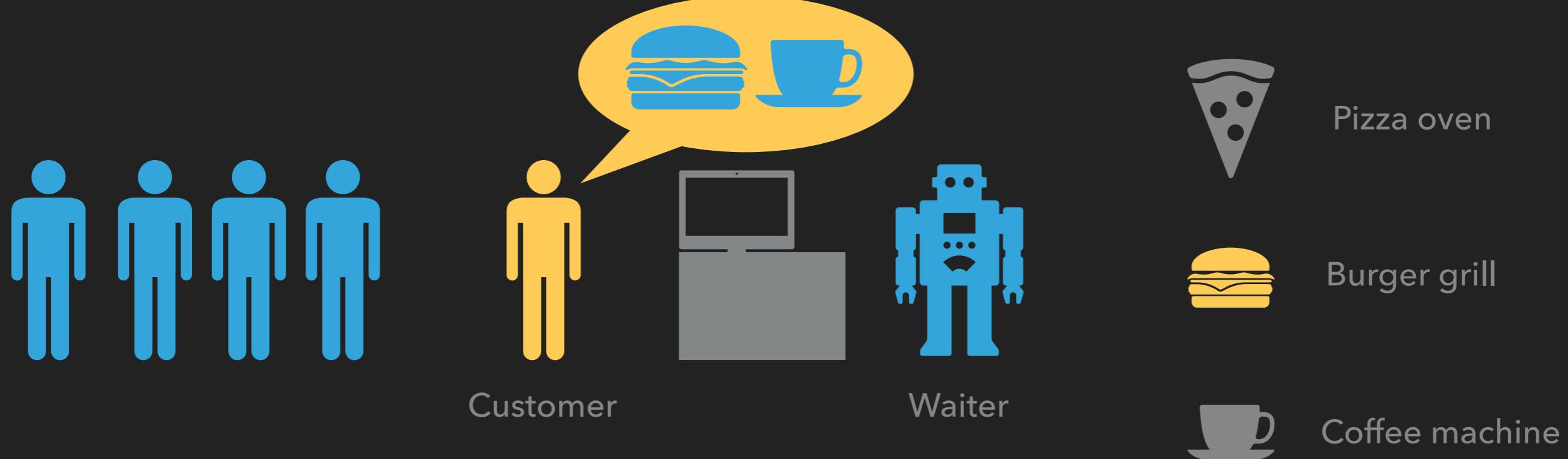


ACCIDENT, MALICE,
INCOMPETENCE?

WHY DID IT
HAPPEN?

CONFIDENTIAL BURGERS INC.

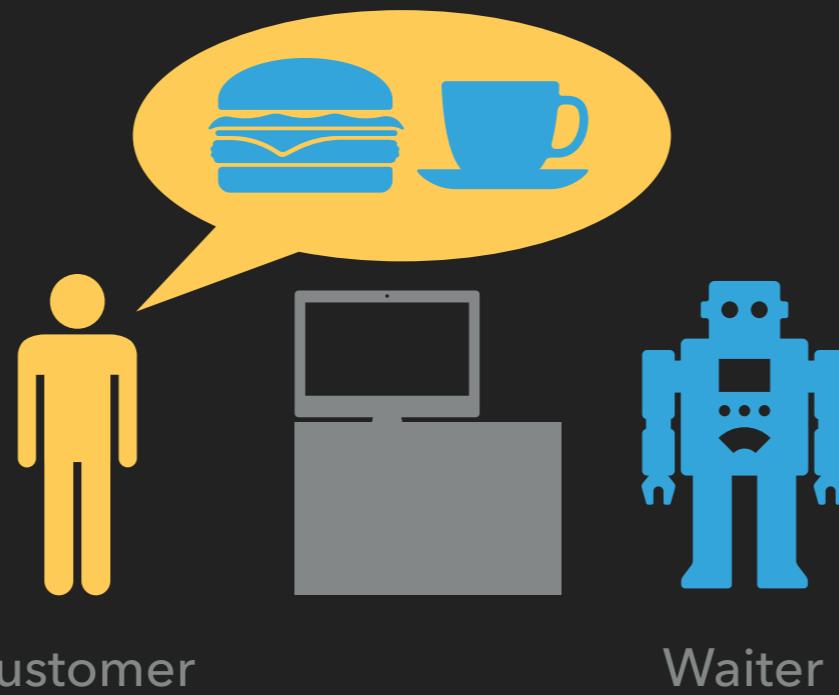
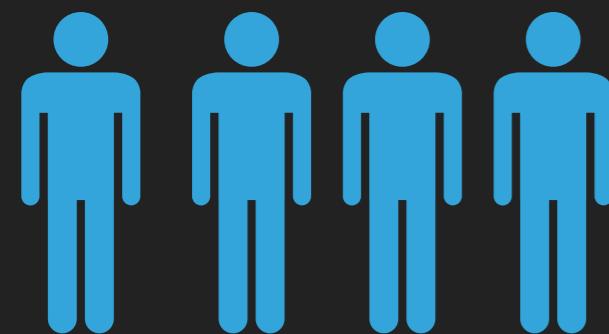
Confidential Burgers inc. sells burgers, pizza, and coffee.



Grand Opening Today

CONFIDENTIAL BURGERS INC.

Confidential Burgers inc. sells burgers, pizza, and coffee.



The waiter (CPU) will



Pizza oven



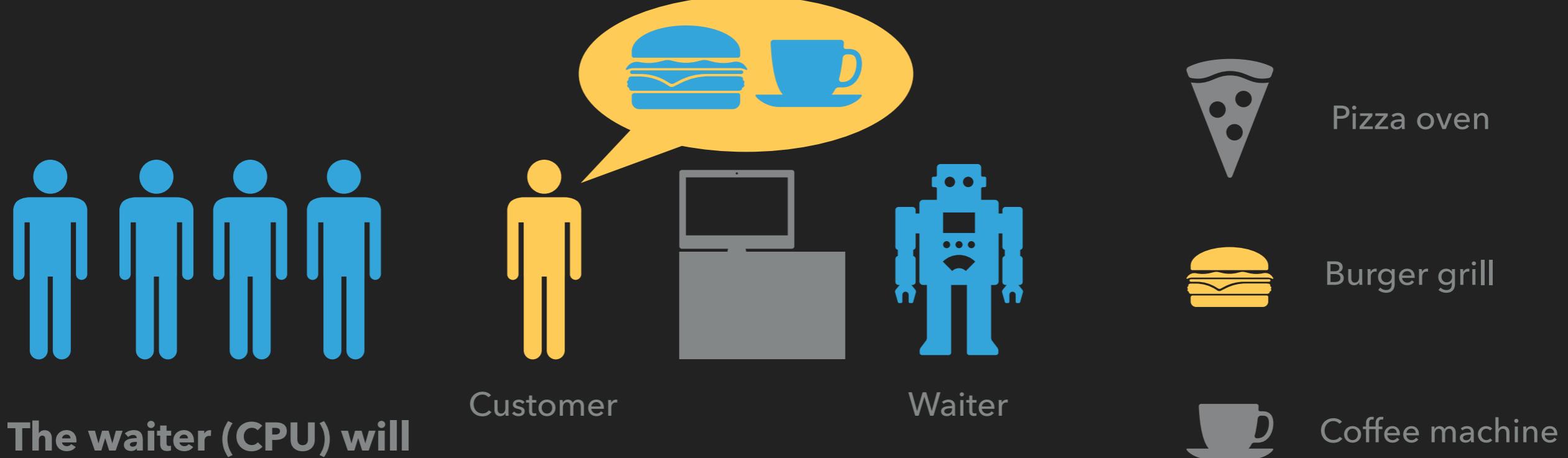
Burger grill



Coffee machine

CONFIDENTIAL BURGERS INC.

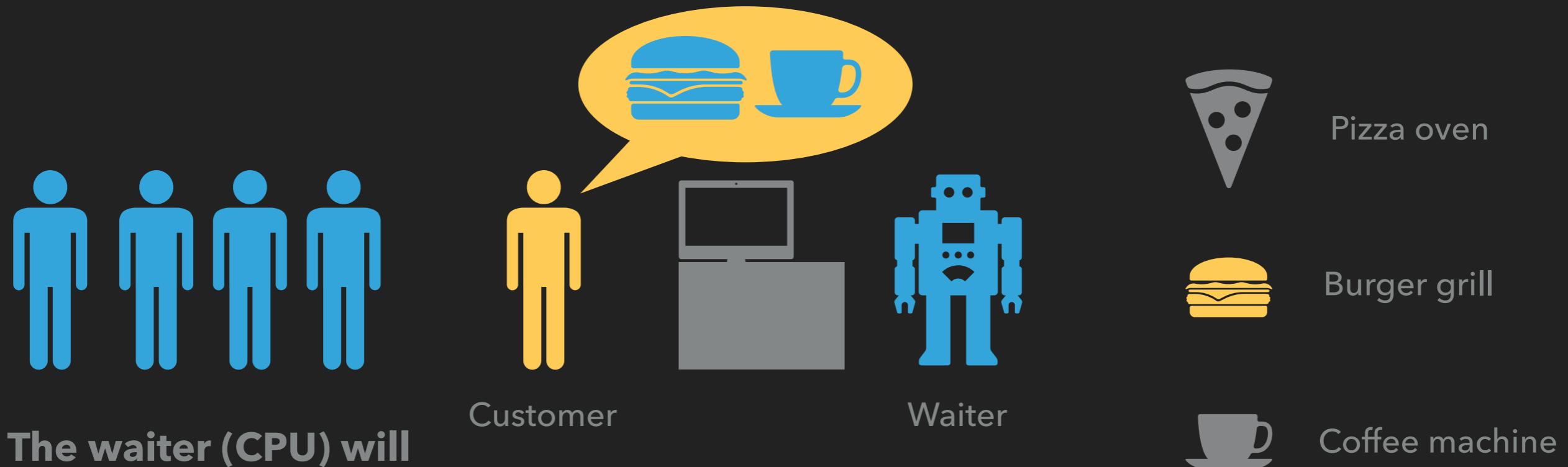
Confidential Burgers inc. sells burgers, pizza, and coffee.



1. take an order from a customer (CPU instruction)

CONFIDENTIAL BURGERS INC.

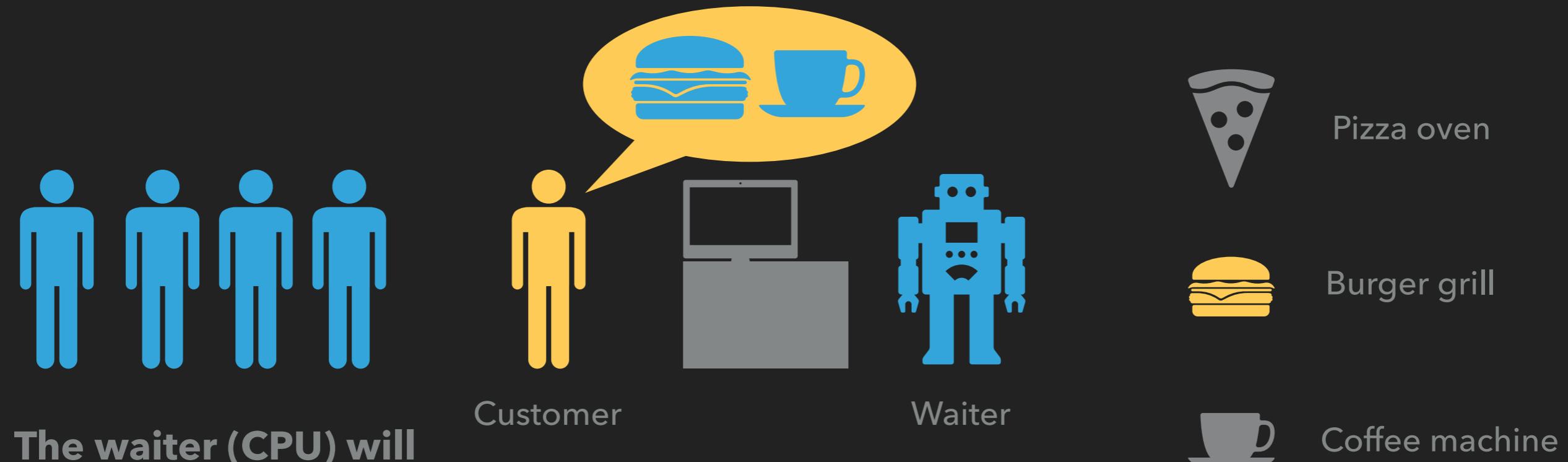
Confidential Burgers inc. sells burgers, pizza, and coffee.



1. take an order from a customer (CPU instruction)
2. break the order (instruction) down into micro operations (μ OPs - grilling a burger, baking a pizza, ...)

CONFIDENTIAL BURGERS INC.

Confidential Burgers inc. sells burgers, pizza, and coffee.

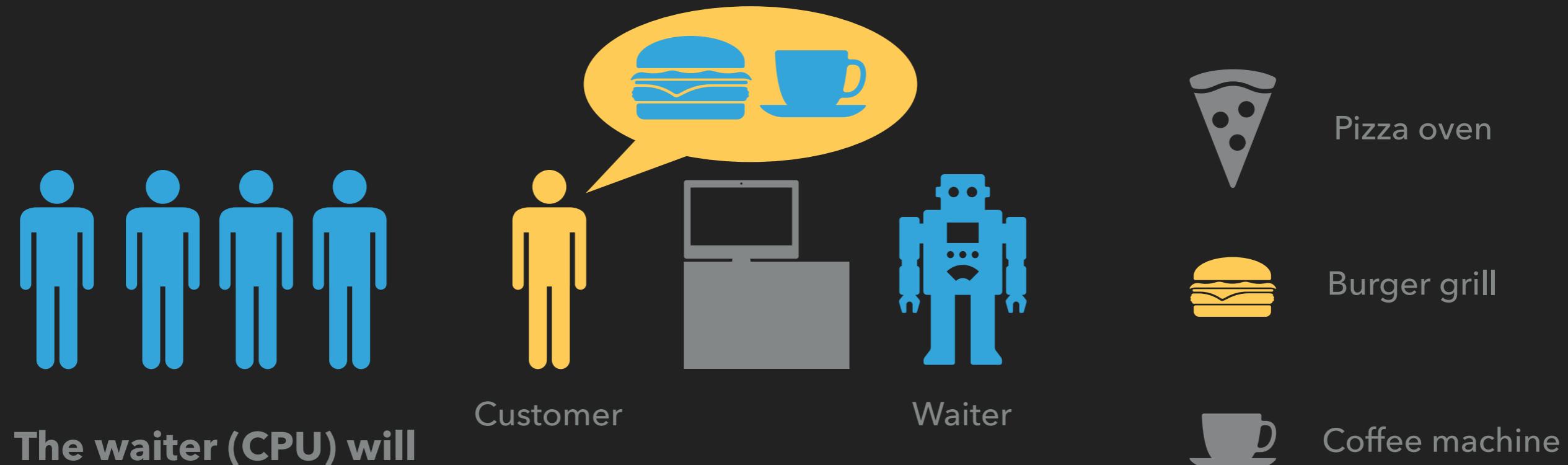


The waiter (CPU) will

1. **take an order from a customer (CPU instruction)**
2. **break the order (instruction) down into micro operations (μ OPs - grilling a burger, baking a pizza, ...)**
3. **schedule and execute the μ OPs**

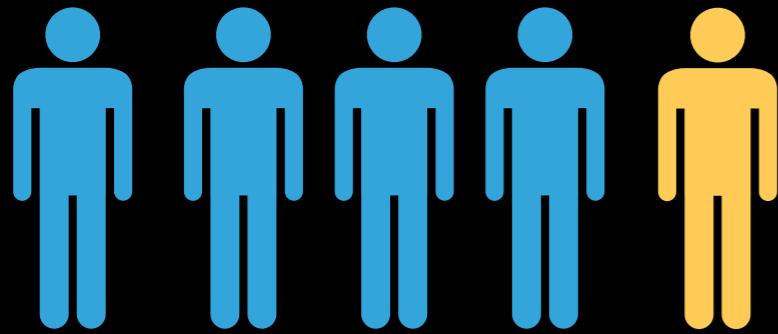
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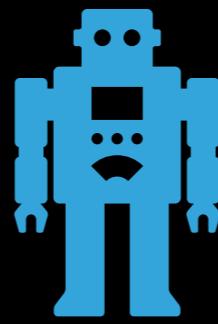


1. take an order from a customer (CPU instruction)
2. break the order (instruction) down into micro operations (μ OPs - grilling a burger, baking a pizza, ...)
3. schedule and execute the μ OPs
4. complete the order (retire the instruction)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



Customer



Waiter



Pizza oven

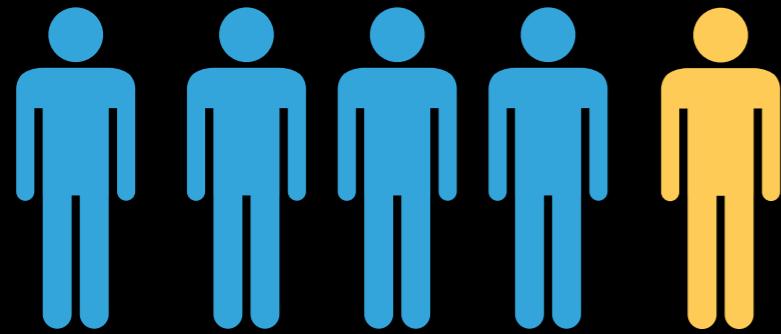


Burger grill

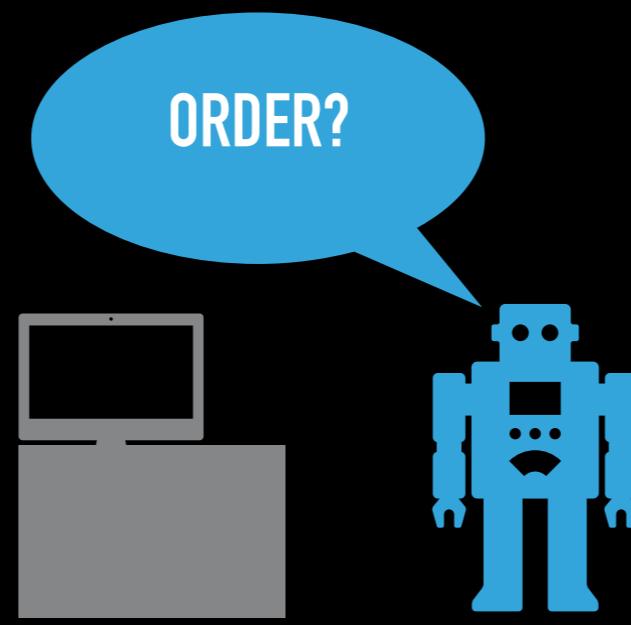


Coffee machine

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



Customer



Waiter



Pizza oven

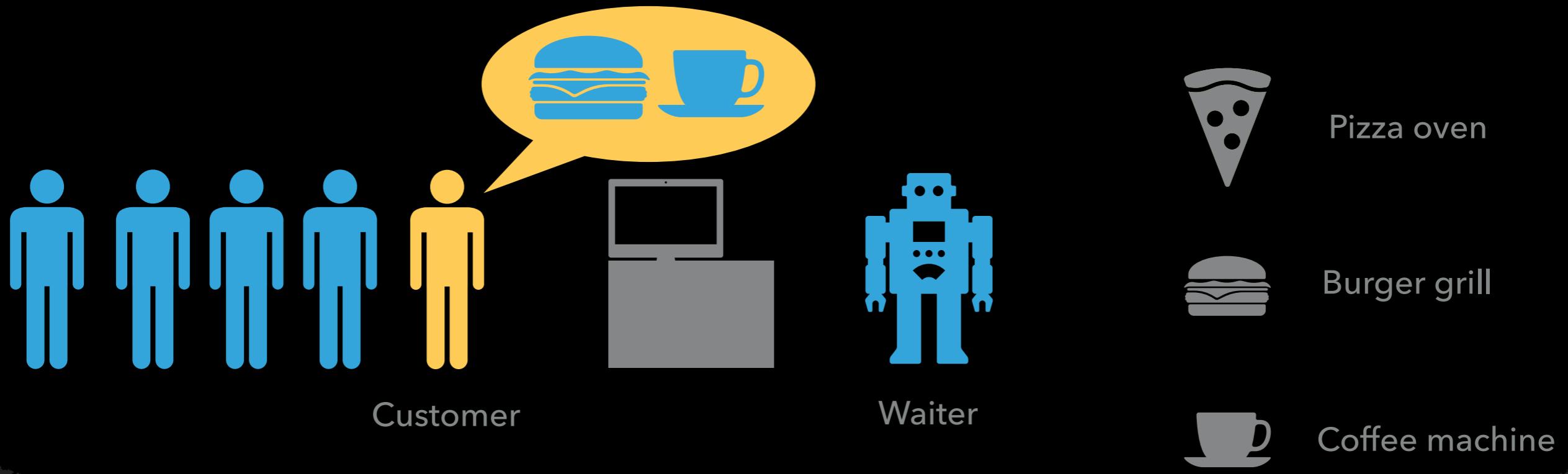


Burger grill



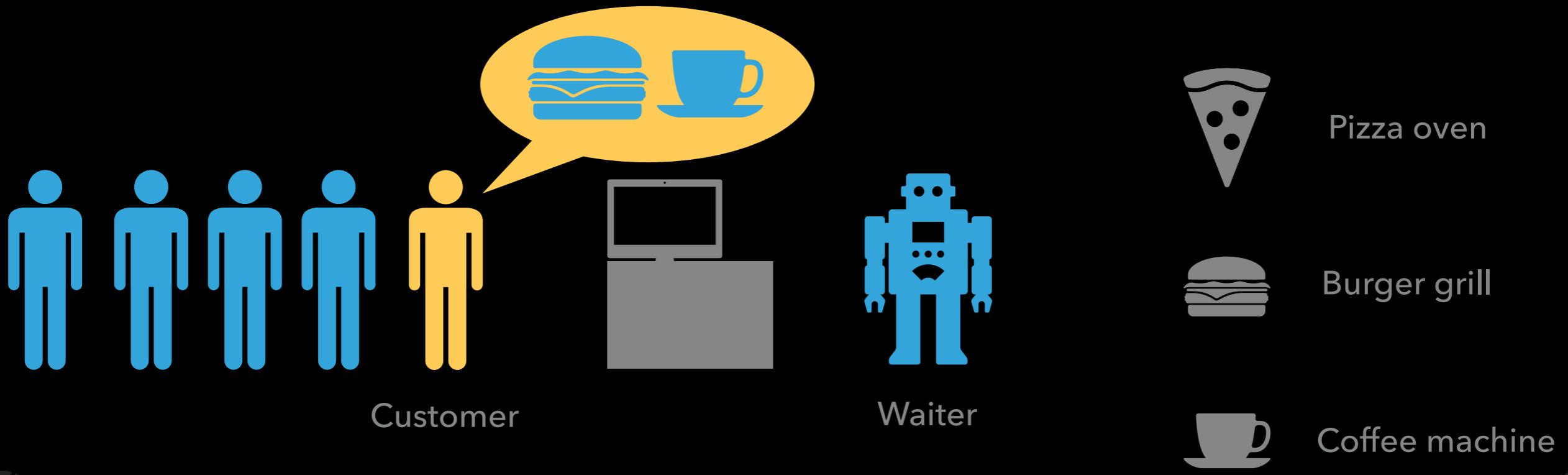
Coffee machine

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



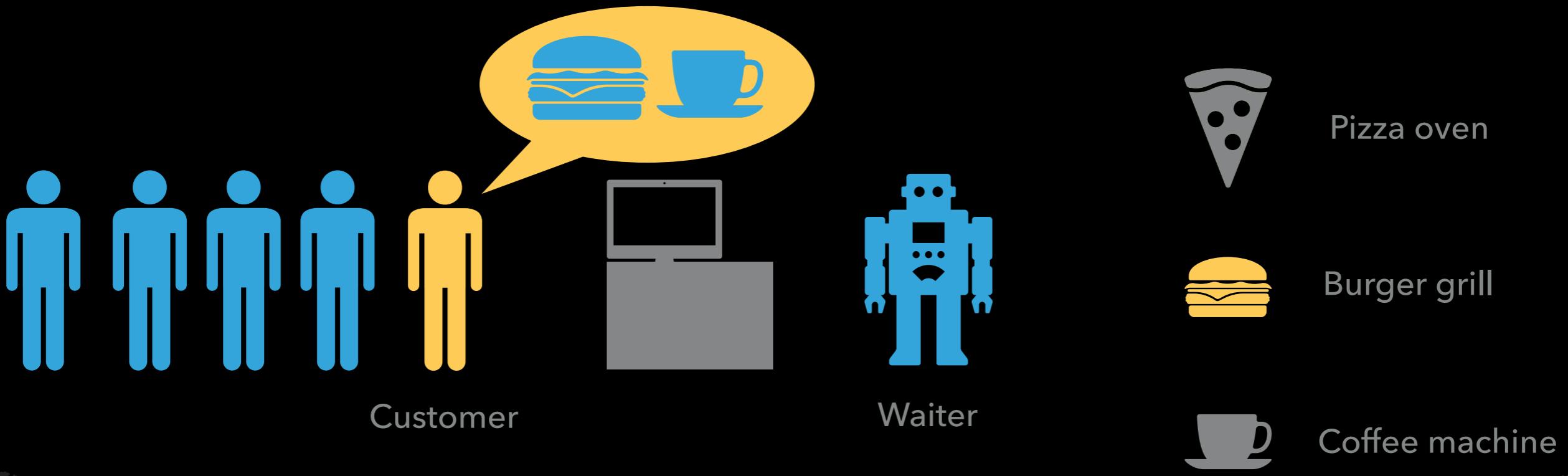
- ▶ Decode instruction into µOPs ("Burger", "Coffee")

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



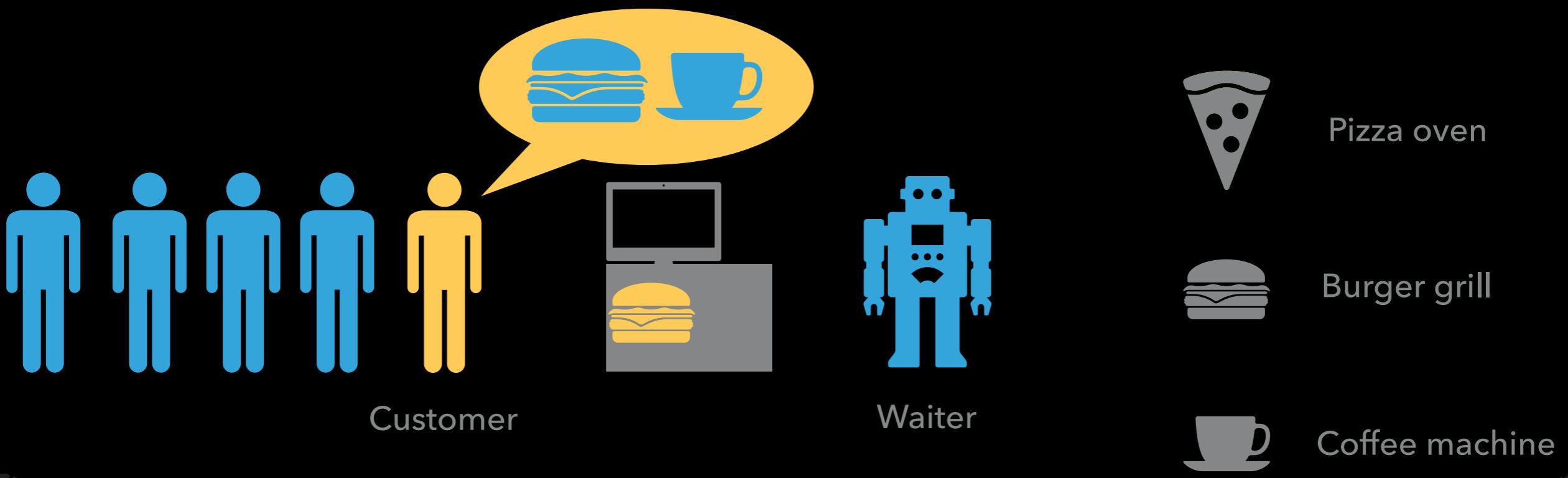
- ▶ Decode instruction into µOPs ("Burger", "Coffee")
- ▶ Schedule µOPs

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



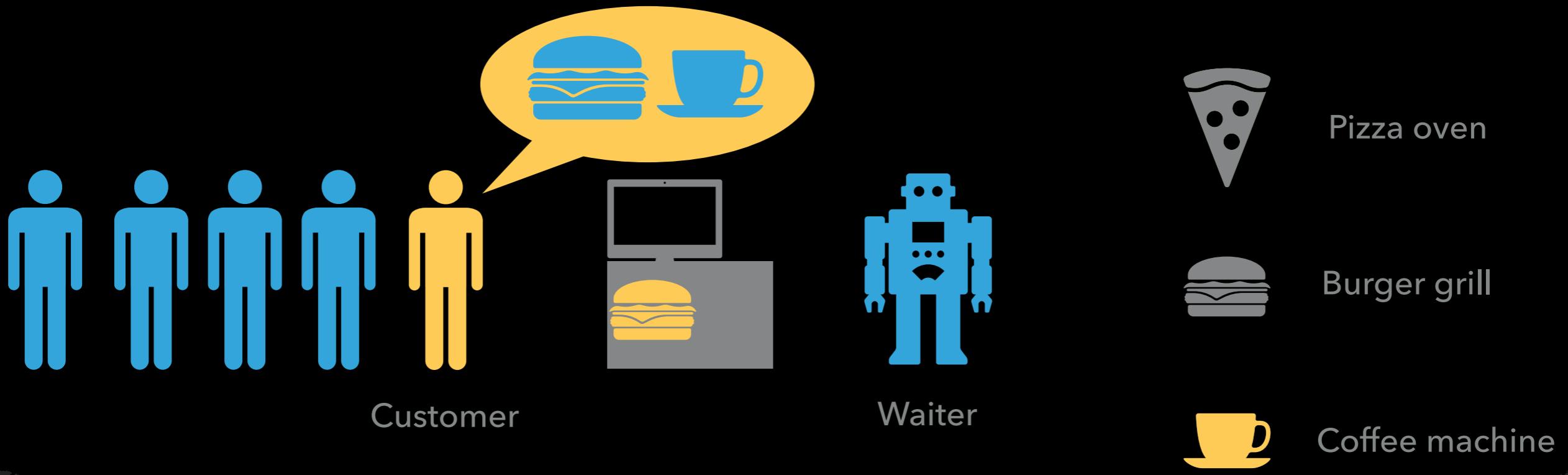
- ▶ Decode instruction into µOPs ("Burger", "Coffee")
- ▶ Schedule µOPs
- ▶ run 1st µOP (grill the burger)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



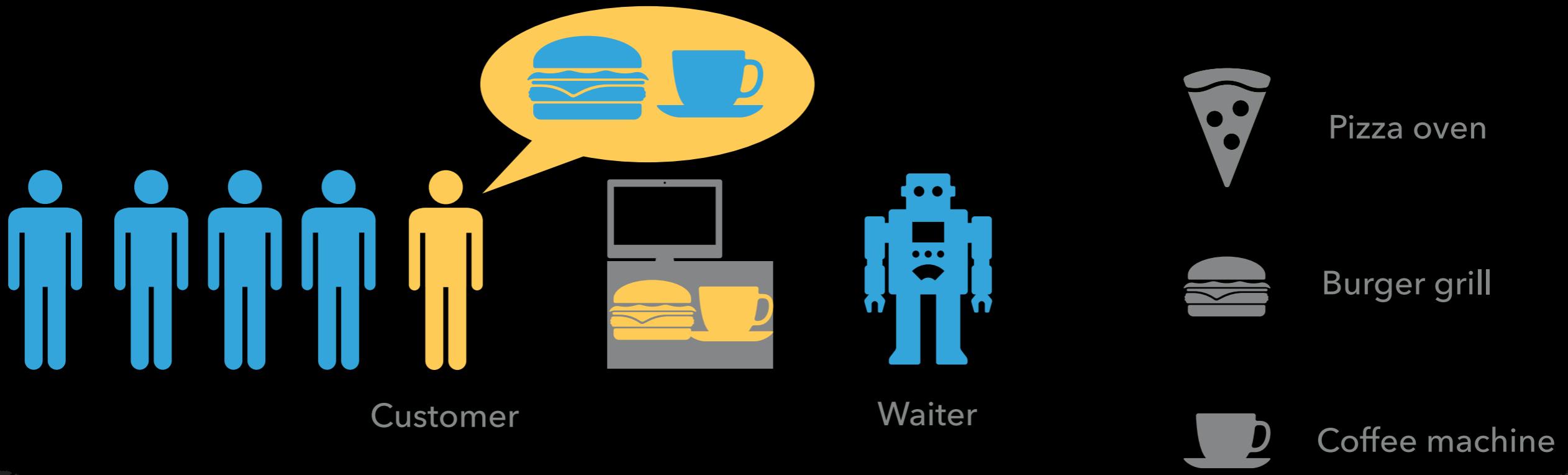
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CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



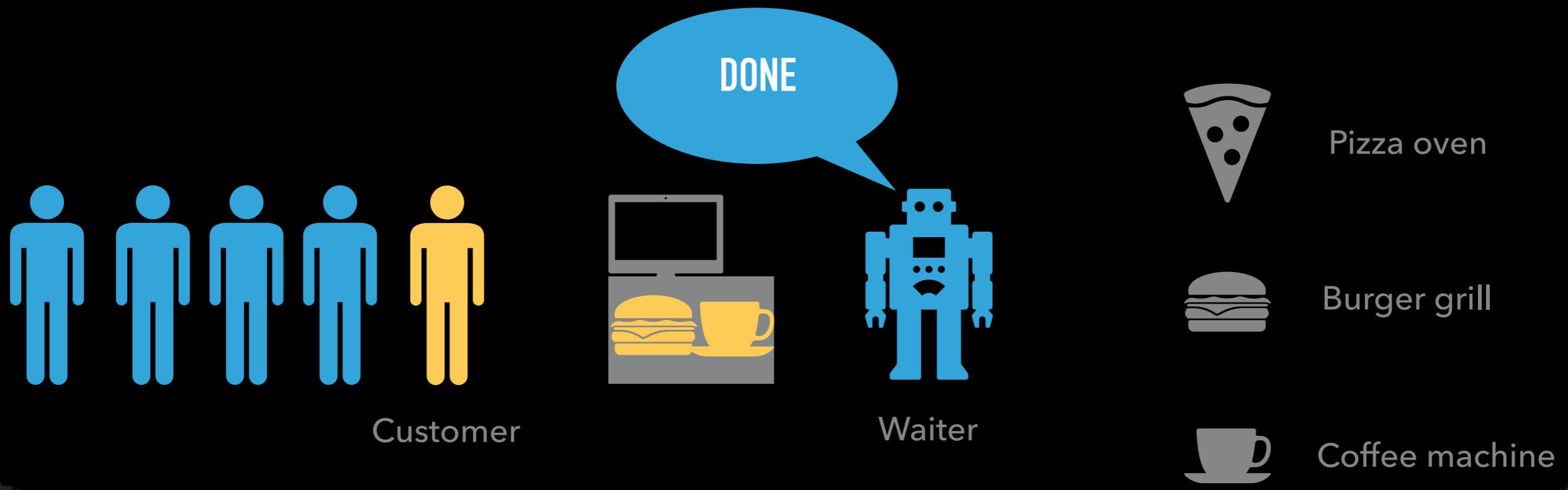
- ▶ Decode instruction into µOPs ("Burger", "Coffee")
- ▶ Schedule µOPs
 - ▶ run 1st µOP (grill the burger)
 - ▶ run 2nd µOP (brew coffee, serial execution)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



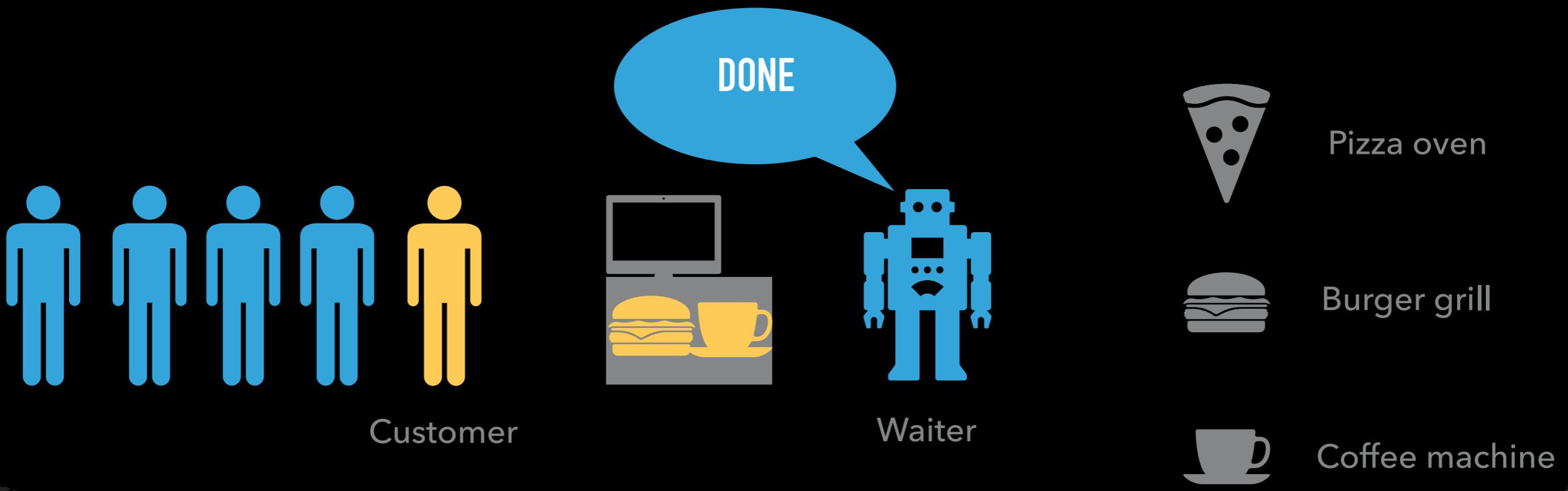
- ▶ Decode instruction into µOPs ("Burger", "Coffee")
- ▶ Schedule µOPs
 - ▶ run 1st µOP (grill the burger)
 - ▶ run 2nd µOP (brew coffee, serial execution)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



- ▶ Decode instruction into µOPs ("Burger", "Coffee")
- ▶ Schedule µOPs
 - ▶ run 1st µOP (grill the burger)
 - ▶ run 2nd µOP (brew coffee, serial execution)
- ▶ Retire instruction (customer)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



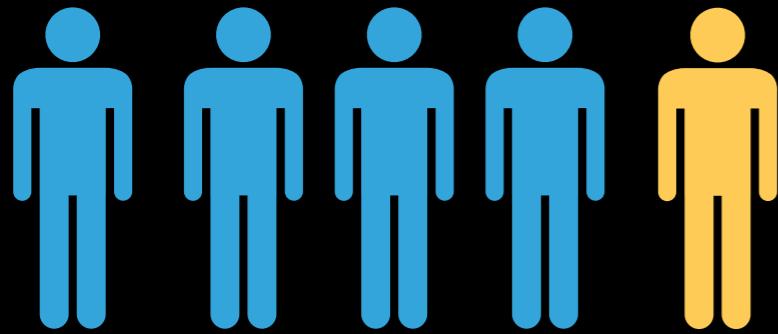
- ▶ One customer¹ after another (in order)
- ▶ Each part of the order ² executed serially

i.e. first the burger, then the coffee

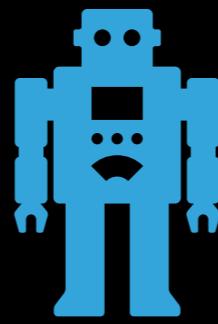
- ▶ PRO: Easy to implement and understand
- ▶ CON: Slow because resources³ not utilised fully

¹ customer == CPU instruction ² part == µOP - micro operation ³ oven, grill, coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION



Customer



Waiter



Pizza oven

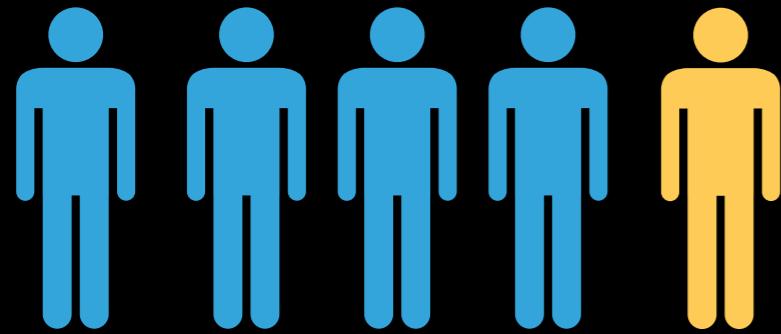


Burger grill

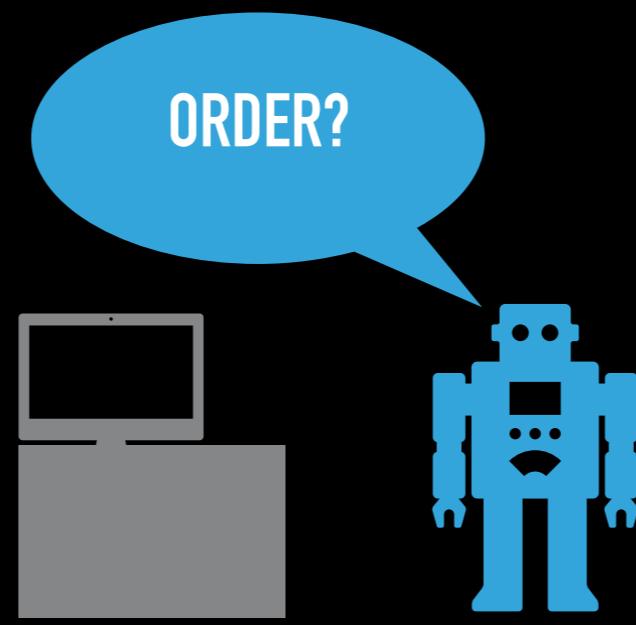


Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION



Customer



Waiter



Pizza oven

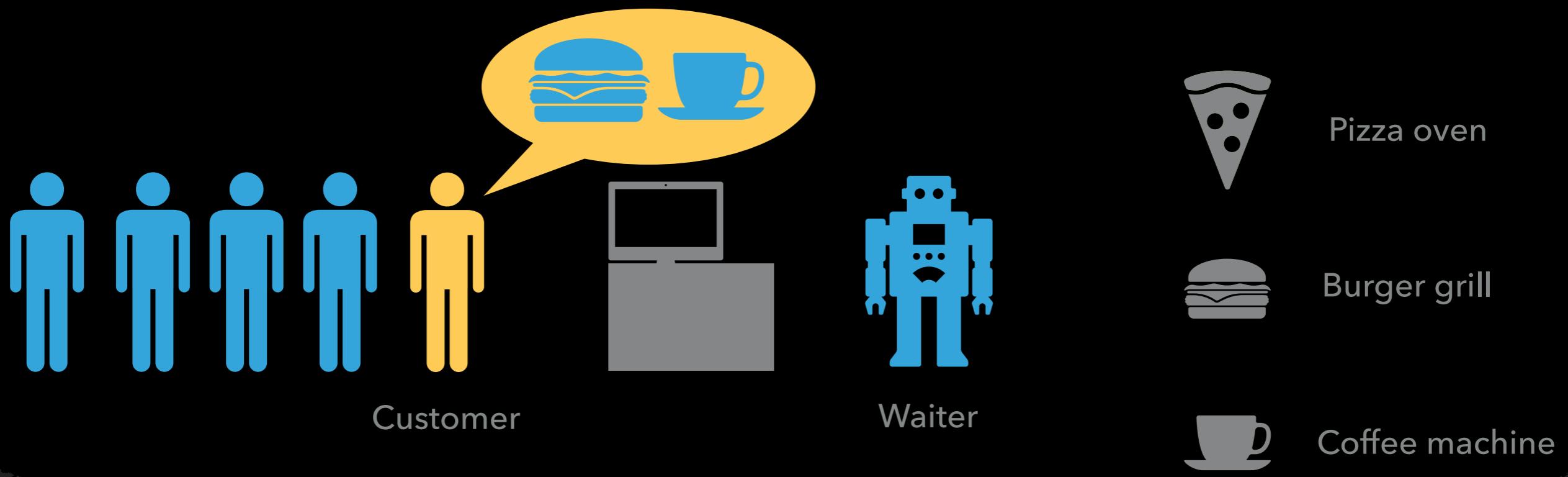


Burger grill



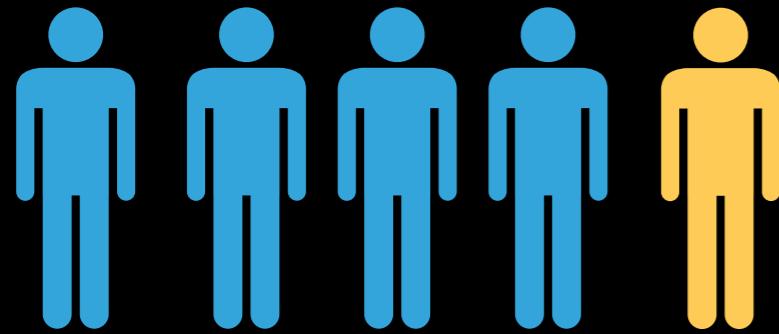
Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION

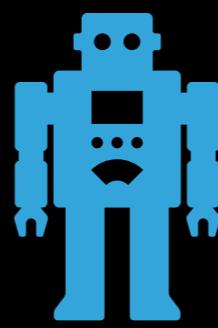


- ▶ Decode instruction into μ OPs

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION



Customer



Waiter



Pizza oven



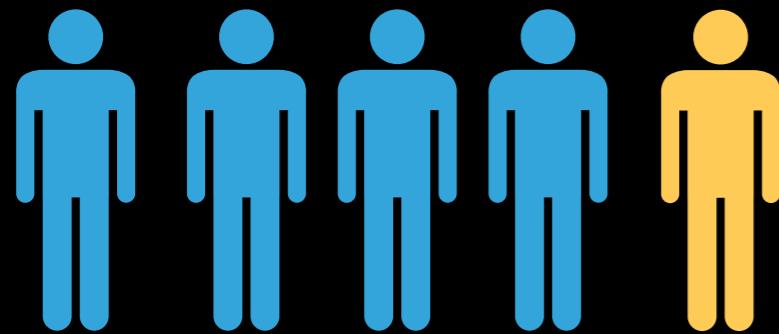
Burger grill



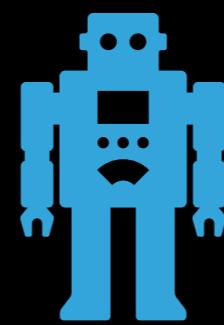
Coffee machine

- ▶ Decode instruction into µOPs
- ▶ Schedule µOPs

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION



Customer



Waiter



Pizza oven



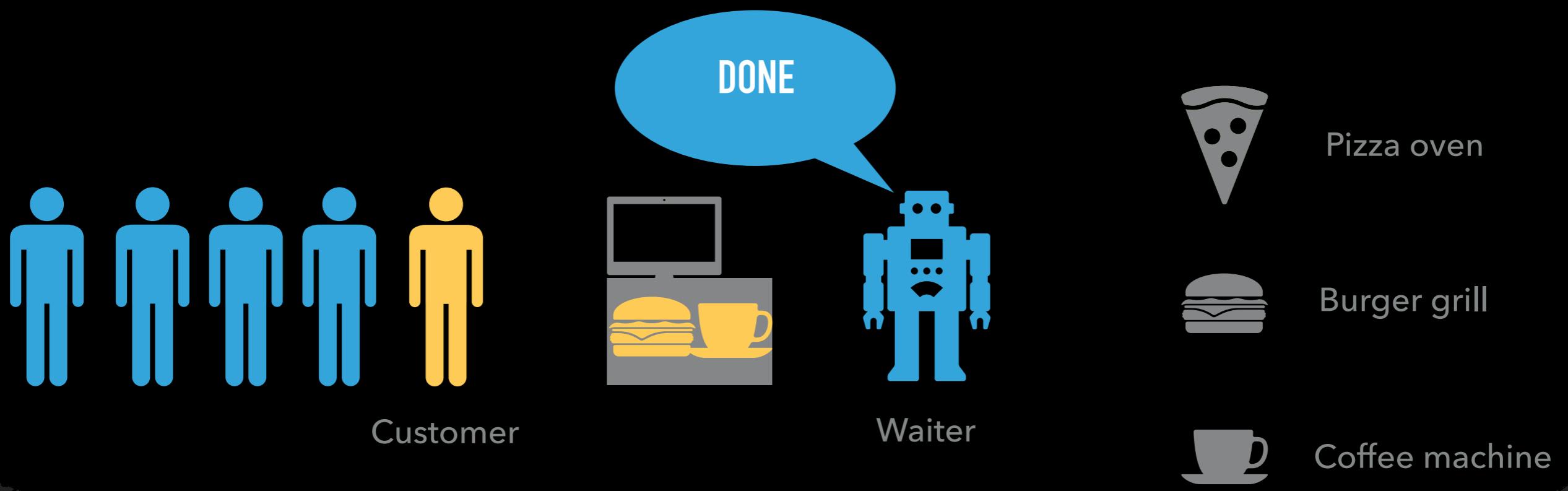
Burger grill



Coffee machine

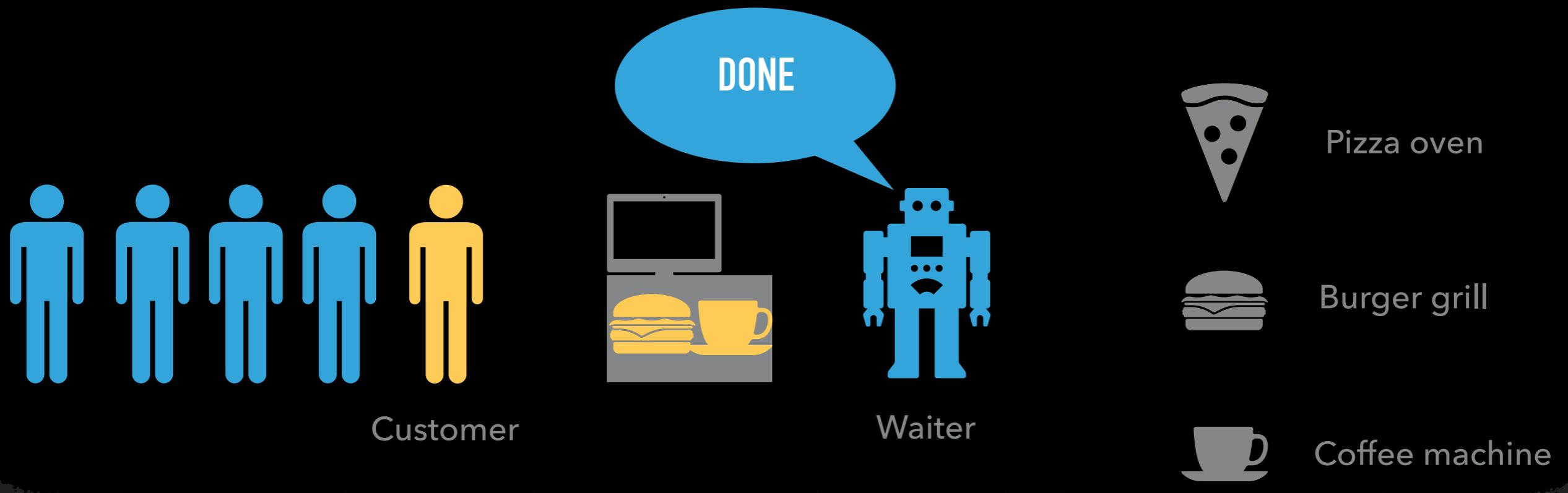
- ▶ Decode instruction into µOPs
- ▶ Schedule µOPs
- ▶ run 1st µOP and 2nd µOP (parallel execution of µOPs)

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION



- ▶ Decode instruction into µOPs
- ▶ Schedule µOPs
 - ▶ run 1st µOP and 2nd µOP (parallel execution of µOPs)
- ▶ retire instruction (customer)

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION

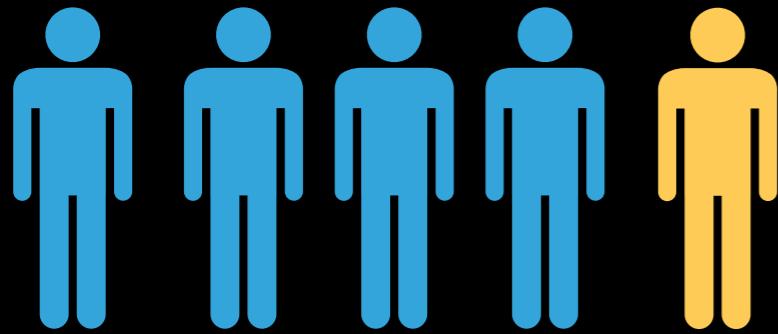


- ▶ One customer¹ after another (in order)
- ▶ Each part of the order ² executed in parallel

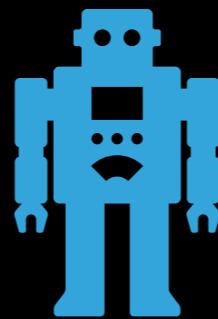
i.e. burger and coffee prepared at the same time

- ▶ PRO: **Faster bc. of better resource utilisation.**
- ▶ CON: Still not perfect, more complex

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



Customer



Waiter



Pizza oven

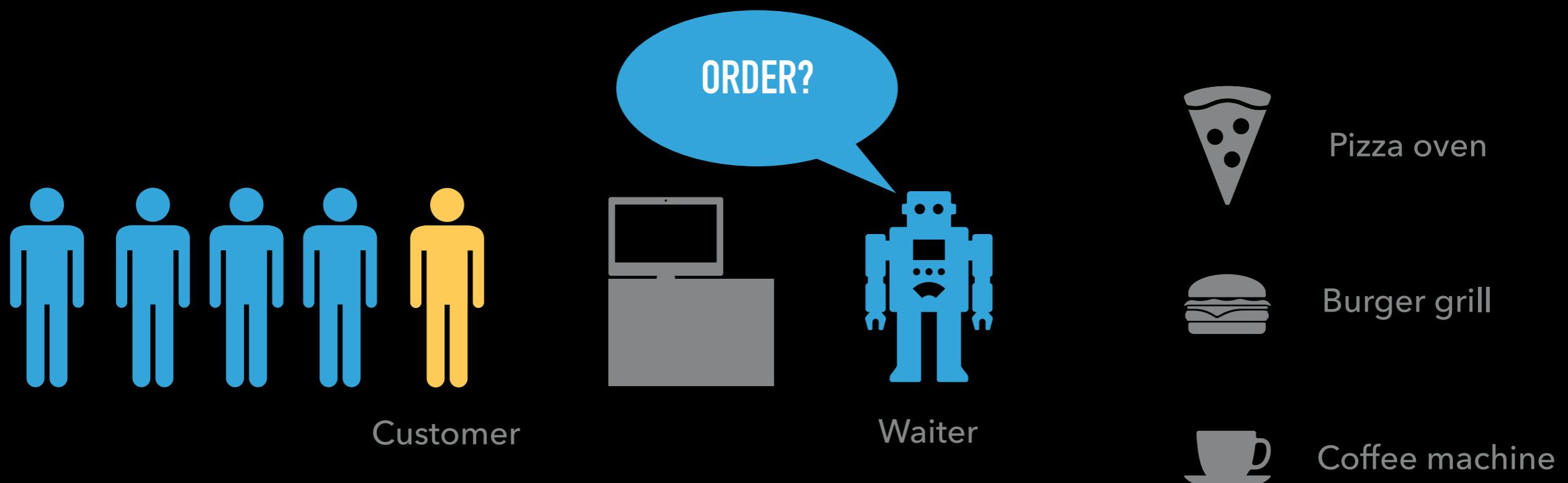


Burger grill

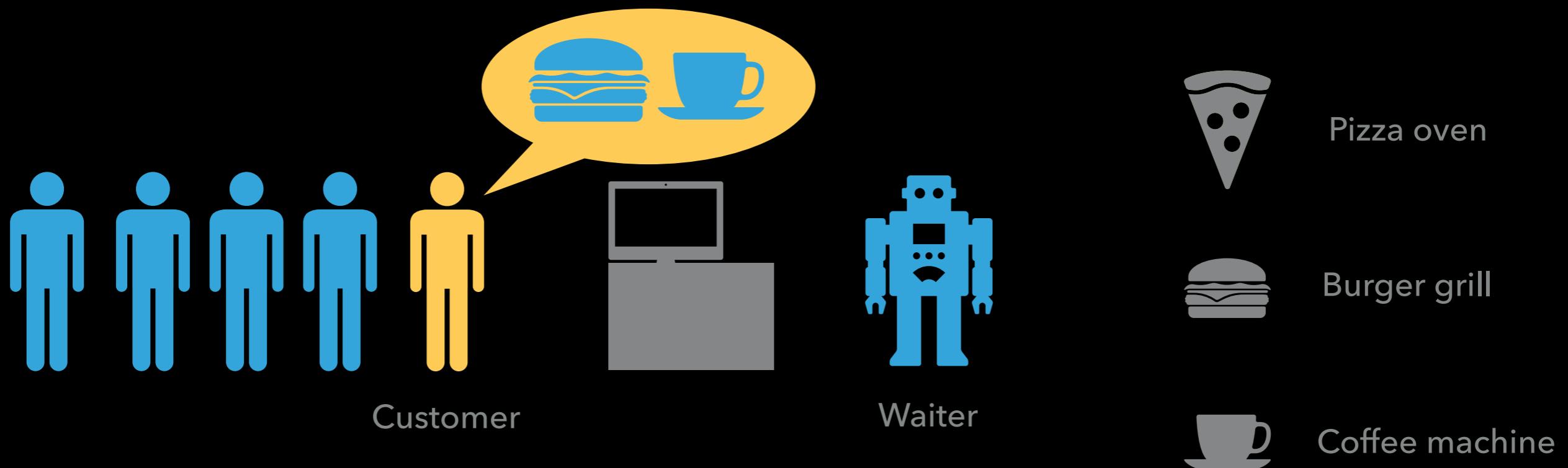


Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



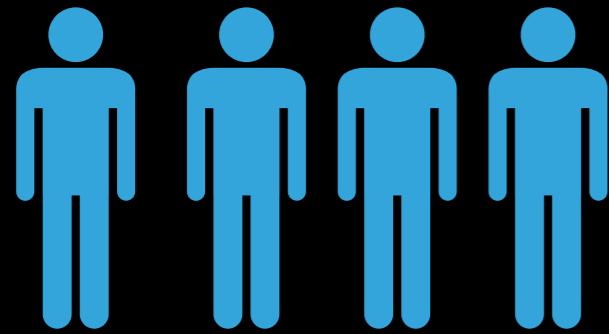
CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



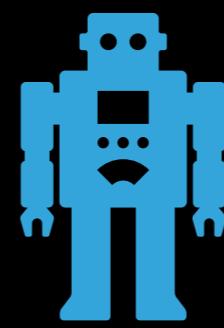
CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



Customer



Waiter



Pizza oven



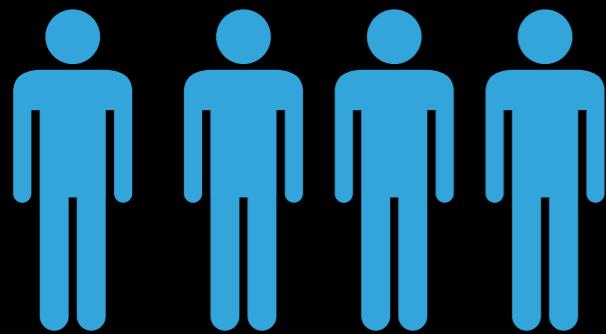
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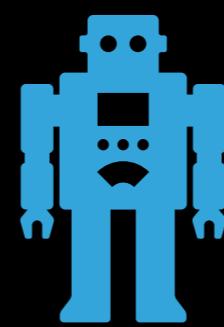
Coffee machine



CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



Customer



Waiter



Pizza oven



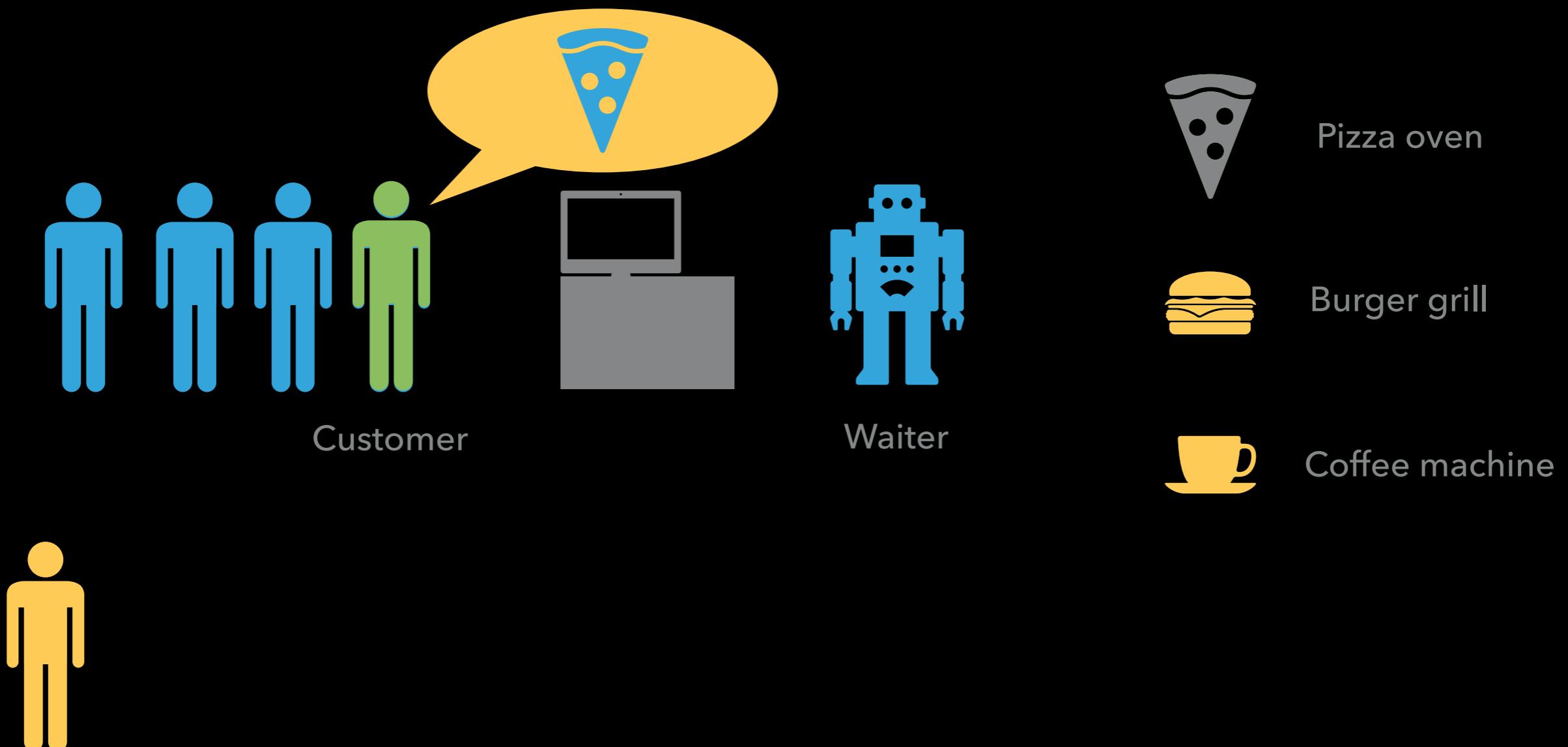
Burger grill



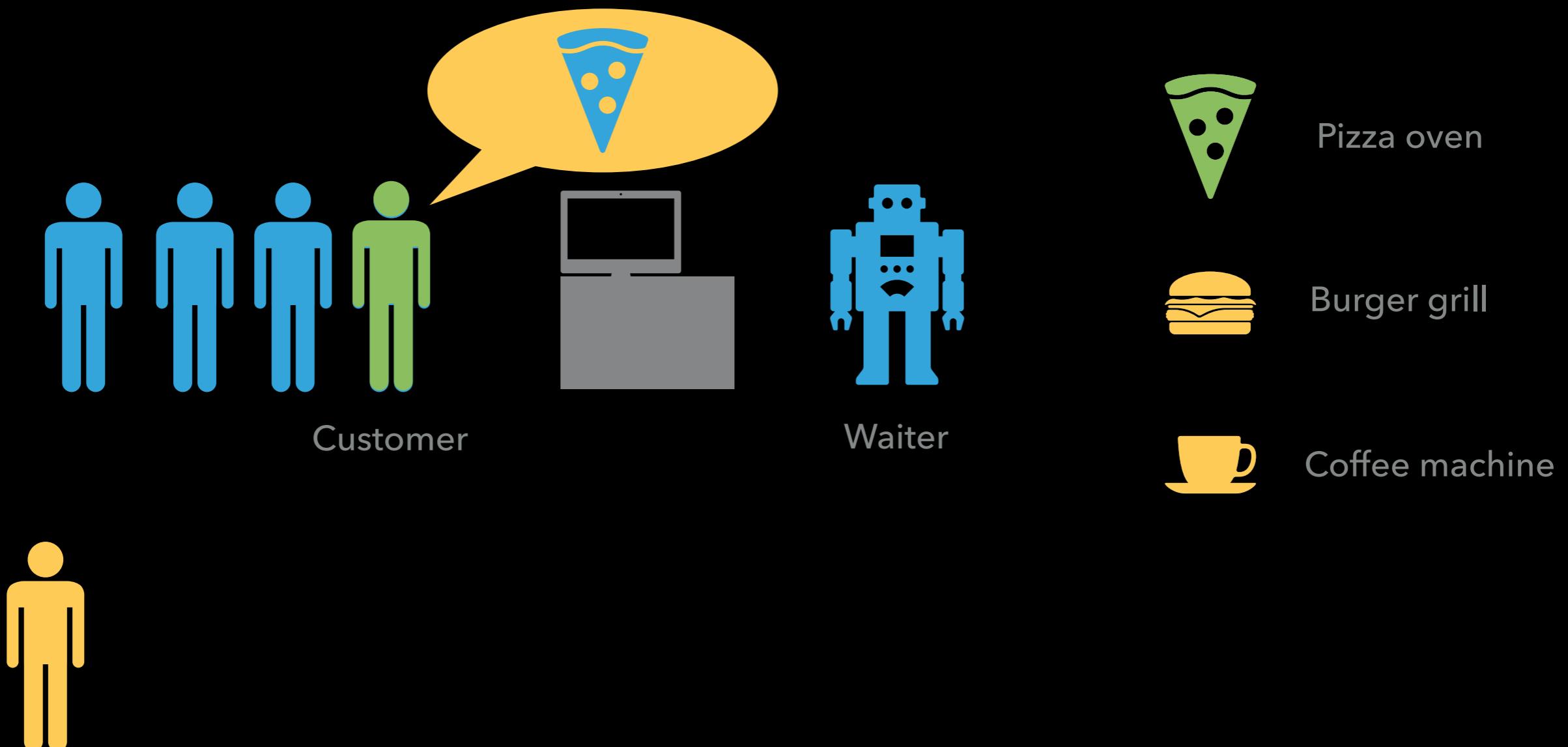
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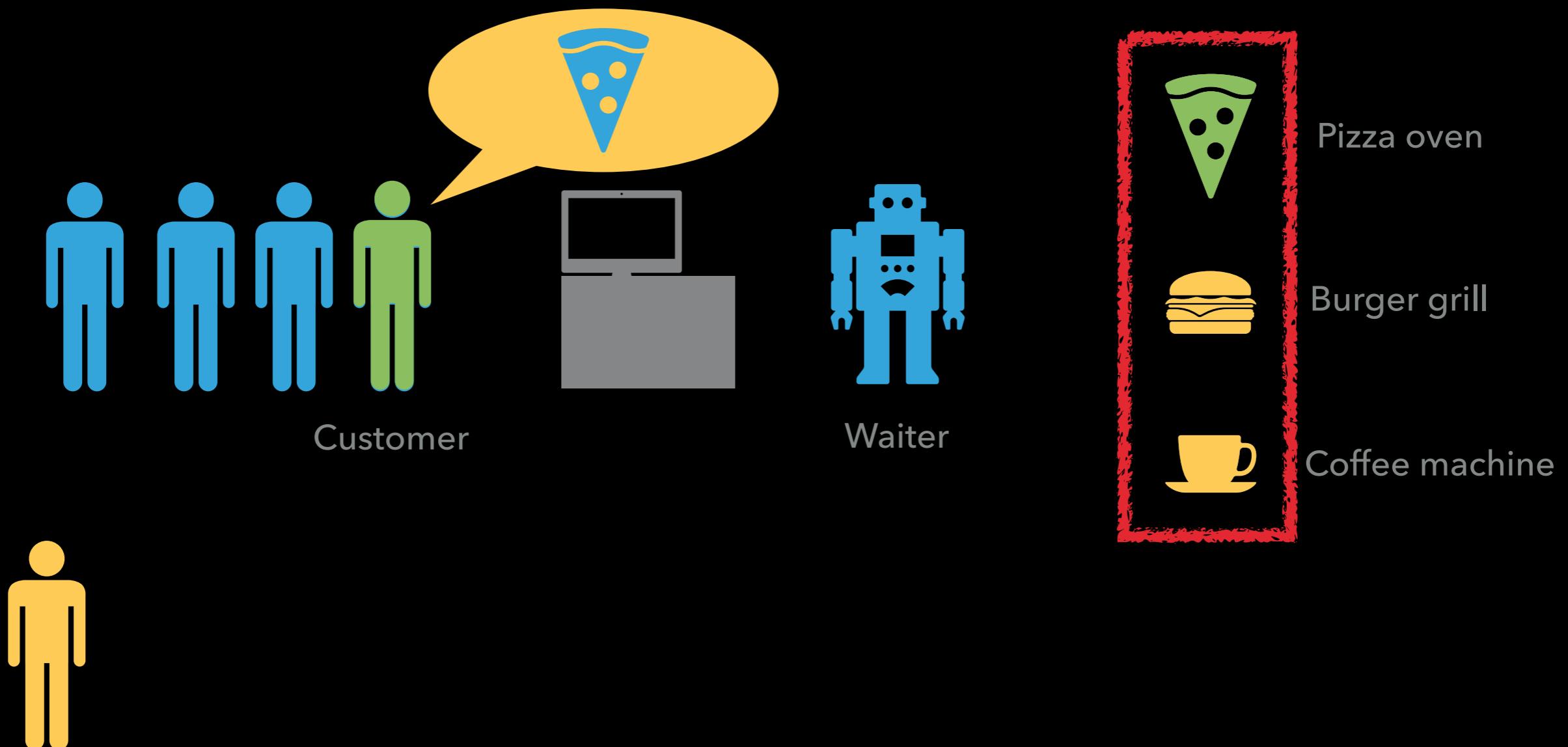
CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



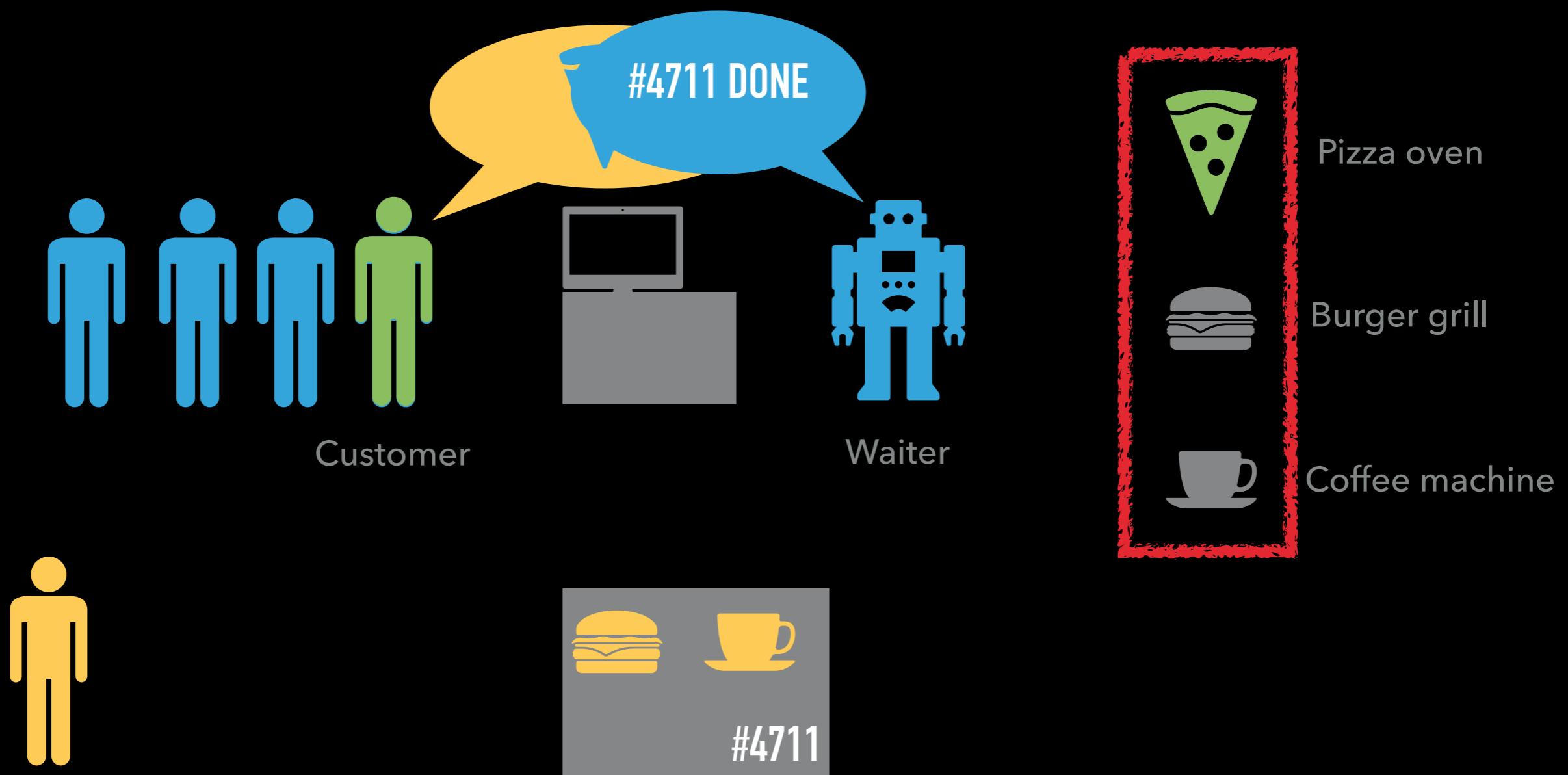
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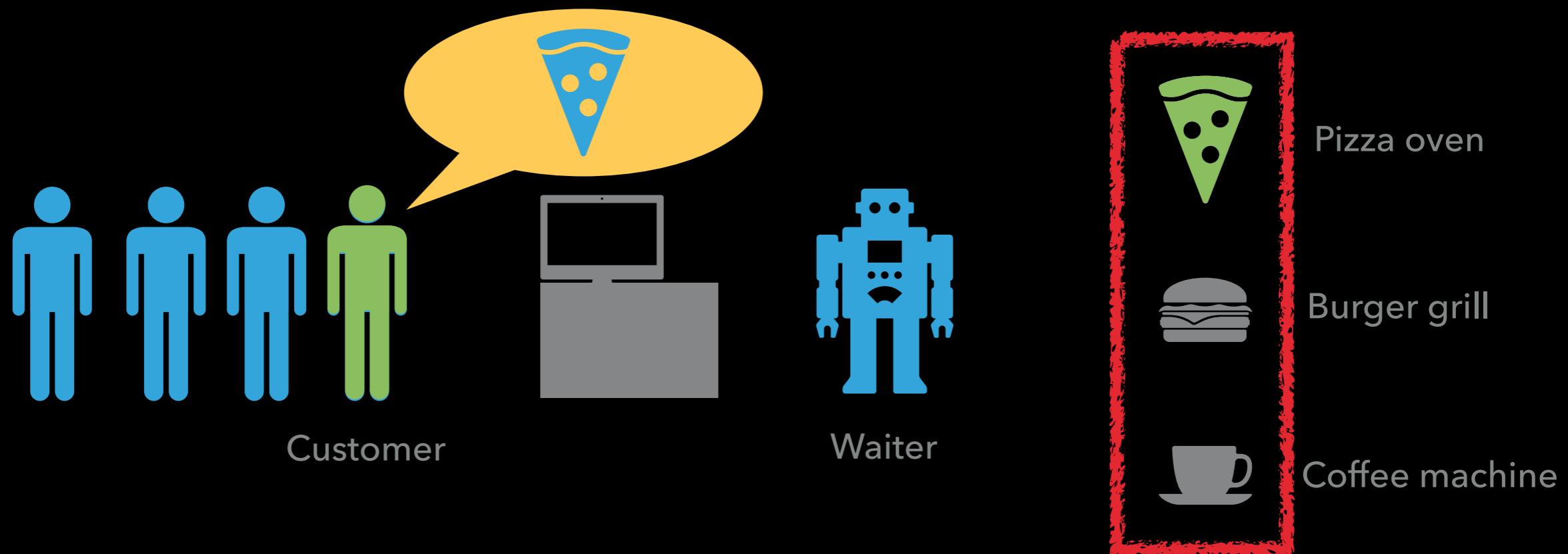
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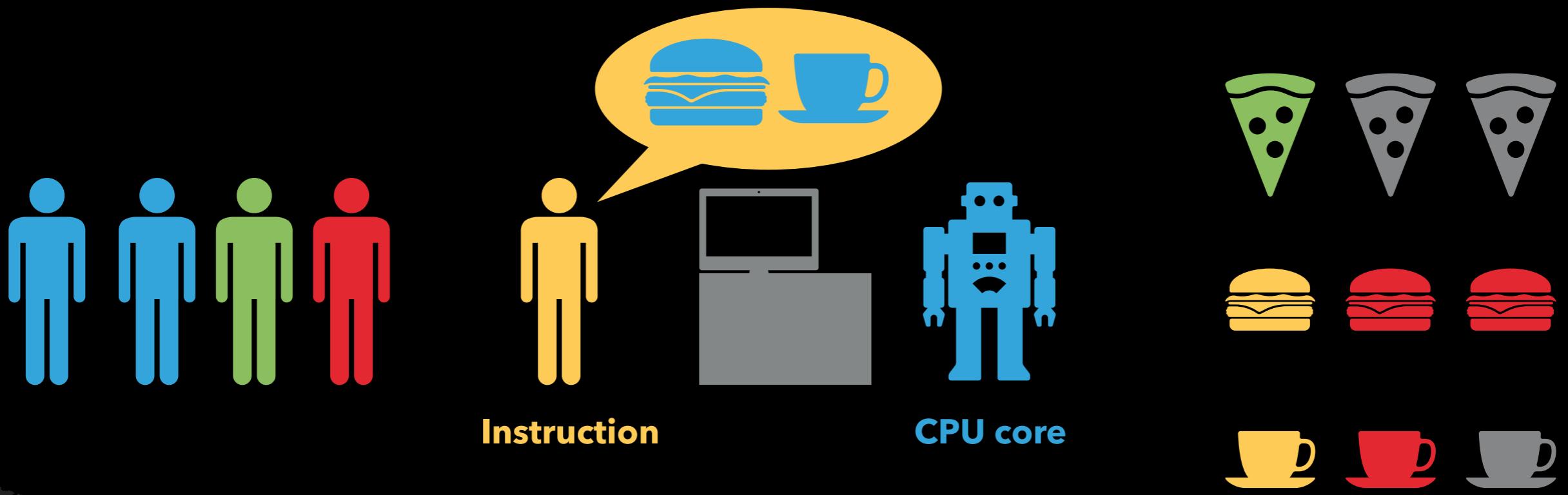
- ▶ Multiple customers' orders executed in parallel¹ and delivered (retired) **in order**

i.e. multiple orders prepared at the same time

- ▶ PRO: **Faster because resources are utilised even better**
- ▶ CON: More difficult to implement

¹ this is called *superscalar*

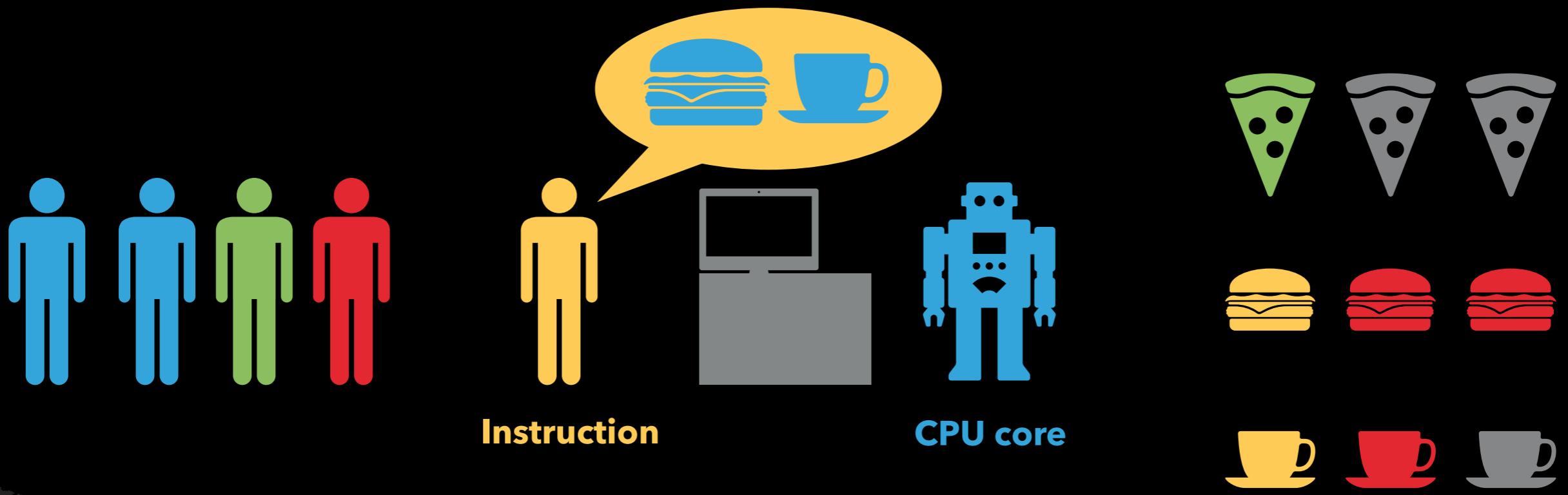
CONFIDENTIAL BURGERS INC.



Adding more resources increase parallelism & throughput.

This is all on one CPU core.

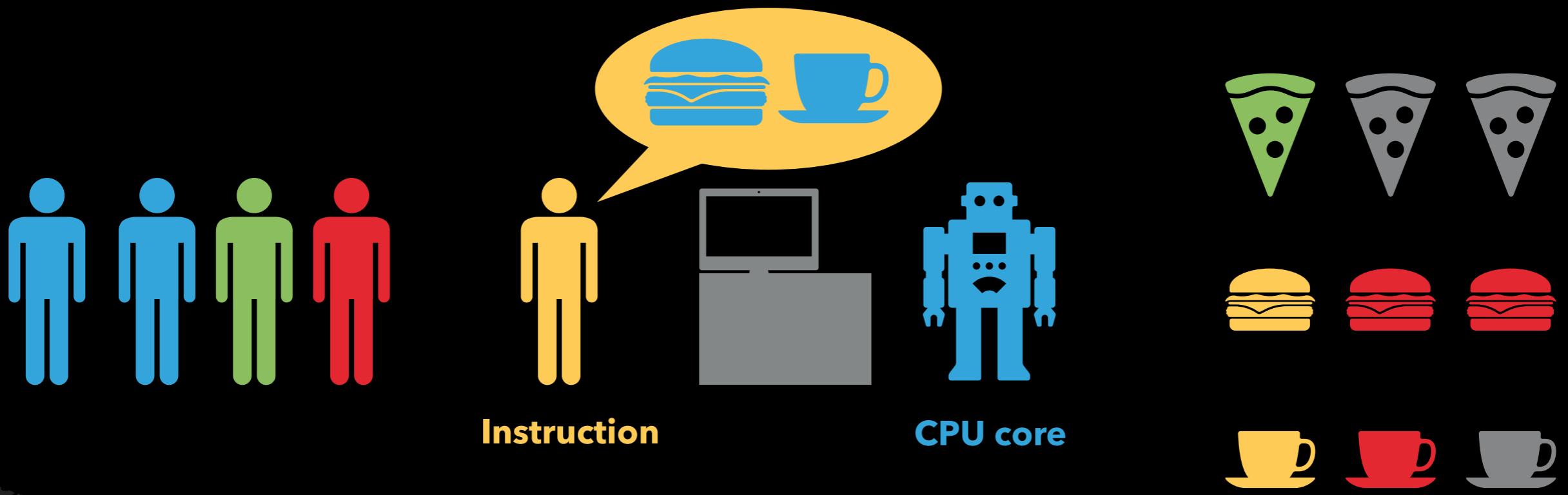
CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT



The green instruction will finish before the red instruction.

The CPU ensures that red is seen before green.

CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT



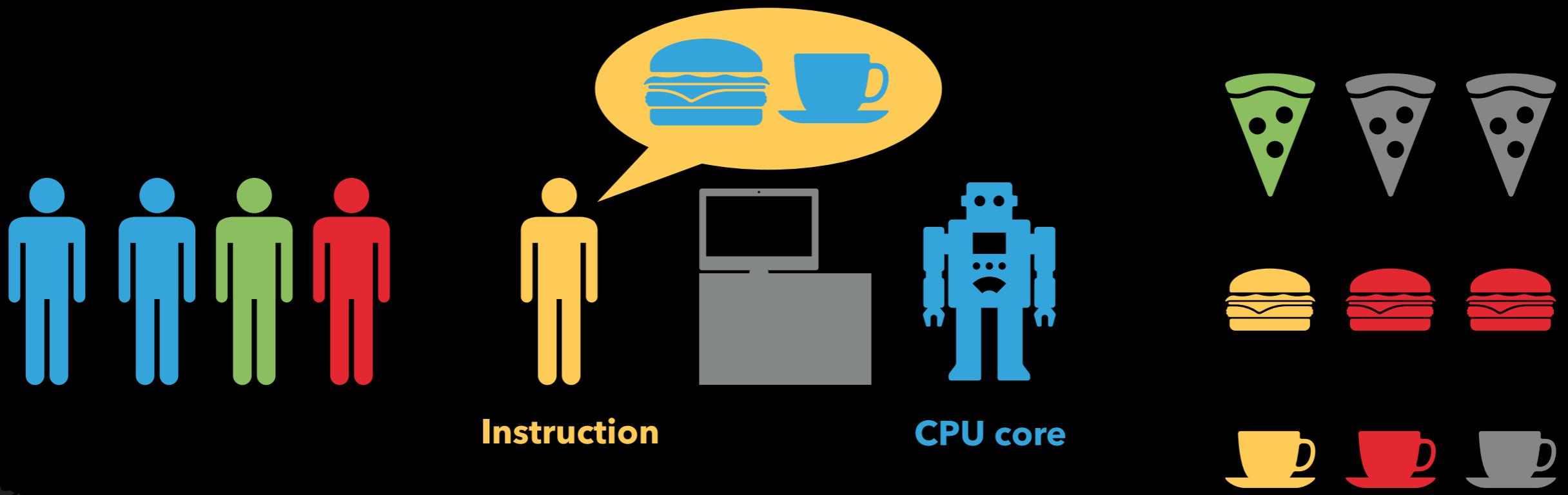
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Actual µOP execution order

CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT



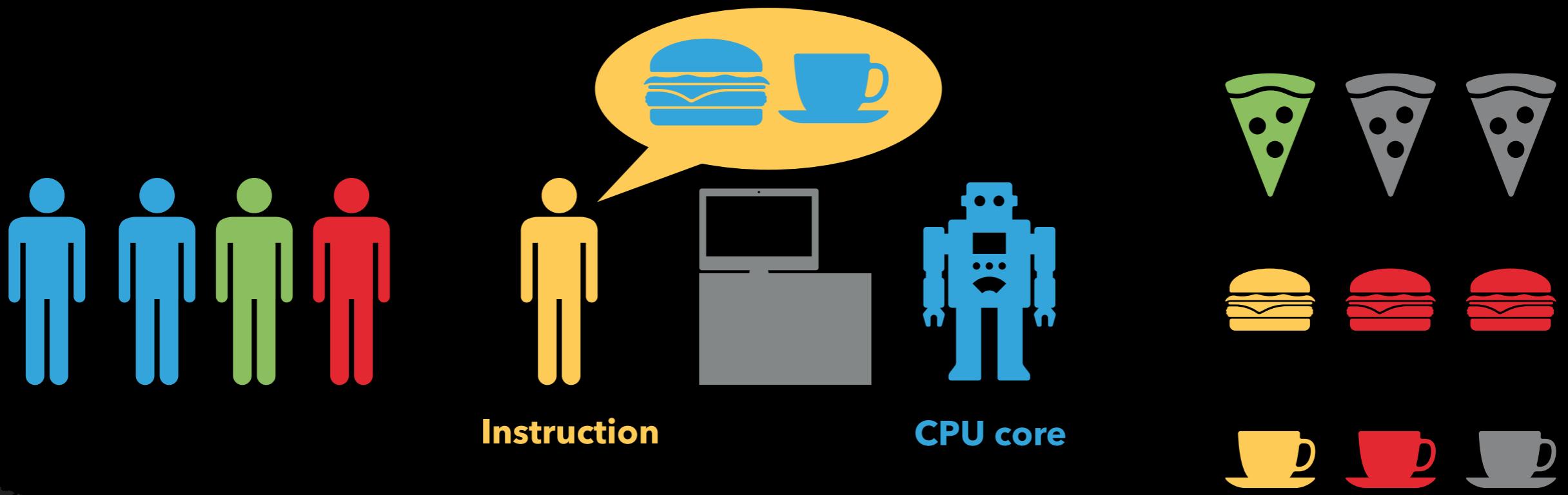
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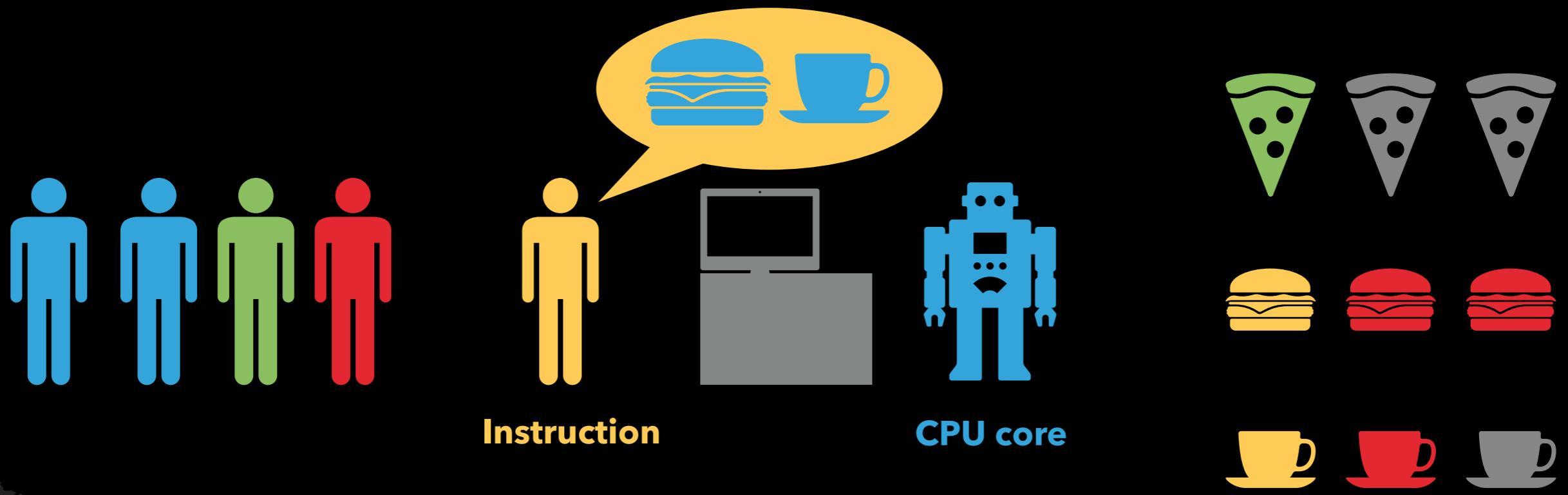
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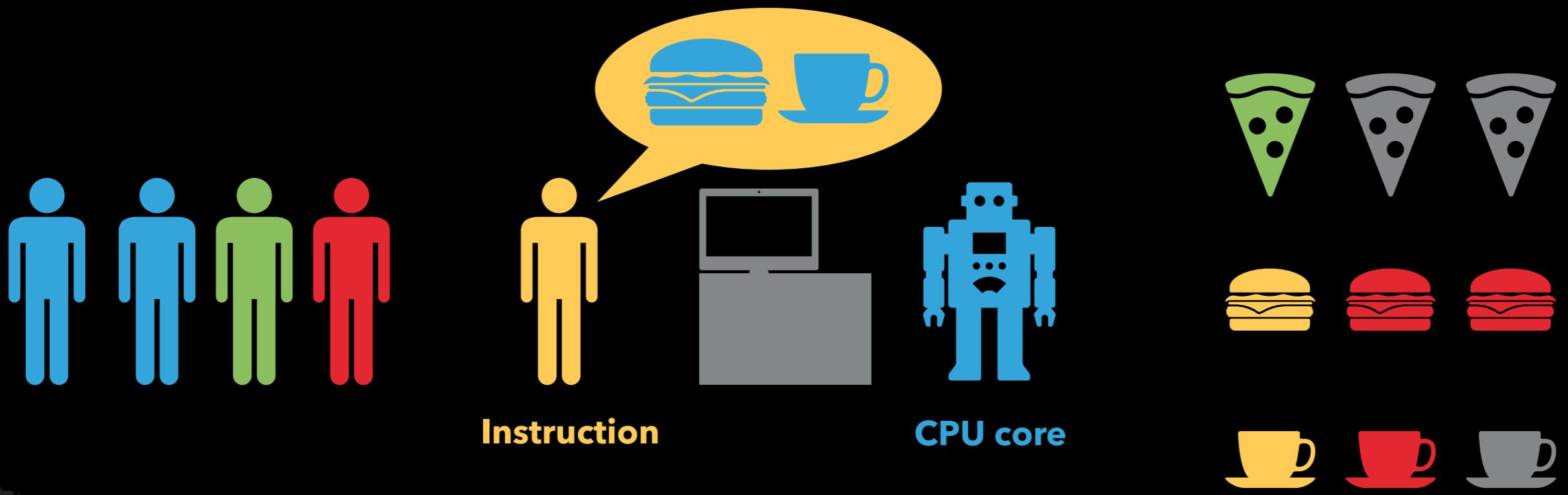
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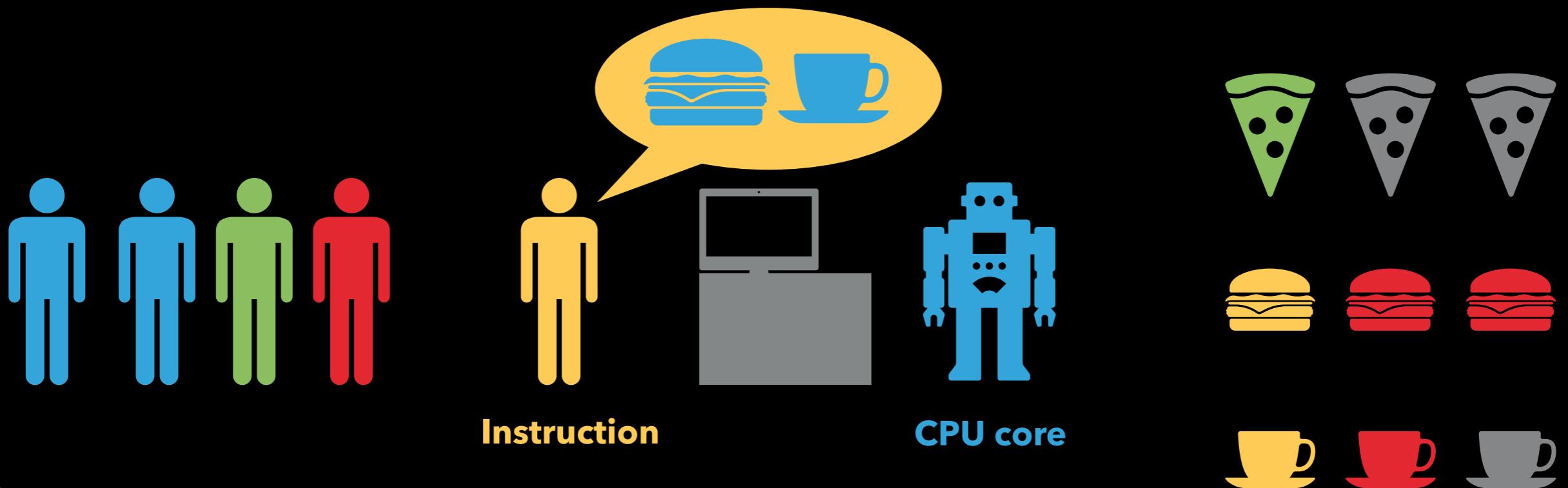


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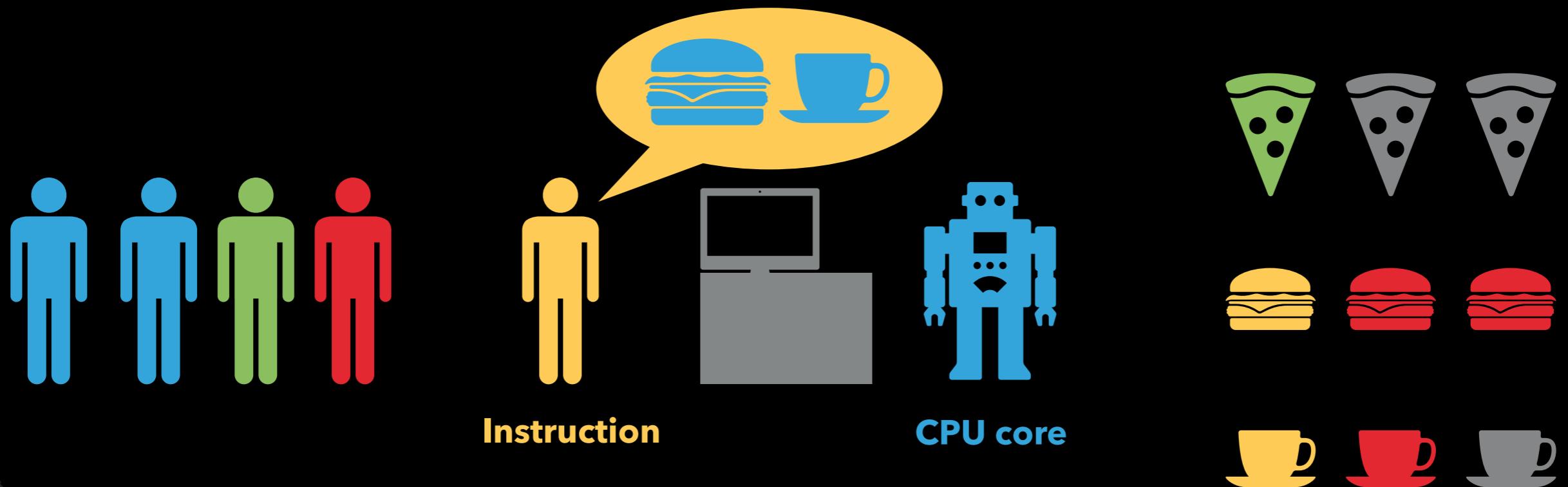
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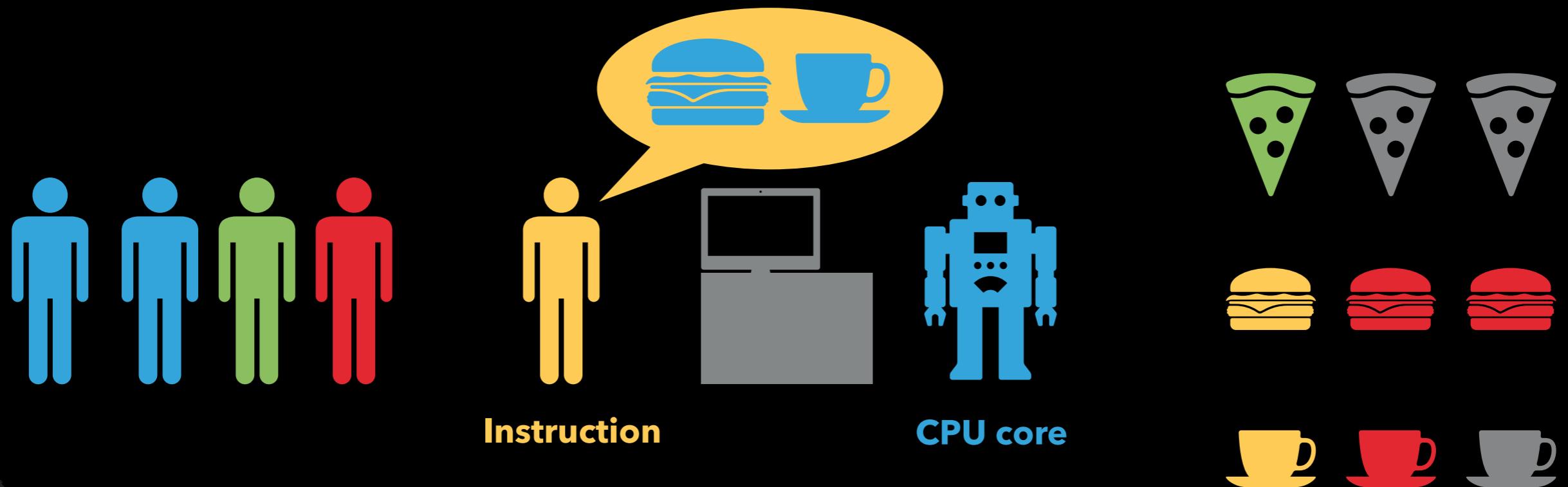
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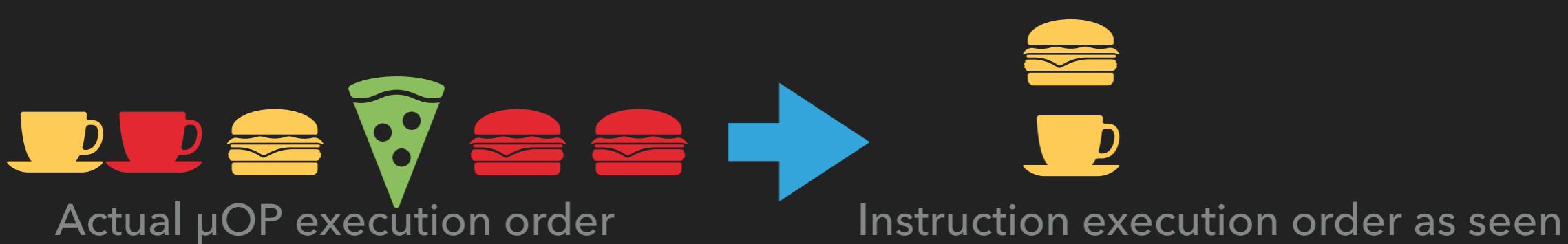
Instruction execution order as seen

CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT

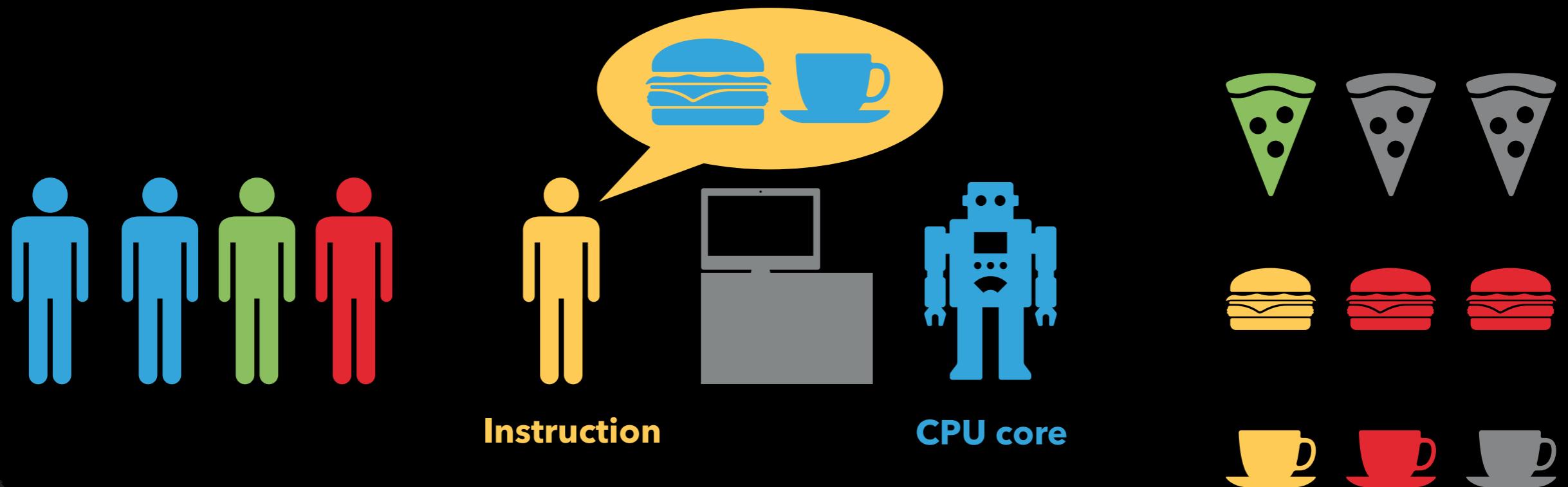


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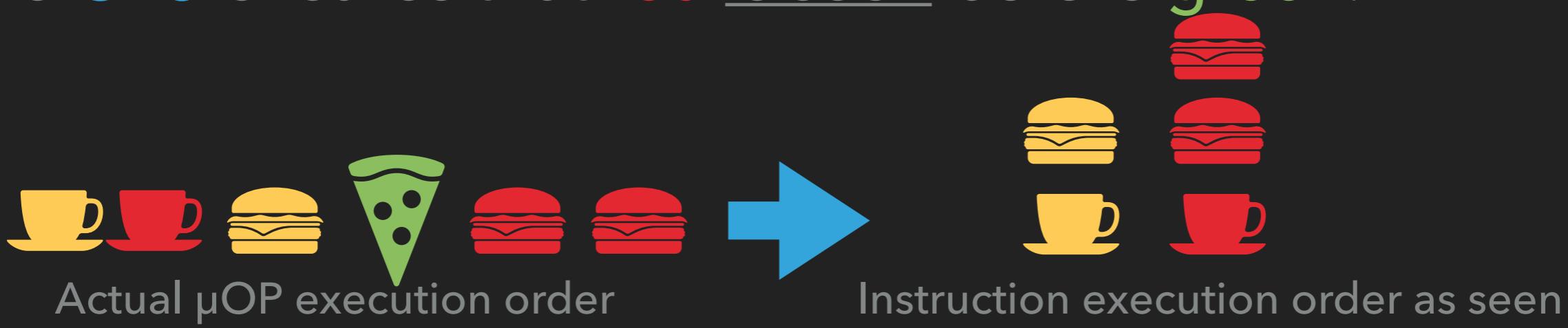


CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT

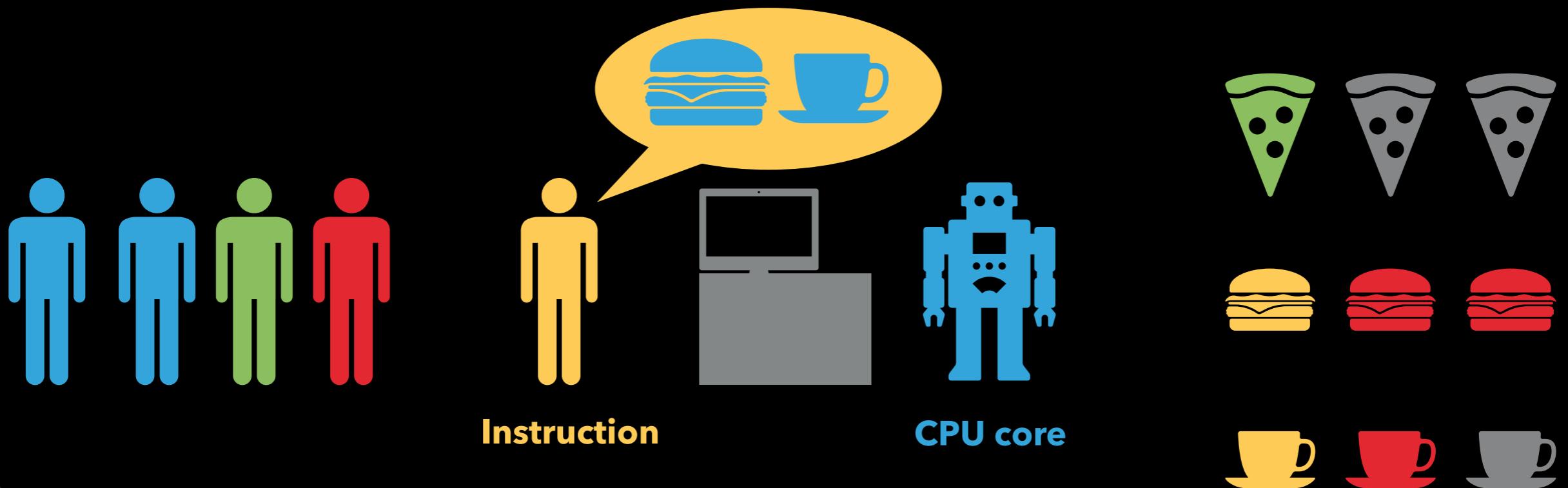


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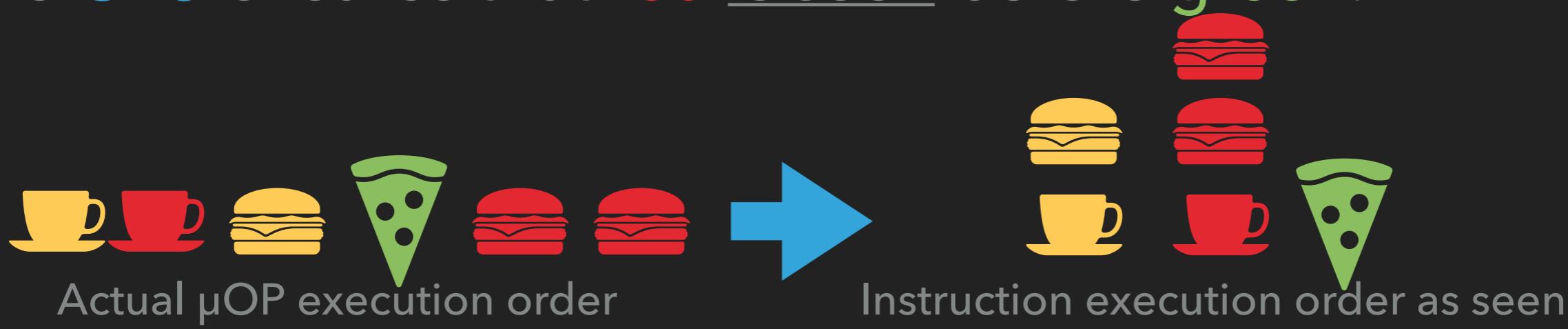


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WHY DID MELTDOWN & SPECTRE HAPPEN?

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...
MISUNDERSTANDINGS AND NEGLECT
CREATE MORE CONFUSION IN THIS WORLD
THAN TRICKERY AND MALICE. AT ANY RATE, THE
LAST TWO ARE CERTAINLY MUCH LESS
FREQUENT.

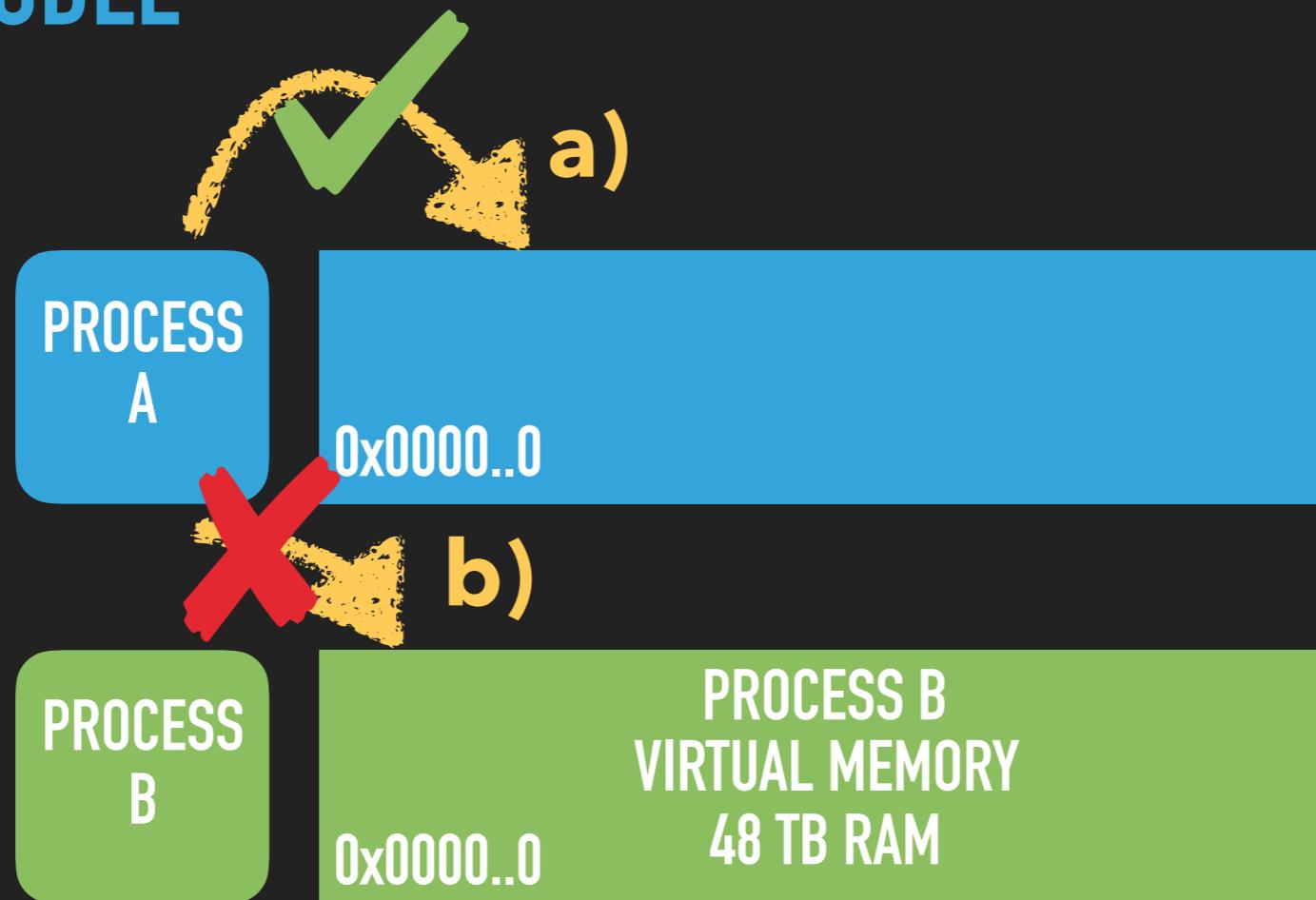
Goethe's The Sorrows of Young Werther



♩ ♪ INTERLUDE ♪ ♪

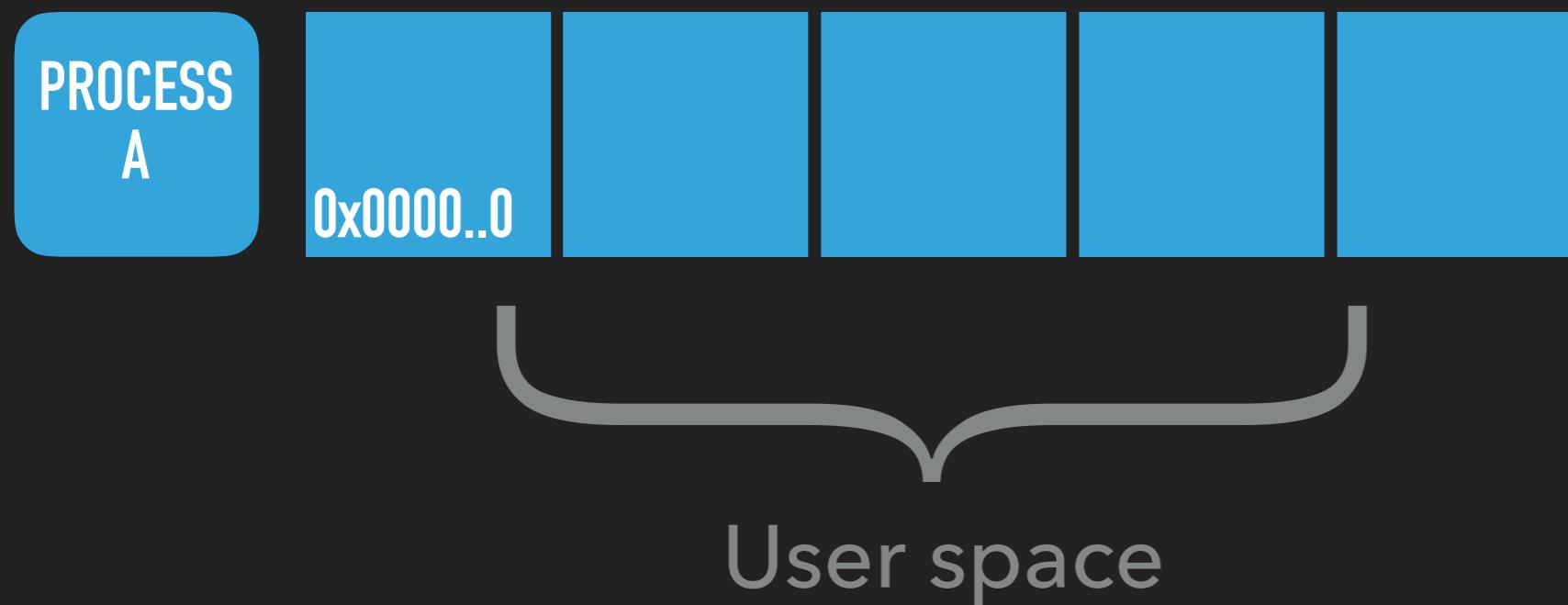
MEMORY MODEL

MEMORY MODEL

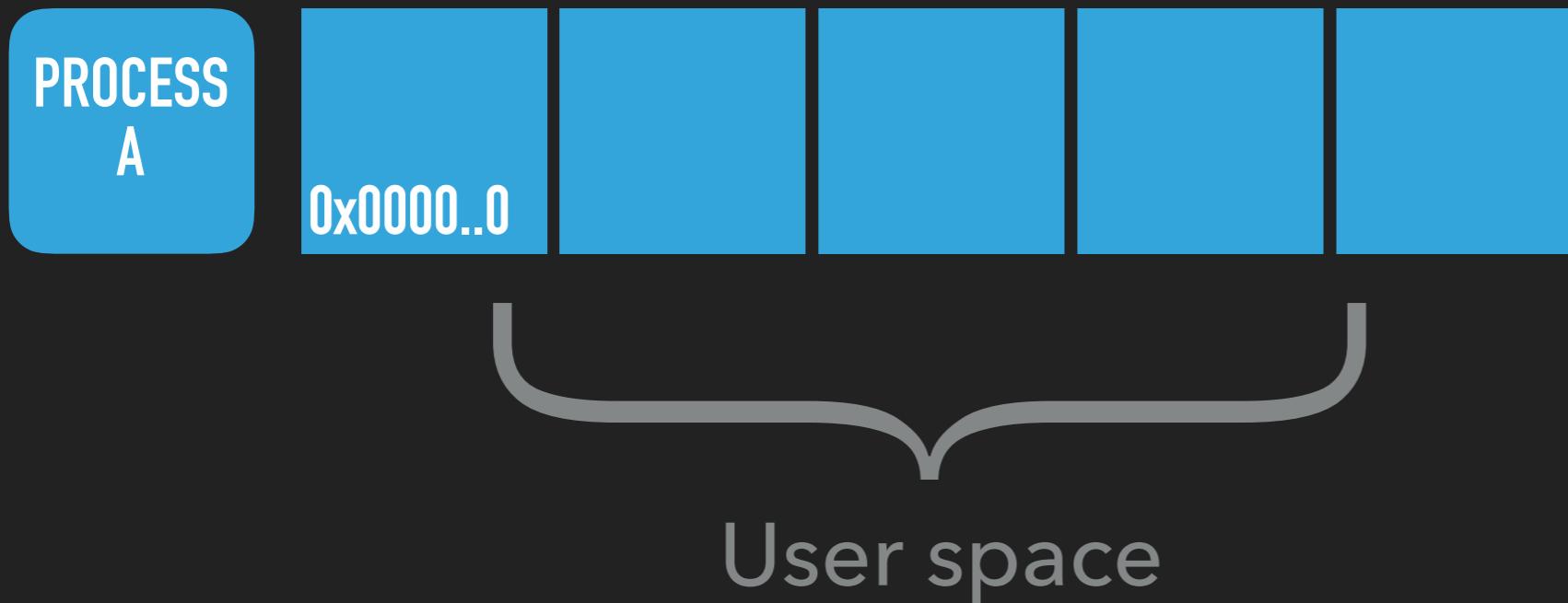


- ▶ CPU and OS isolate processes memory from each other
- ▶ *Virtual Memory* gives each process its own *address space*
- ▶ Each address space starts at “virtual address **0x000..0**”

MEMORY MODEL

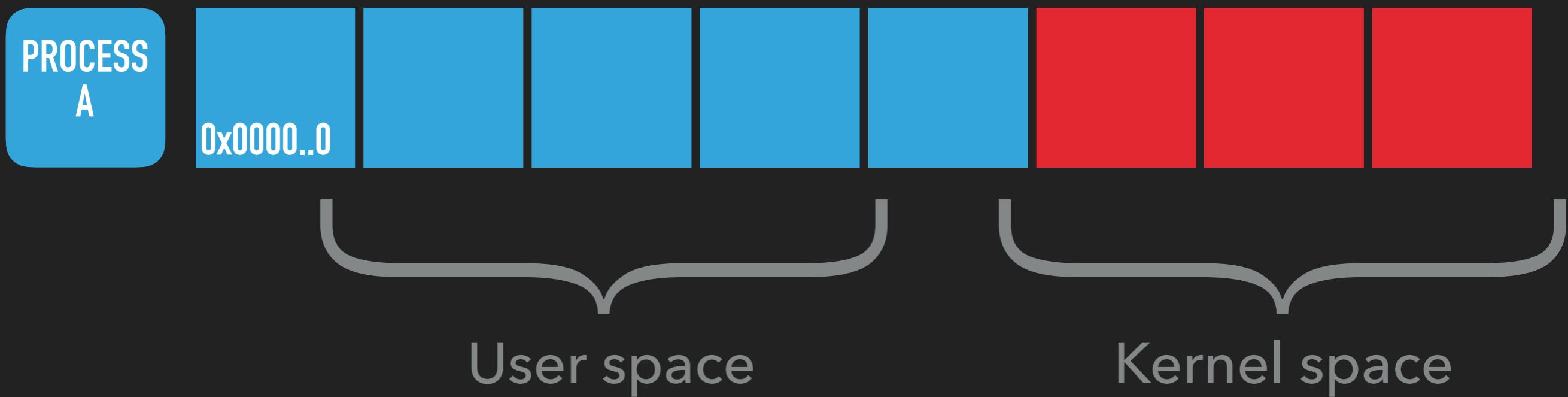


MEMORY MODEL



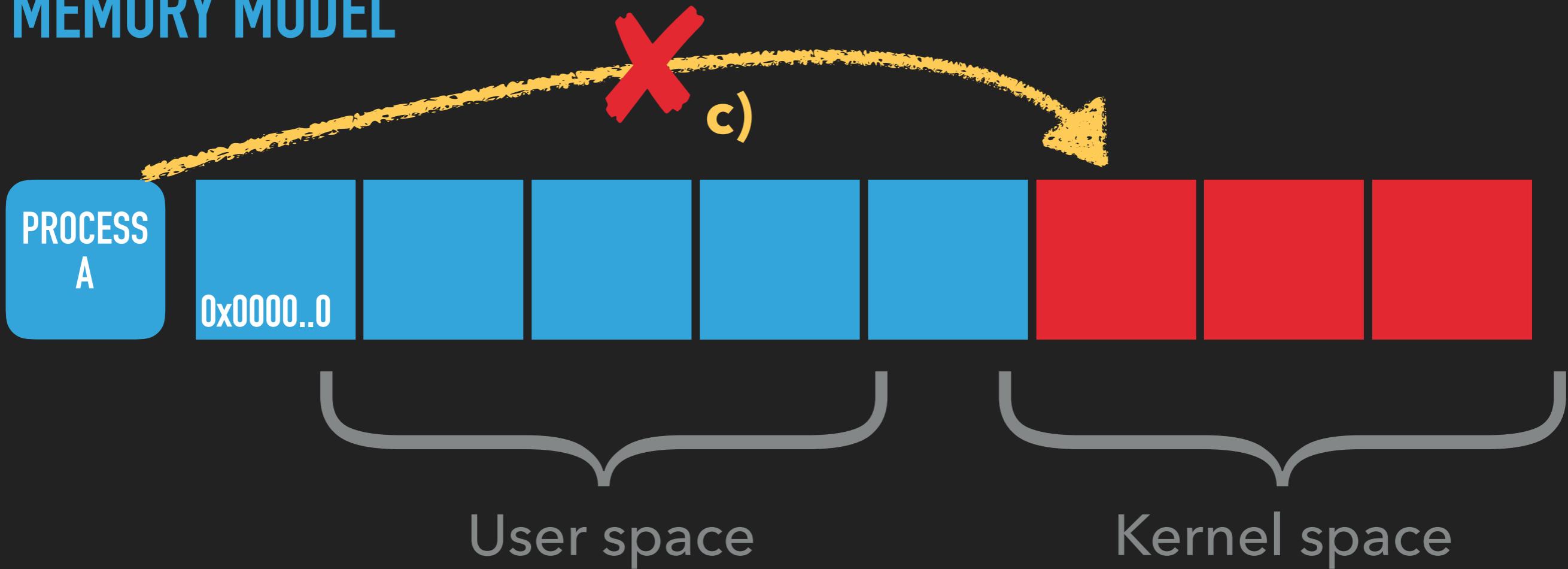
- ▶ Memory is split into *pages* (each 4KiB on x86)

MEMORY MODEL



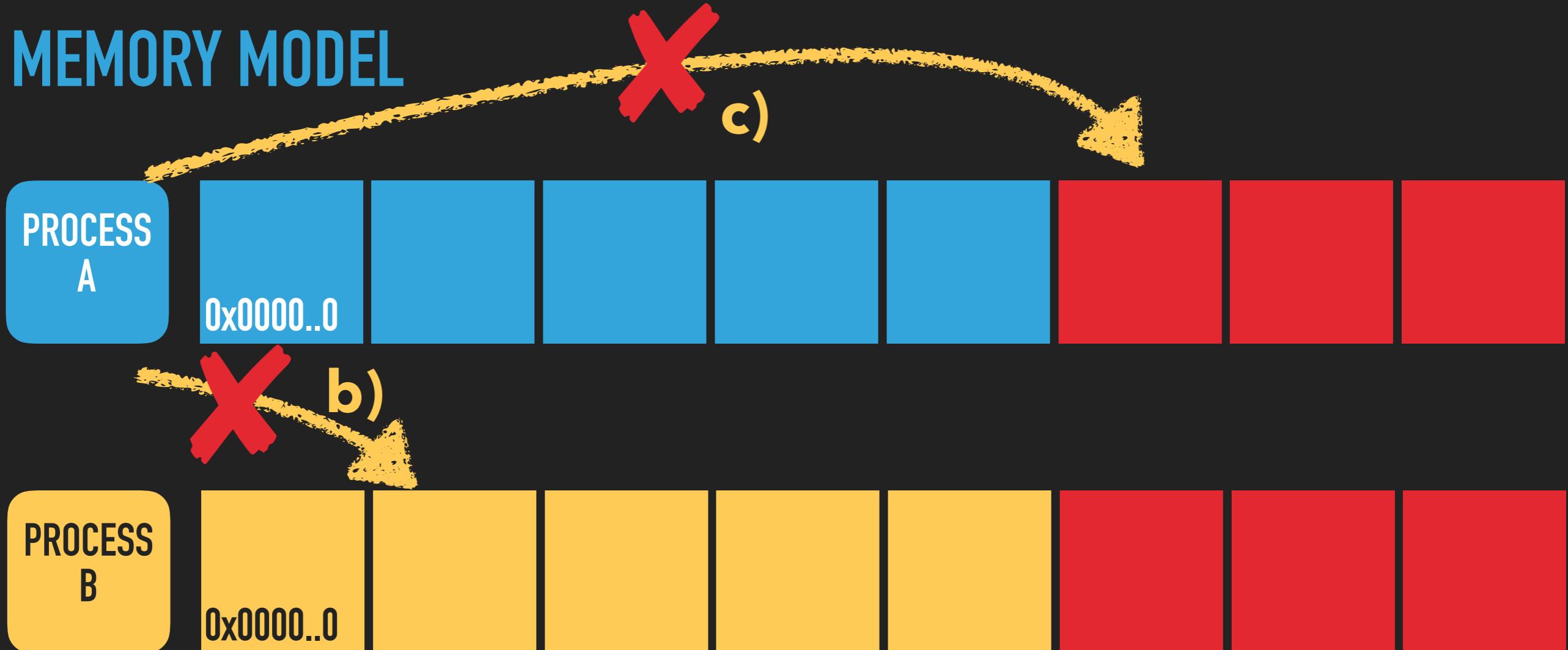
- ▶ Memory is split into *pages* (each 4KiB on x86)
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MEMORY MODEL



- ▶ Memory is split into *pages* (each 4KiB on x86)
- ▶ The kernel *maps* its own memory into each process
- ▶ This “kernel” memory is only accessible by the kernel

MEMORY MODEL

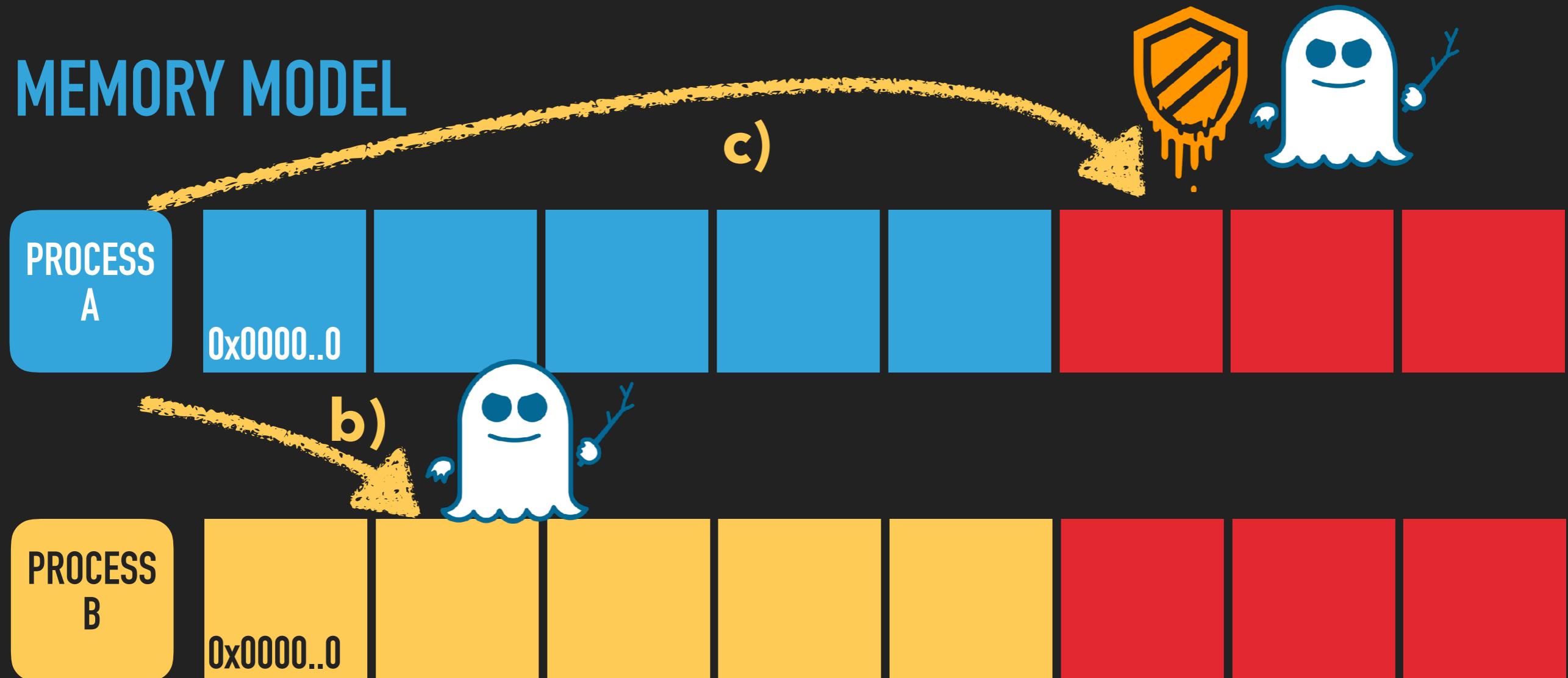


b) and c) are completely different error scenarios

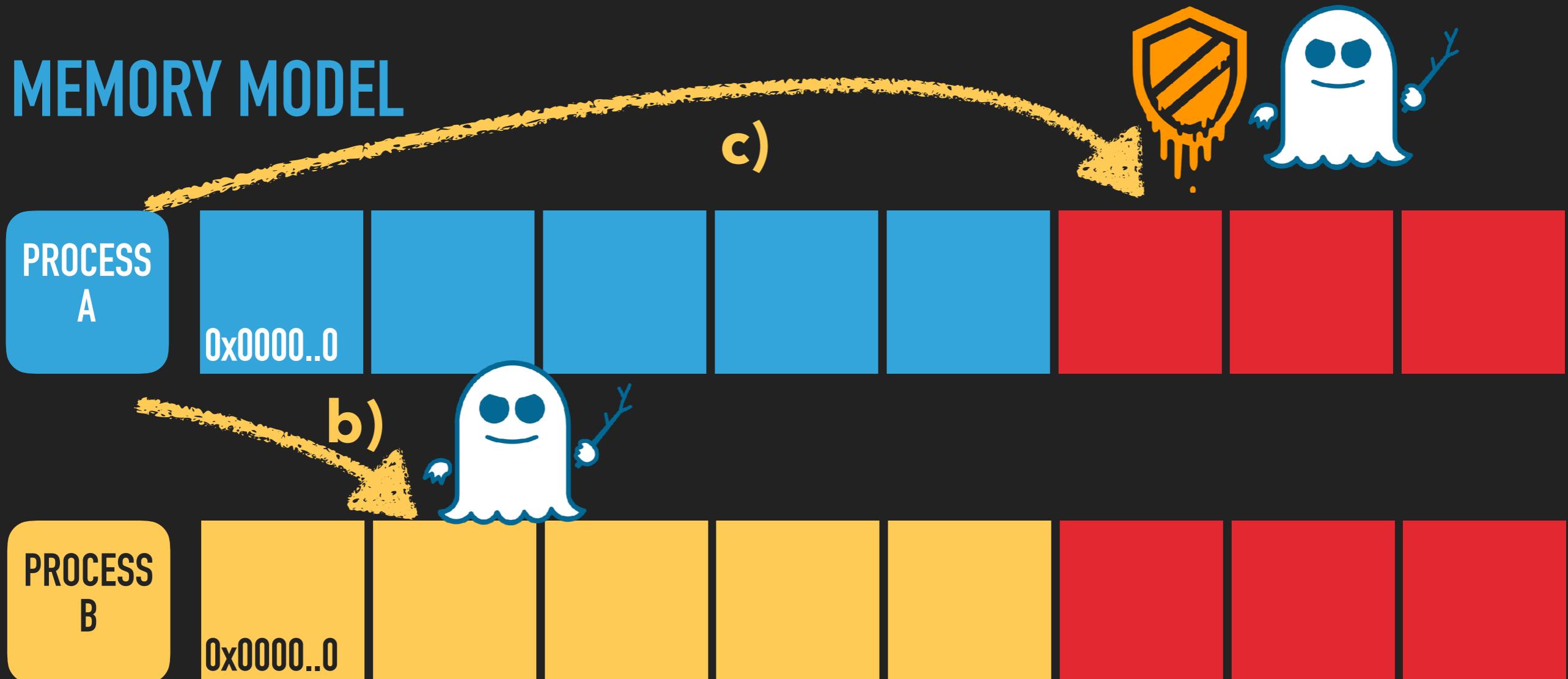
- ▶ **c)** Kernel memory pages are marked “kernel only” but the process could try to access the pages via a pointer
- ▶ **b)** Process **B** has no possibility to even *describe* the address

MELTDOWN & SPECTRE FOR NORMAL PEOPLE

MEMORY MODEL



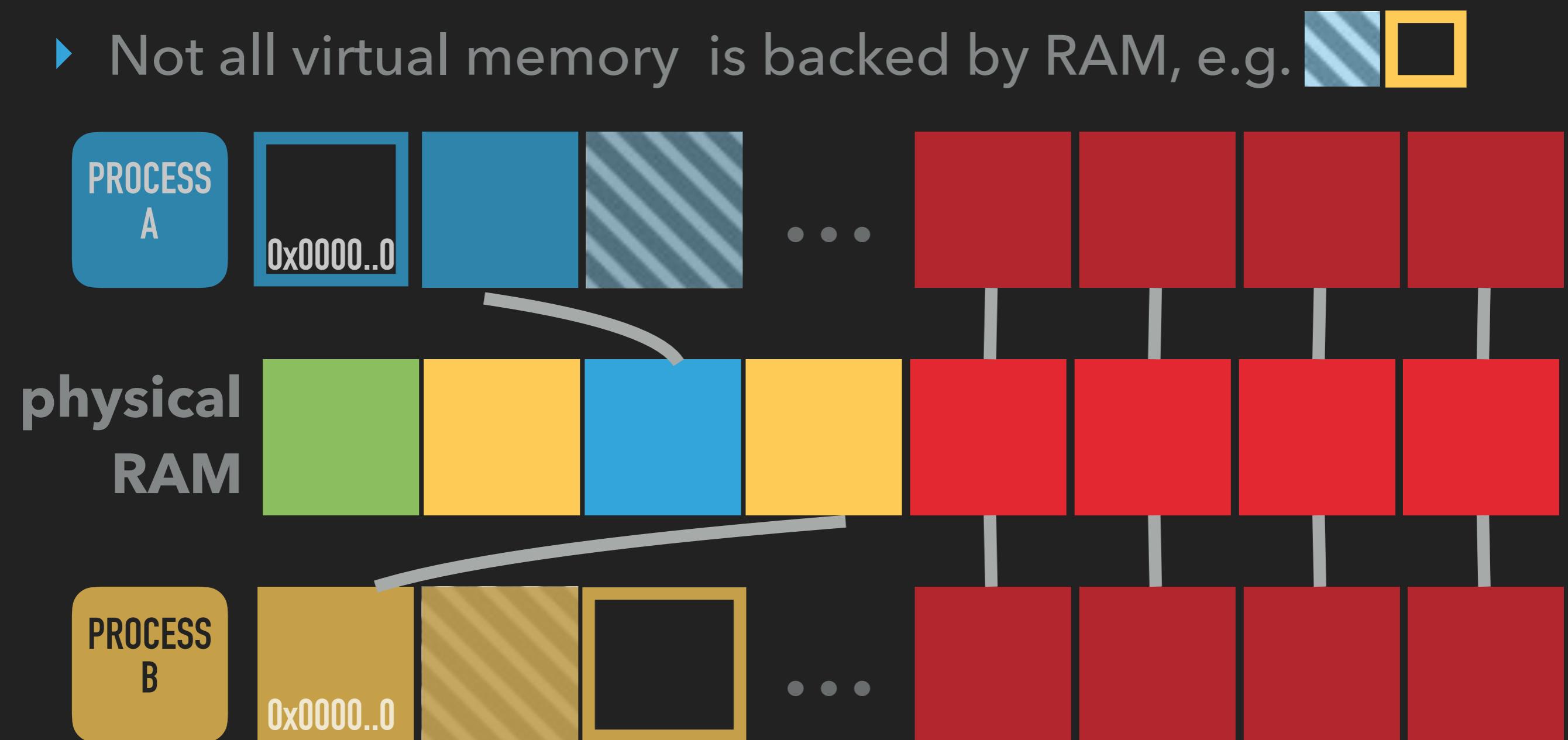
MEMORY MODEL



- ▶ **c)** is vulnerable to Meltdown and Spectre
- ▶ **b)** is vulnerable to Spectre

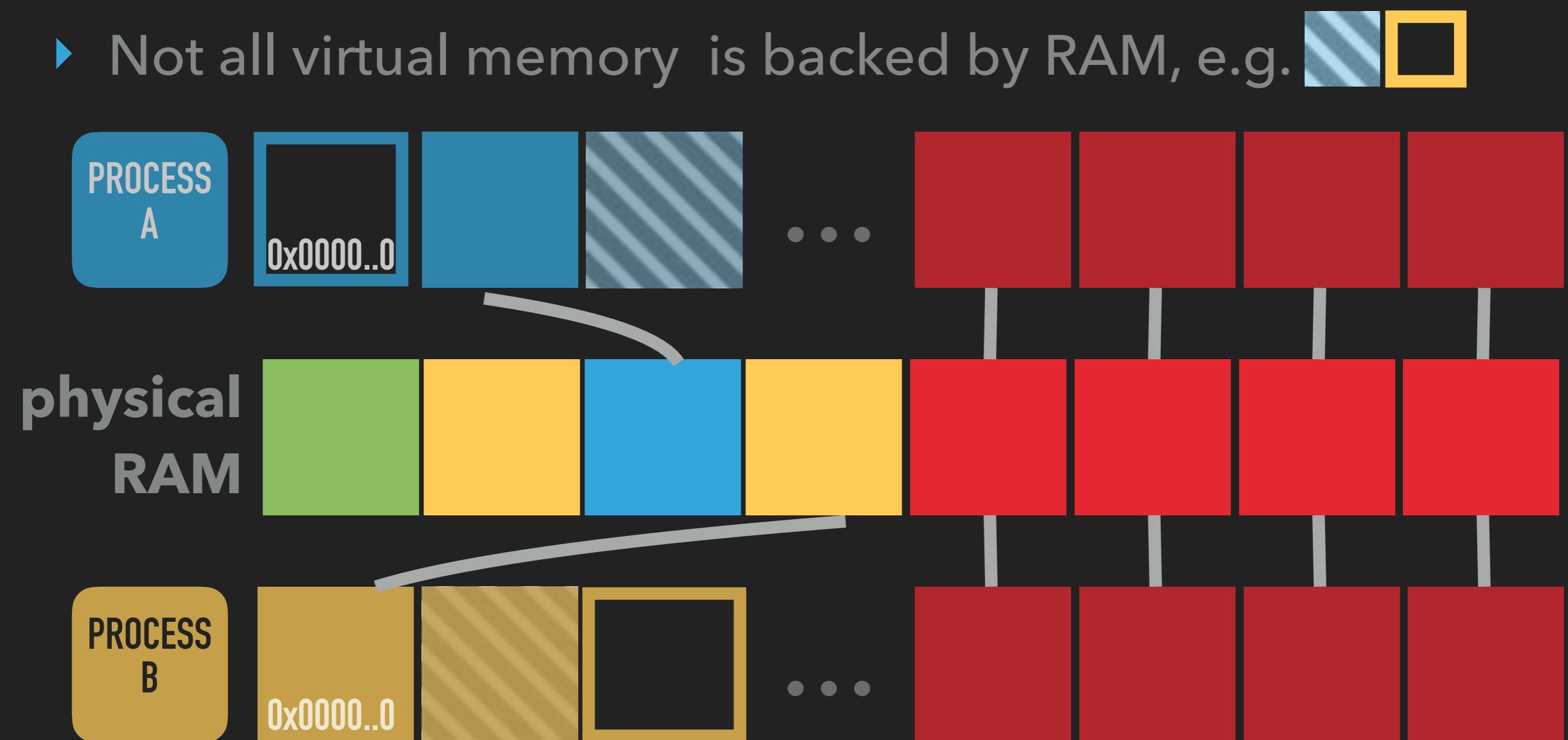
MEMORY MODEL

- ▶ Virtual memory is backed by physical RAM
- ▶ Virtual memory is much, much larger than physical RAM
- ▶ Not all virtual memory is backed by RAM, e.g.  



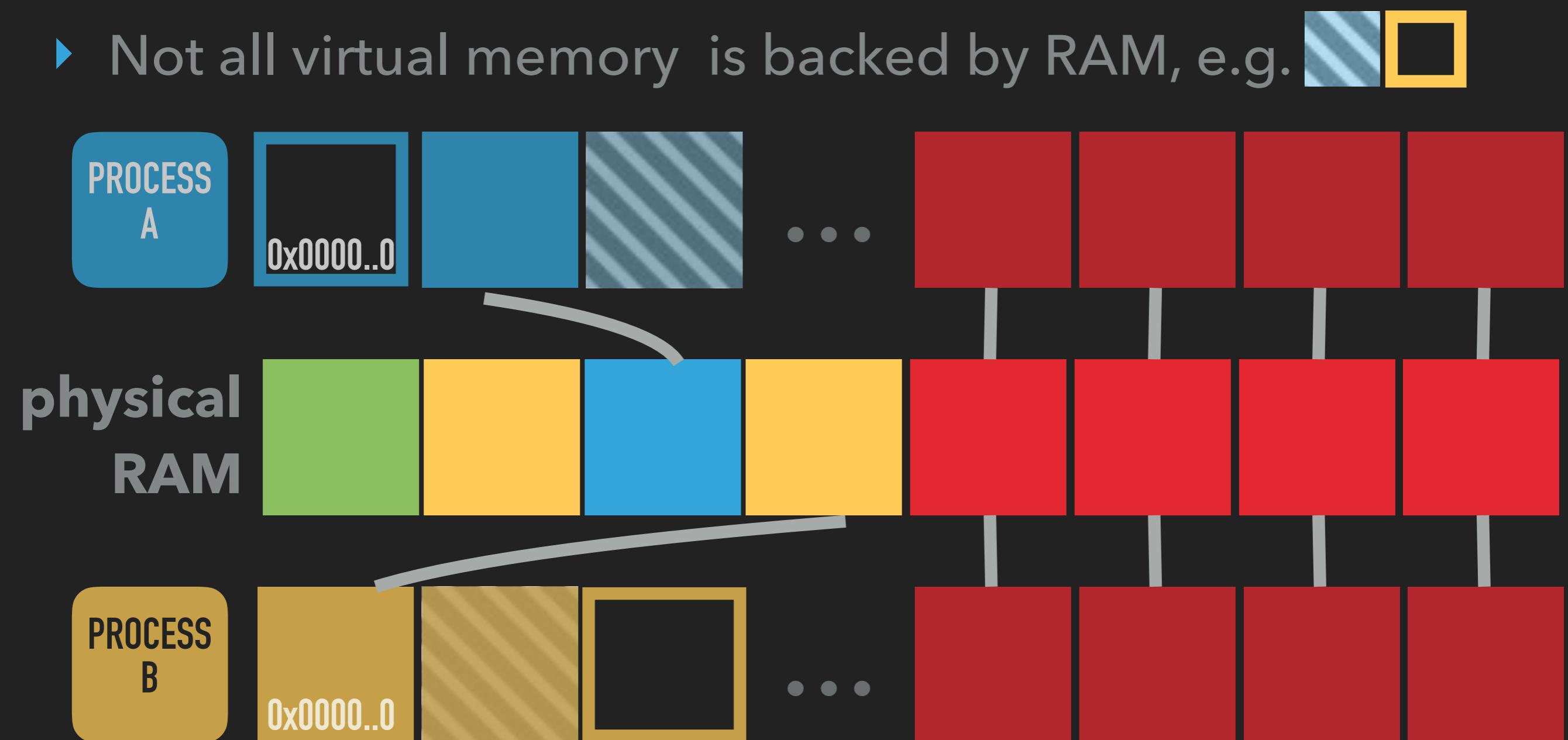
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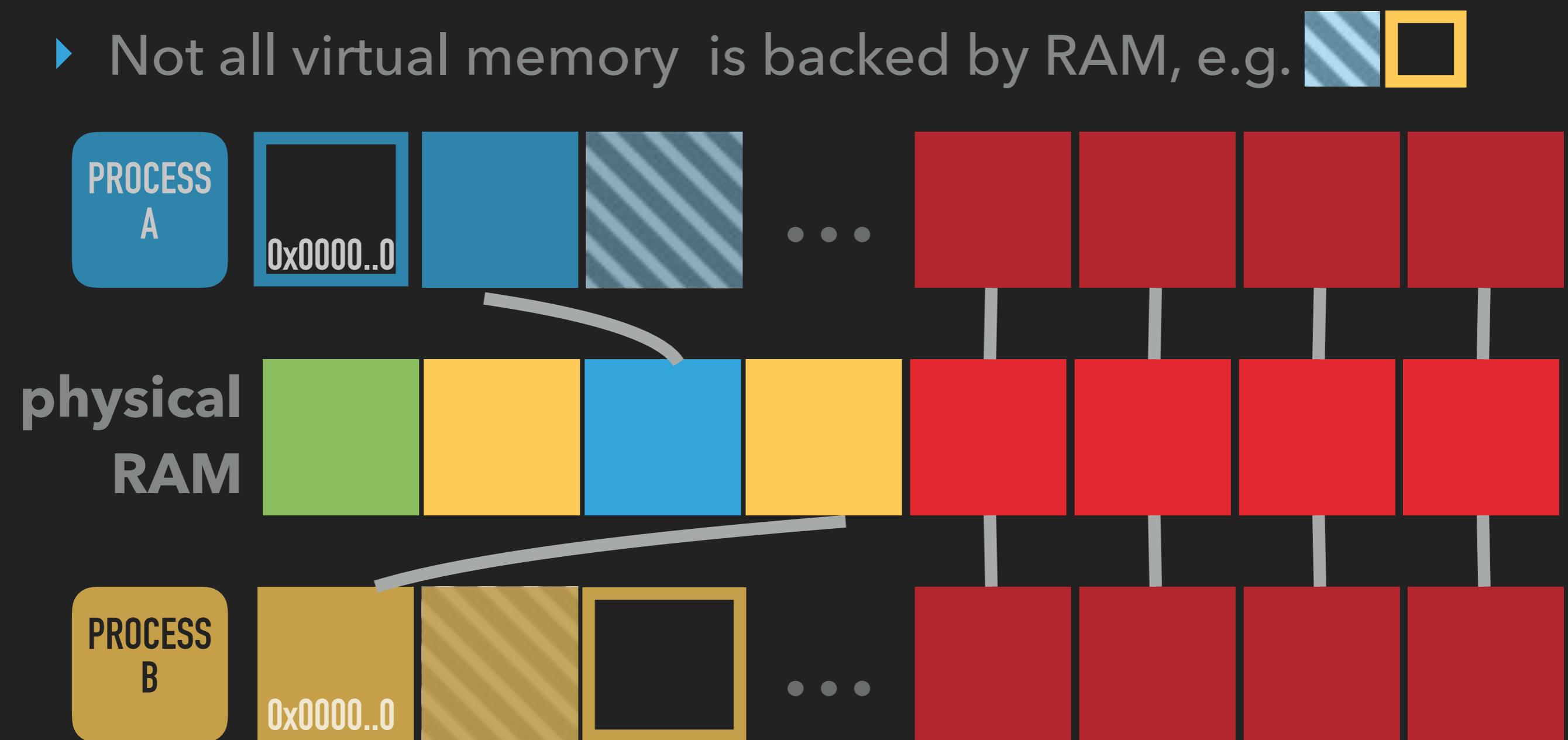
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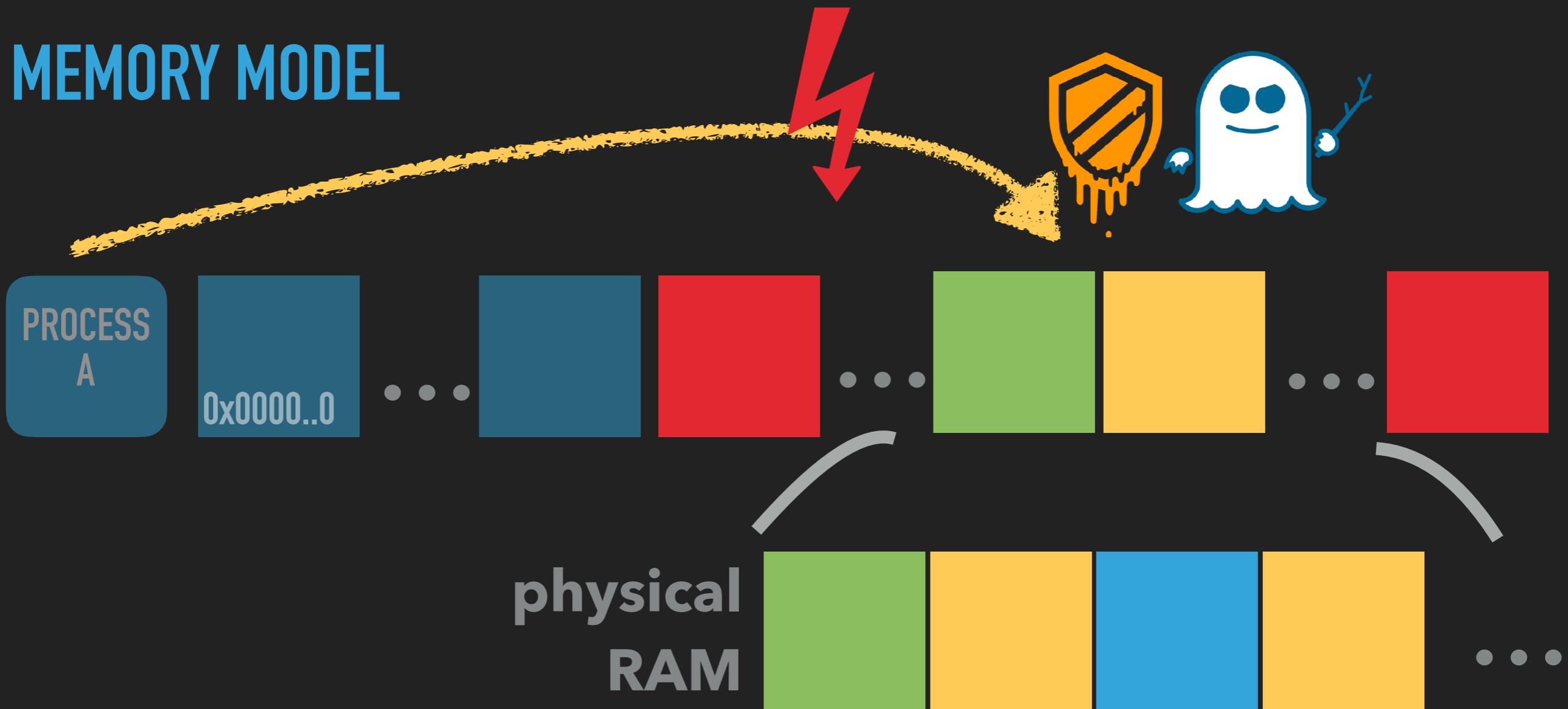


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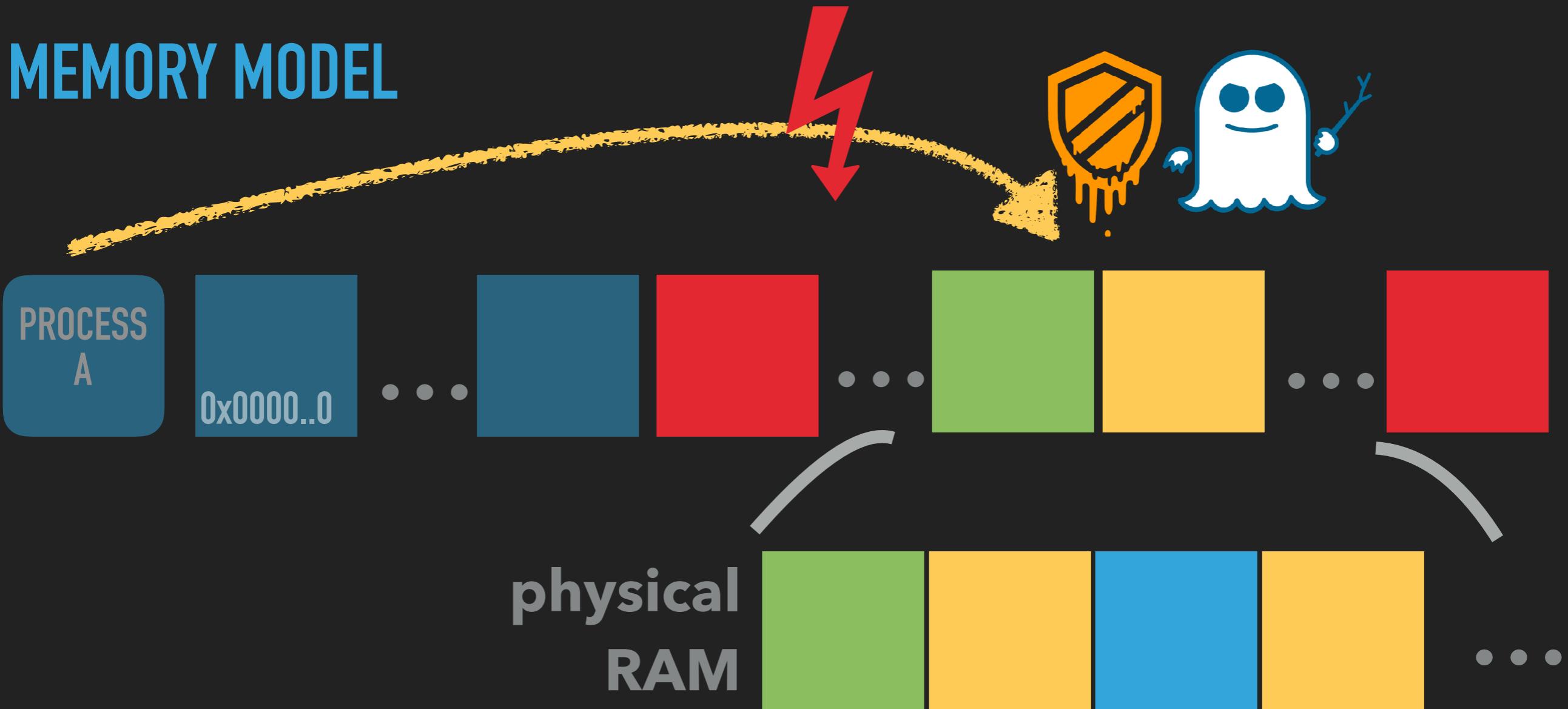
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MEMORY MODEL



MEMORY MODEL



- ▶ Like a matryoshka doll the kernel *maps all physical* memory into its address space
- ▶ Reading kernel memory allows reading of all (mapped) memory of all processes

MEMORY MODEL

Virtual memory map with 4 level page tables:

```
0000000000000000 - 00007fffffffffffff (=47 bits) user space, different per mm
hole caused by [47:63] sign extension
ffff800000000000 - ffff87fffffffffffff (=43 bits) guard hole, reserved for hypervisor
ffff880000000000 - ffffc7fffffffffffff (=64 TB) direct mapping of all phys. memory
fffffc80000000000 - ffffc8fffffffffffff (=40 bits) hole
fffffc90000000000 - ffffe8fffffffffffff (=45 bits) vmalloc/ioremap space
fffffe90000000000 - ffffe9fffffffffffff (=40 bits) hole
ffffea0000000000 - ffffeaafffffffffffffff (=40 bits) virtual memory map (1TB)
... unused hole ...
fffffec0000000000 - ffffffbfffffff (=44 bits) kasan shadow memory (16TB)
... unused hole ...
          vaddr_end for KASLR
fffffe0000000000 - ffffffe7fffffffffffff (=39 bits) cpu_entry_area mapping
fffffe8000000000 - ffffffeffffffffff (=39 bits) LDT remap for PTI
ffffff0000000000 - ffffff7fffffffffffff (=39 bits) %esp fixup stacks
... unused hole ...
fffffefef00000000 - ffffffefefffffff (=64 GB) EFI region mapping space
... unused hole ...
fffffff80000000 - ffffffff9fffffffffffff (=512 MB) kernel text mapping, from phys 0
fffffff80000000 - ffffffffeffffff (1520 MB) module mapping space
[fixmap start] - ffffffff5fffff kernel-internal fixmap range
fffffff600000 - ffffffff600fff (=4 kB) legacy vsyscall ABI
fffffff800000 - ffffffffeffffff (=2 MB) unused hole
```



OUT OF ORDER
EXECUTION

MELTDOWN

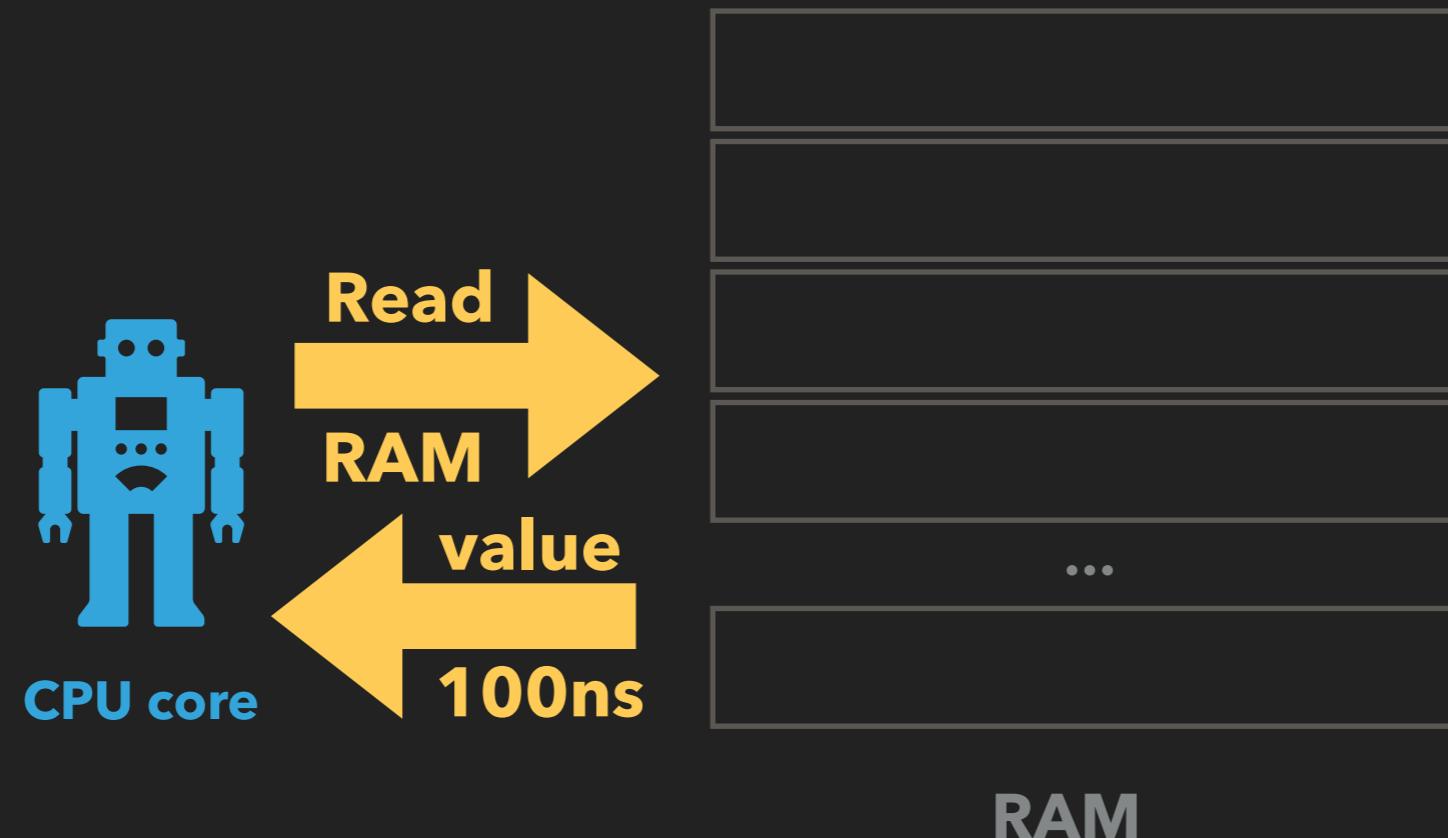
MELTDOWN



Meltdown basically works like this:

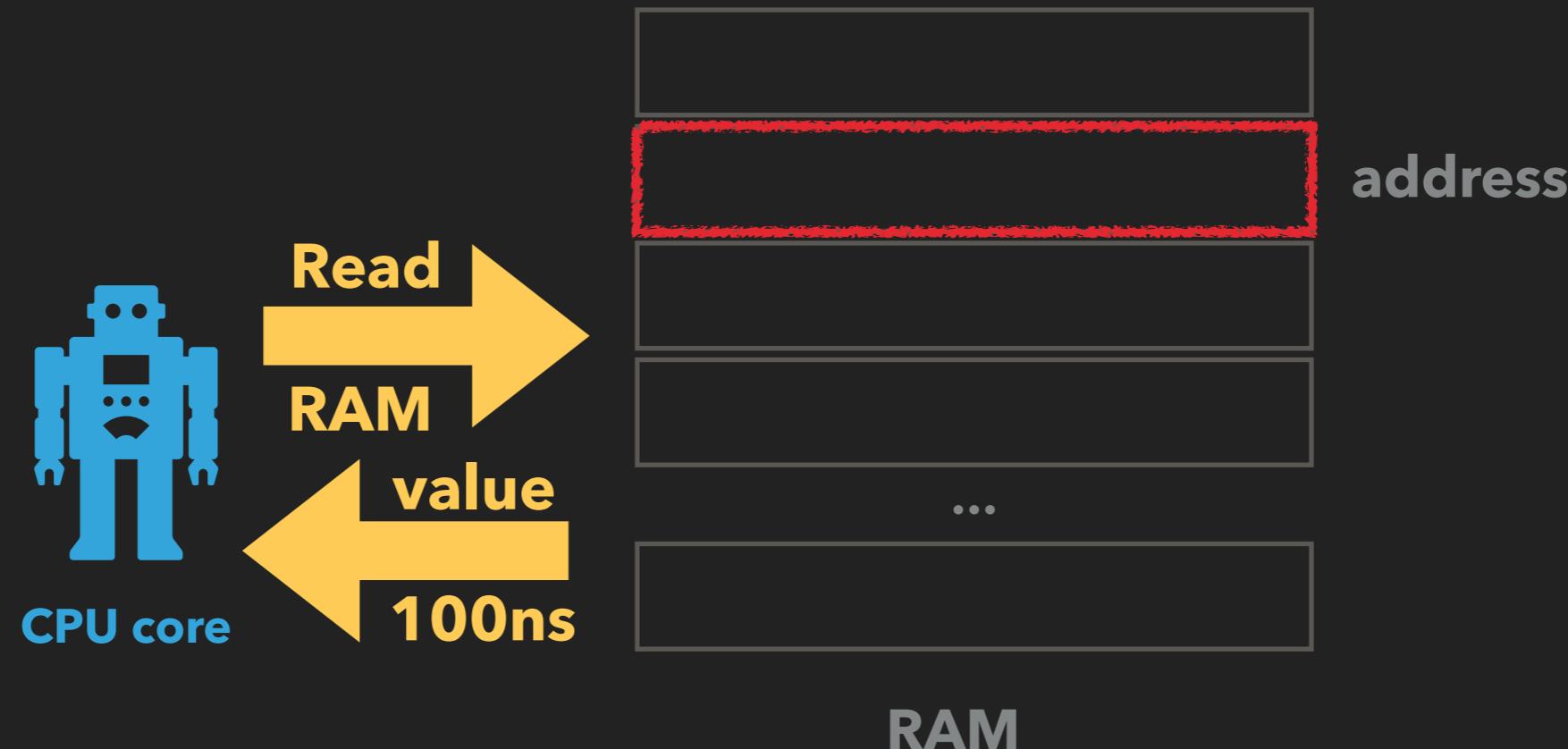
- READ secret from forbidden address
- Stash away secret before CPU detects wrongdoing
- Retrieve secret

MELTDOWN: STASHING AWAY - SIDECHANNEL



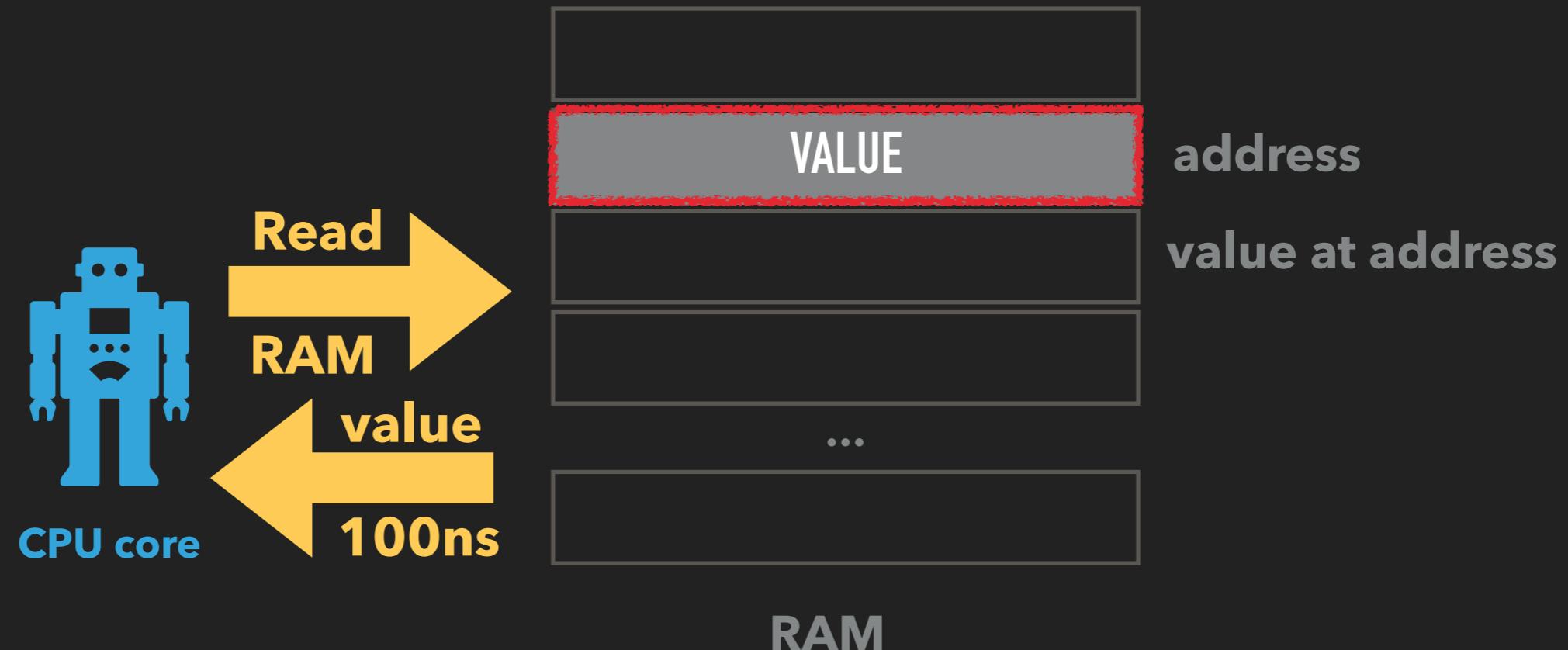
- ▶ Data is stored in RAM
- ▶ RAM is very slow
- ▶ Reading one byte stalls the CPU for hundreds of µOPs

MELTDOWN: STASHING AWAY - SIDECHANNEL



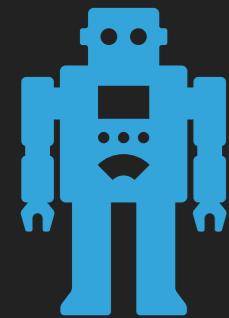
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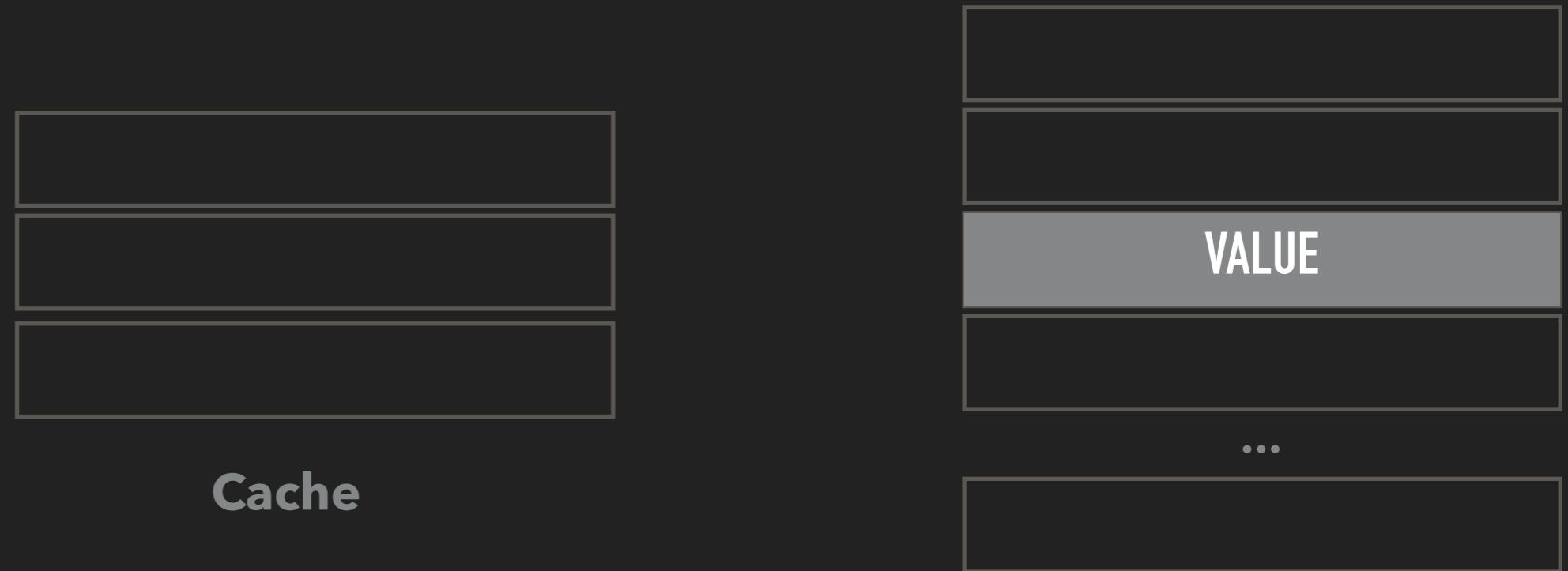


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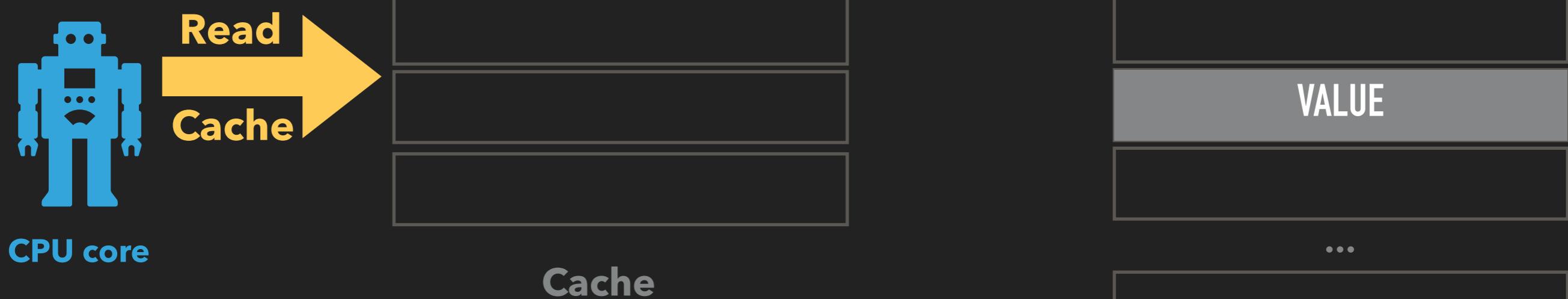
CPU core



- ▶ Reading one byte stalls the CPU for hundreds of µOPs
- ▶ CPU caches considerably speed this up
- ▶ E.g. reading cached takes 3ns, reading uncached 103ns

The cache speeds up "*what is the value at address X?*". This is called "*(address) X is cached*"

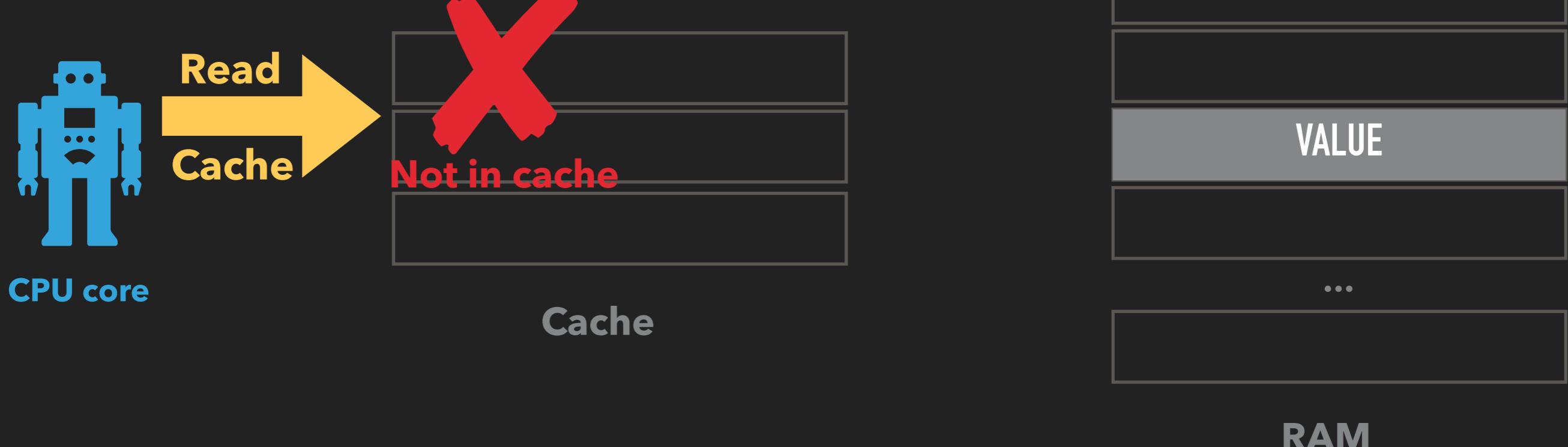
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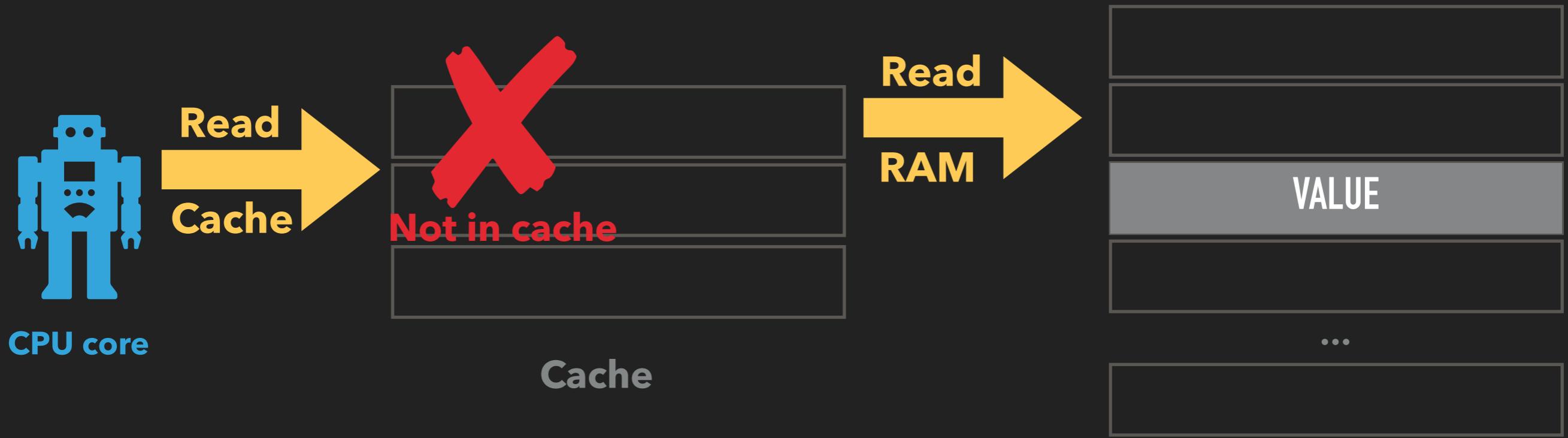
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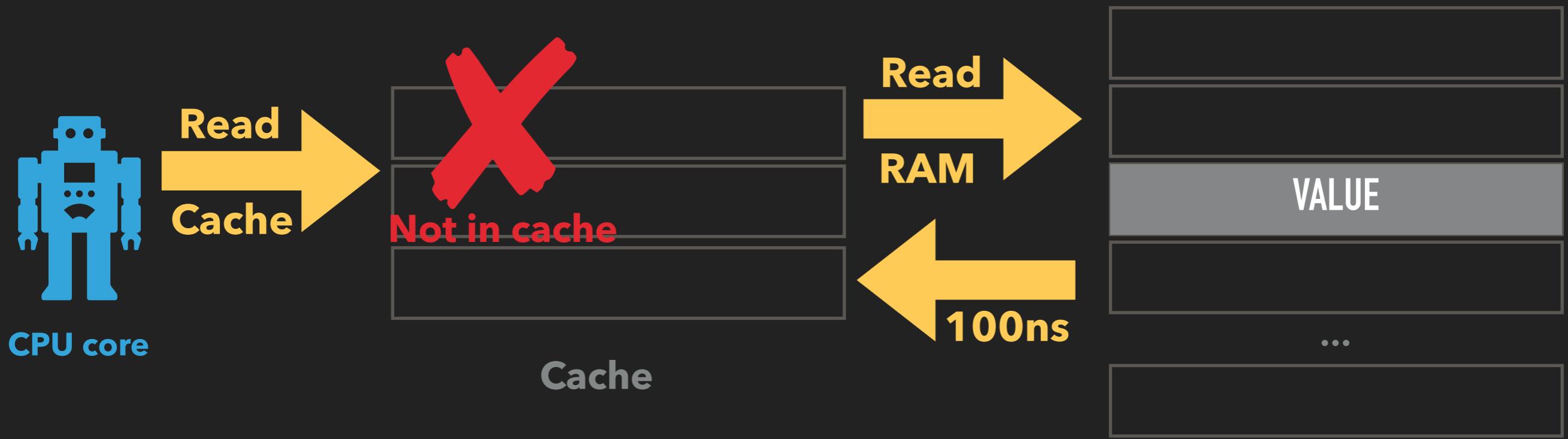
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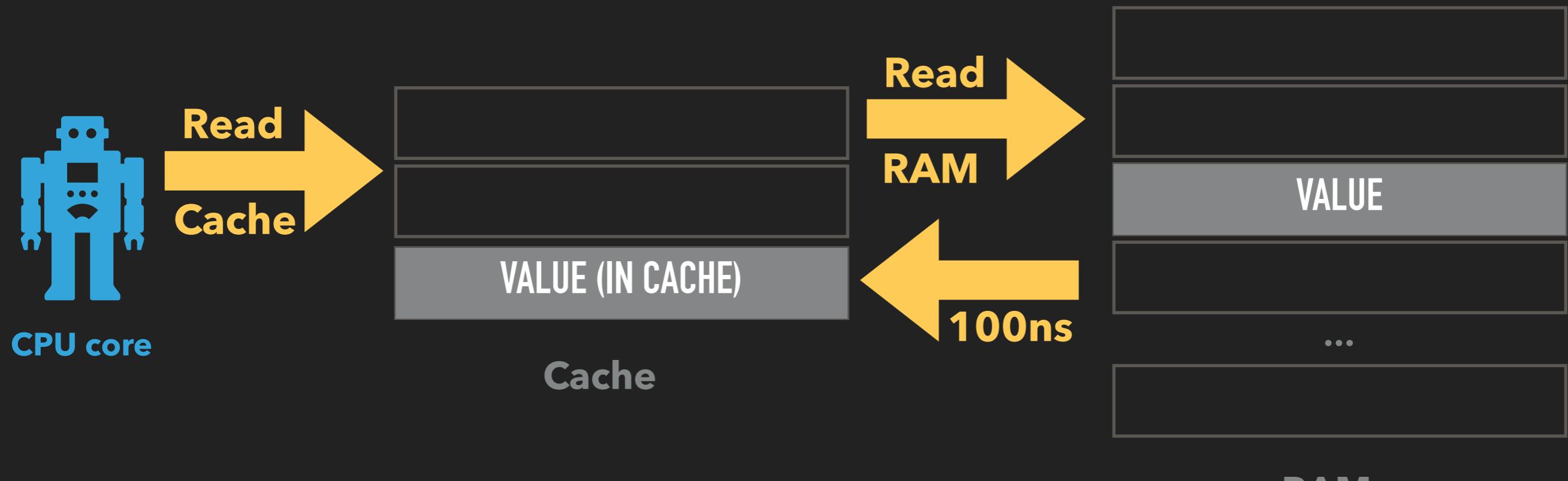
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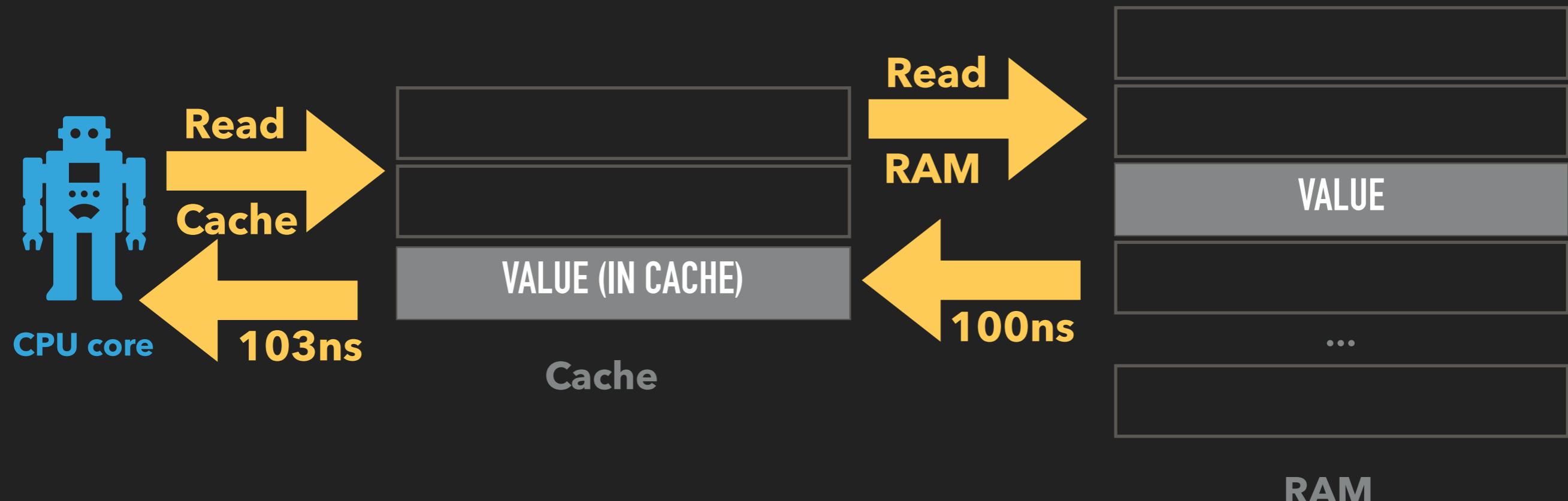
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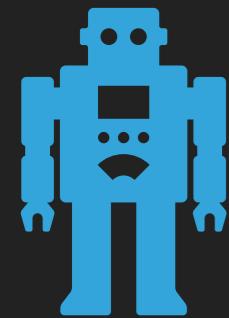
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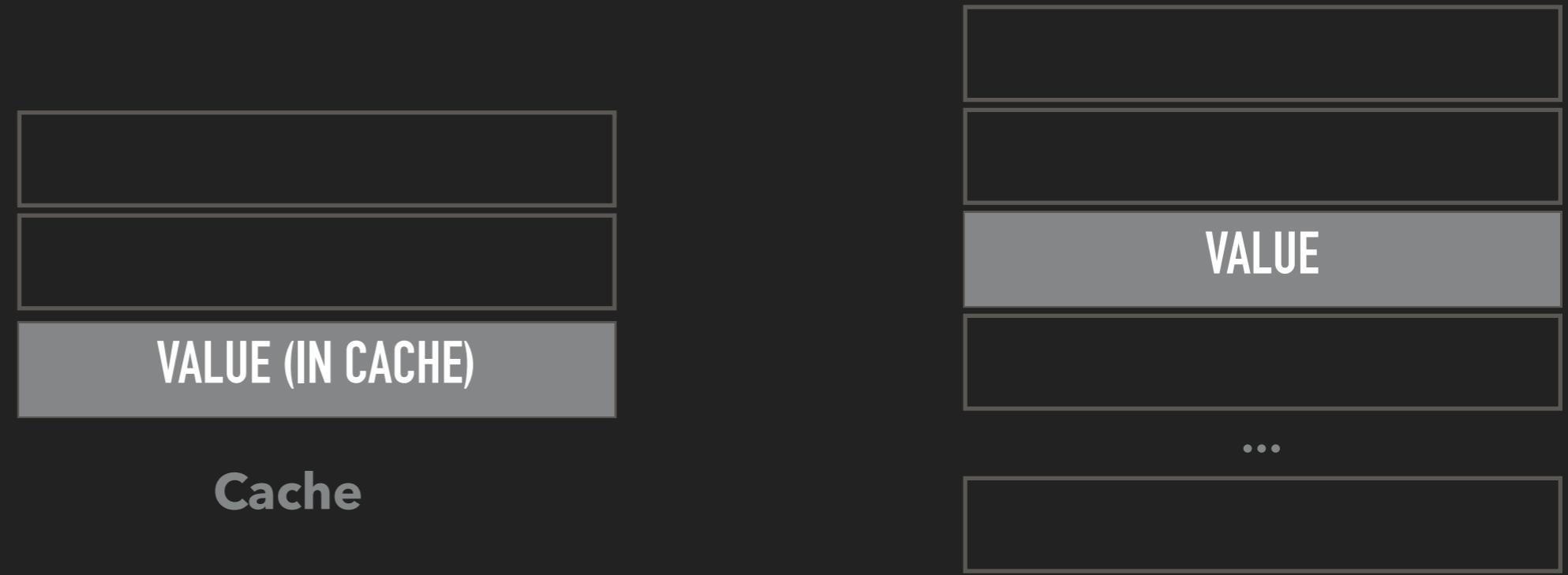
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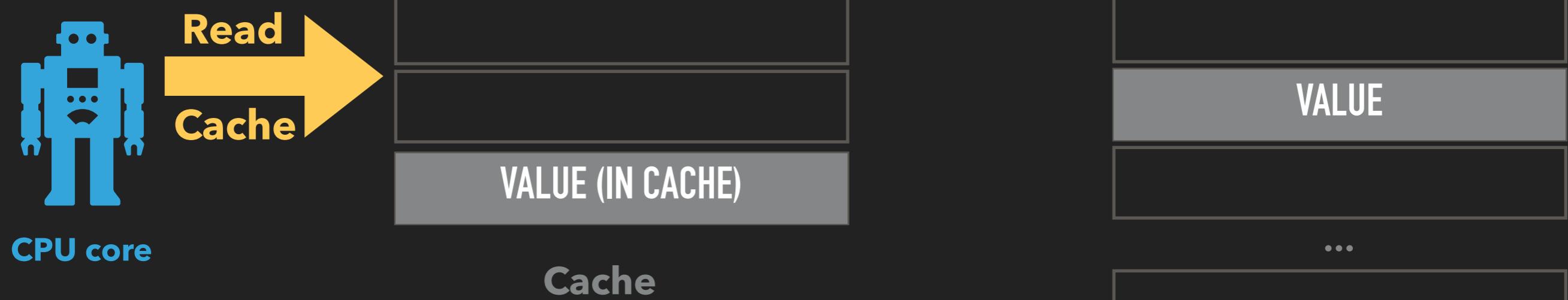
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The cache speeds up "*what is the value at address X?*". This is called "*(address) X is cached*"

MELTDOWN: STASHING AWAY - SIDECHANNEL



- ▶ Reading one byte stalls the CPU for hundreds of µOPs
- ▶ CPU caches considerably speed this up
- ▶ E.g. reading cached takes 3ns, reading uncached 103ns

The cache speeds up "*what is the value at address X?*". This is called "*(address) X is cached*"

MELTDOWN: STASHING AWAY - SIDECHANNEL



- ▶ Reading one byte stalls the CPU for hundreds of μ OPs
- ▶ CPU caches considerably speed this up
- ▶ E.g. reading cached takes 3ns, reading uncached 103ns

The cache speeds up "*what is the value at address X?*". This is called "(address) X is cached"

“READ” INSTRUCTION

For a CPU the “READ value from memory at 4711” instruction looks like this (μ OPs):

1. Check that program may read from address
2. Store the value at address in register¹

If 1 fails the program is aborted.

This can be handled by the program.

¹ Register: The CPUs scratchpad

“READ” INSTRUCTION

For a CPU the “READ value from memory at 4711” instruction looks like this (μ OPs):

1. Check that program may read from address
2. Store the value at address in register¹

If 1 fails the program is aborted.

This can be handled by the program.

In our burger example:

1. Customer orders a burger & coffee
2. Burger is ready, coffee machine breaks
3. Customer does not get his burger

¹ Register: The CPUs scratchpad

MELTDOWN: READING FORBIDDEN DATA



Meltdown basically works like this:

- READ secret from forbidden address
- 1. Check that program may read from address
- 2. Store the read value in register
- Stash away secret
- 1 *Magic*
- Retrieve secret (*later*)

μOPs: 1 2 1

MELTDOWN: READING FORBIDDEN DATA



μOPs ordered by *instruction*

1 Check access

2 Read into register

1 *Magic*

μOPs ordered by *execution*

2 Read into register

1 *Magic*

1 Check access

The re-ordering on the right happens, when the “forbidden data” is already cached (because cache access is so fast).

MELTDOWN: READING FORBIDDEN DATA



μOPs ordered by *instruction*

1 Check access

2 Read into register

1 *Magic*

μOPs ordered by *execution*

2 Read into register

1 *Magic*

1 Check access

The re-ordering on the right happens, when the “forbidden data” is already cached (because cache access is so fast).

Reordering is not a problem because the CPU will ensure that is only seen *iff* succeeds.

MELTDOWN: READING FORBIDDEN DATA



μOPs ordered by *instruction*

1 Check access

2 Read into register

1 Magic

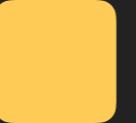
μOPs ordered by *execution*

2 Read into register

1 Magic

1 Check access

The re-ordering on the right happens, when the “forbidden data” is already cached (because cache access is so fast).

Reordering is not a problem because the CPU will ensure that  is only seen *iff*  succeeds.

Unless  is able to hide the secret in such a way that the attacker can find it later.

MELTDOWN: READING FORBIDDEN DATA



μOPs ordered by *instruction*

1 Check access

2 Read into register

1 Magic

μOPs ordered by *execution*

2 Read into register

1 Magic

1 Check access

The re-ordering on the right happens, when the “forbidden data” is already cached (because cache access is so fast).

Reordering is not a problem beca-

that is only seen *iff* succe-

Unless is able to hide the secret
attacker can find it later.

In our burger example:

1. Customer orders a burger & coffee
2. Customer gets his burger
3. Coffee machine breaks
4. Customer runs away with burger

MELTDOWN



For Meltdown two actors are needed

The **spy** and a **collector**.

110011010 The **spy** will “steal” the secret and stash it away.
010111010
111100100 The CPU will kill him for accessing the secret
000101101
100110010 information.
Spy

110011010
010111010
111100100
000101101
100110010

The **collector** will find the stashed away secret.

Collector

MELTDOWN: THE SIDECHANNEL (IDEA)

110011010

010111010

111100100

000101101

100110010

Spy

110011010

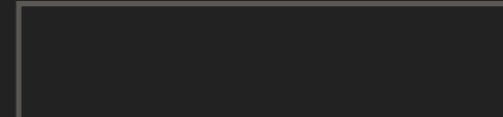
010111010

111100100

000101101

100110010

Collector



...

"IT'S A 1"

"IT'S A 2"

"IT'S A 3"

...

SECRET ("3")

Places





MELTDOWN: THE SIDECHANNEL (IDEA)

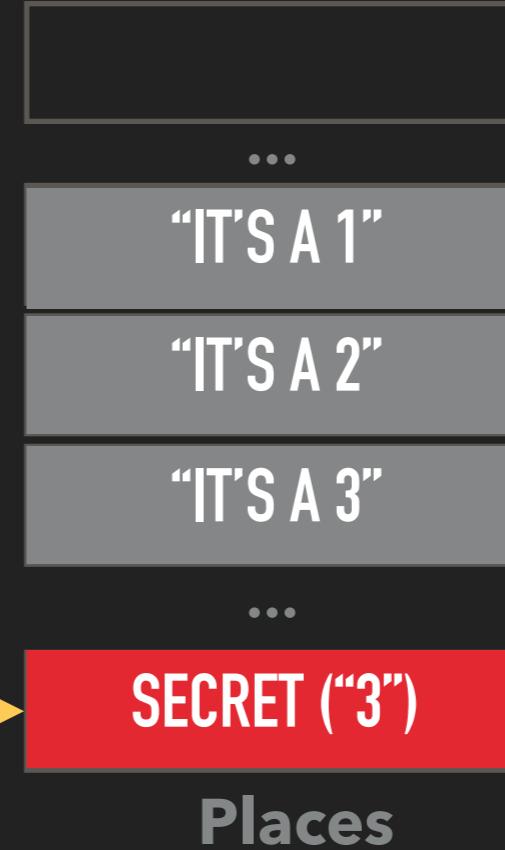
110011010
010111010
111100100
000101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector

■ **Spy** will read the **secret**



MELTDOWN: THE SIDECHANNEL (IDEA)

110011010
010111010
111100100
000101101
100110010

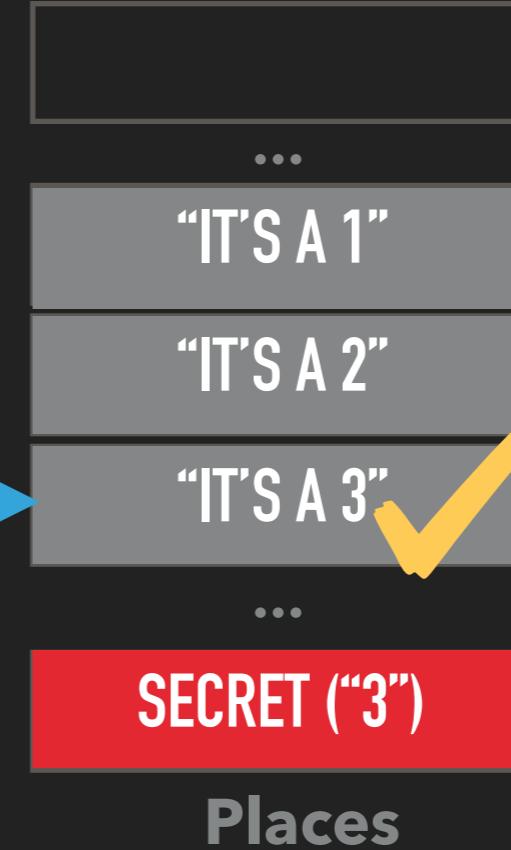
Spy

110011010
010111010
111100100
000101101
100110010

Collector

█ **Spy** will read the **secret**

█ Depending on the **value**, **Spy** will mark a grey block



Places



MELTDOWN: THE SIDECHANNEL (IDEA)

110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector

■ **Spy** will read the **secret**

■ Depending on the **value**, **Spy** will mark a grey block

■ CPU detects **Spys** access validation and terminates **Spy**



Places



MELTDOWN: THE SIDECHANNEL (IDEA)

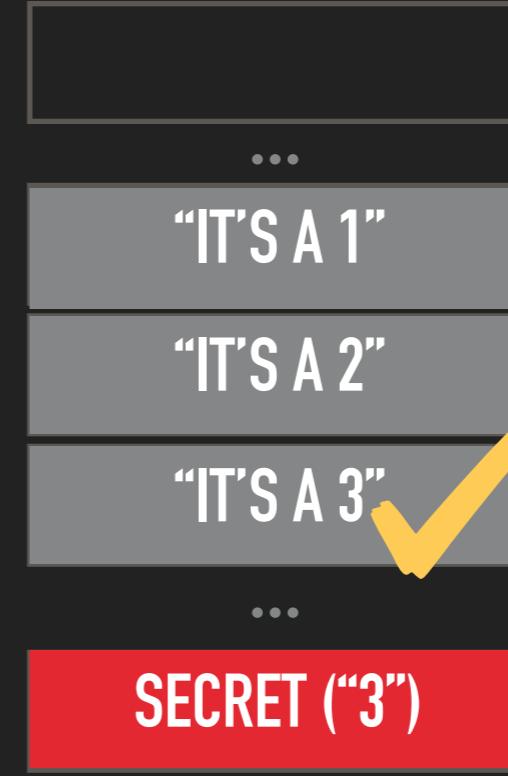


110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



Places

- **Spy** will read the **secret**
- Depending on the **value**, **Spy** will mark a grey block
- CPU detects **Spys** access validation and terminates **Spy**
- **Collector** now looks for **Spys** mark in all grey blocks



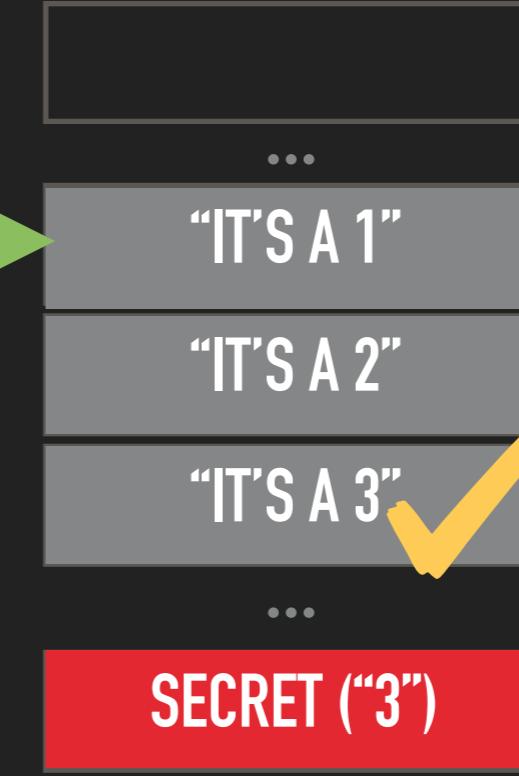
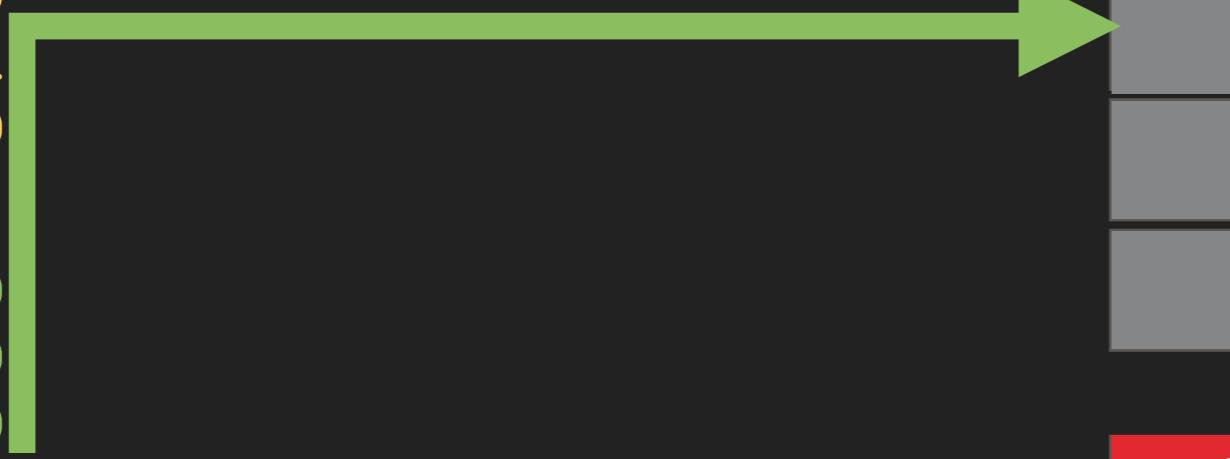
MELTDOWN: THE SIDECHANNEL (IDEA)

110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



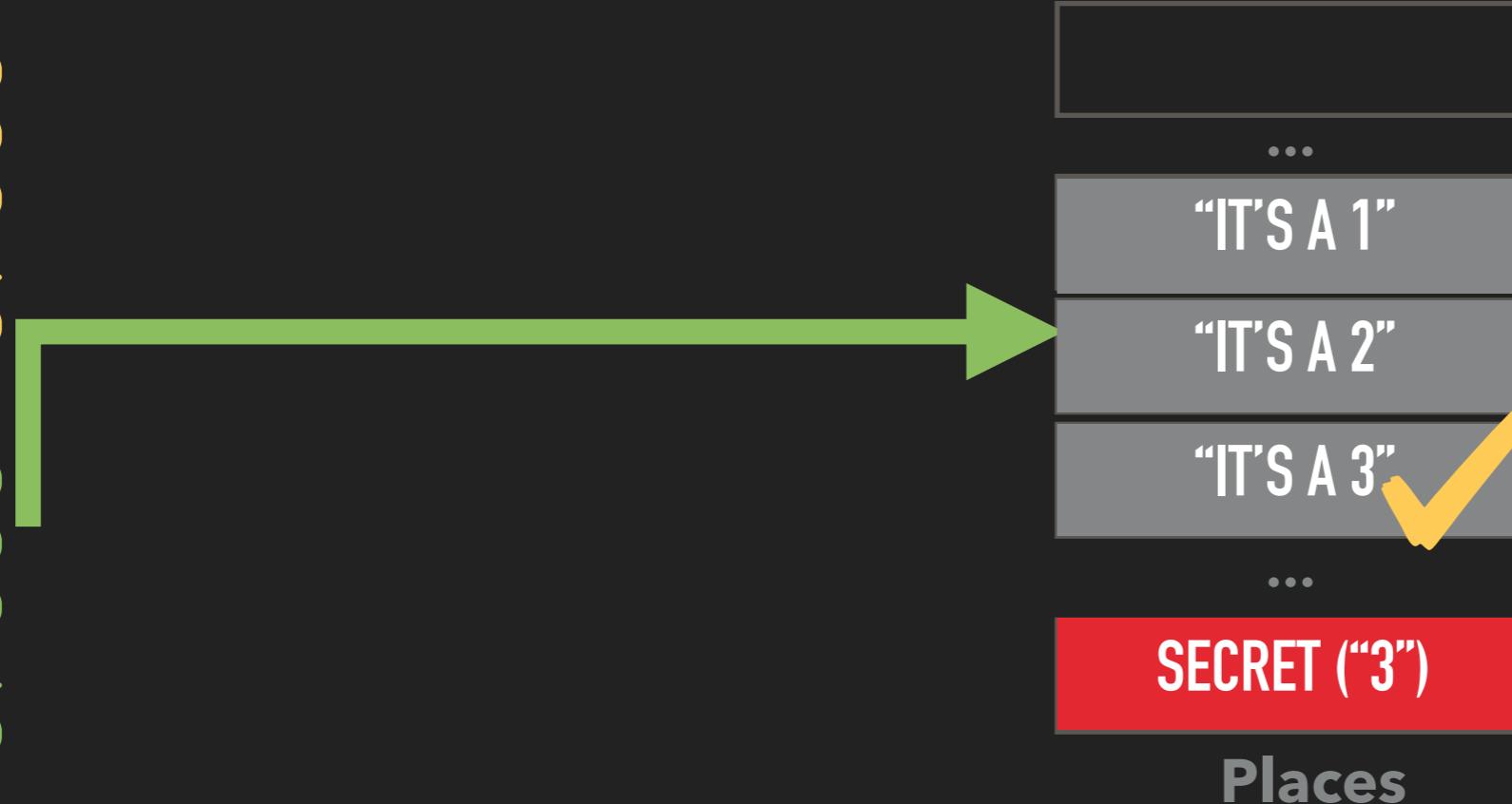
Places

- **Spy** will read the **secret**
- Depending on the **value**, **Spy** will mark a grey block
- CPU detects **Spys** access validation and terminates **Spy**
- **Collector** now looks for **Spys** mark in all grey blocks



MELTDOWN: THE SIDECHANNEL (IDEA)

110011010
010111010
111100100
00101101
100110010
Spy
110011010
010111010
111100100
000101101
100110010
Collector



- **Spy** will read the **secret**
- Depending on the **value**, **Spy** will mark a grey block
- CPU detects **Spys** access validation and terminates **Spy**
- **Collector** now looks for **Spys** mark in all grey blocks



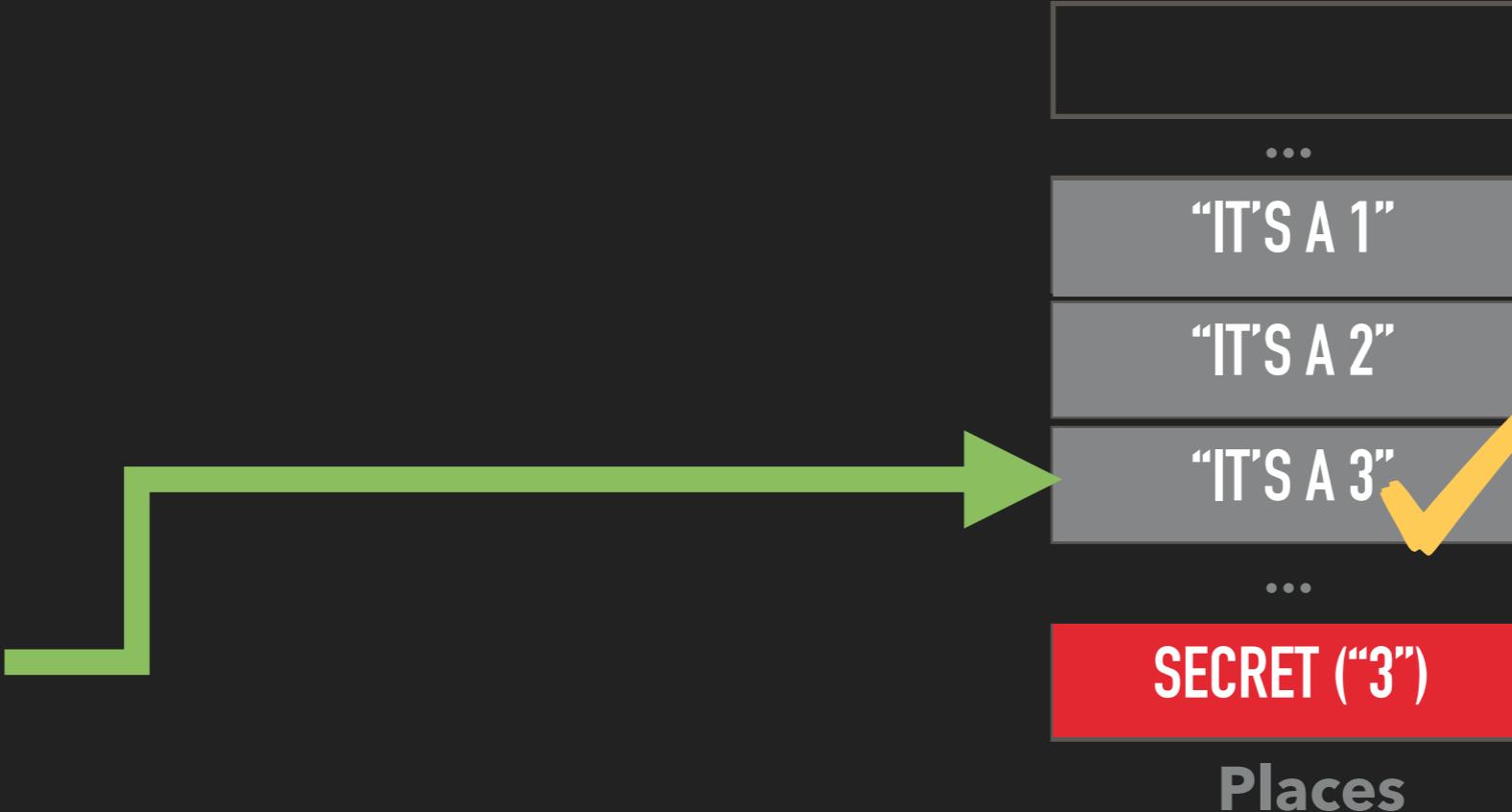
MELTDOWN: THE SIDECHANNEL (IDEA)

110011010
010111010
111100100
001010101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



- **Spy** will read the **secret**
- Depending on the **value**, **Spy** will mark a grey block
- CPU detects **Spys** access validation and terminates **Spy**
- **Collector** now looks for **Spys** mark in all grey blocks

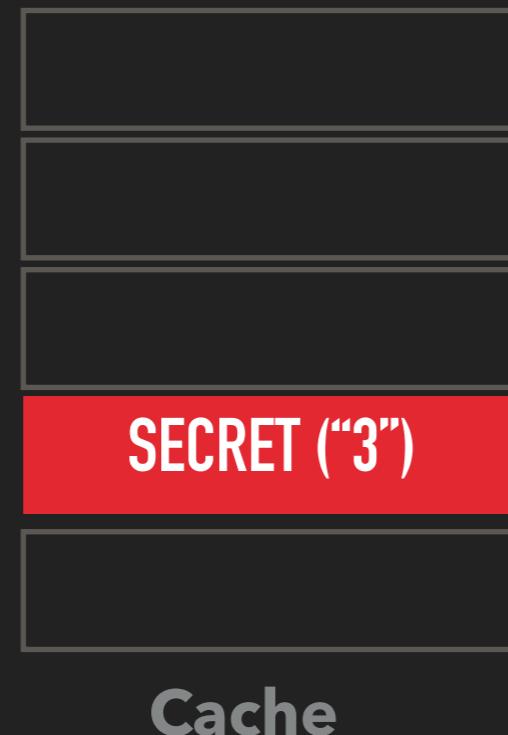
MELTDOWN: THE ATTACK

110011010
010111010
111100100
000101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



grey box:
memory block
tested by **Collector**



allowed to
read?



- ▶ Meltdown needs some preconditions
- ▶ The **secret** is in the cache (value: 3)
- ▶ Both **Spy** and **Collector** can read grey memory blocks

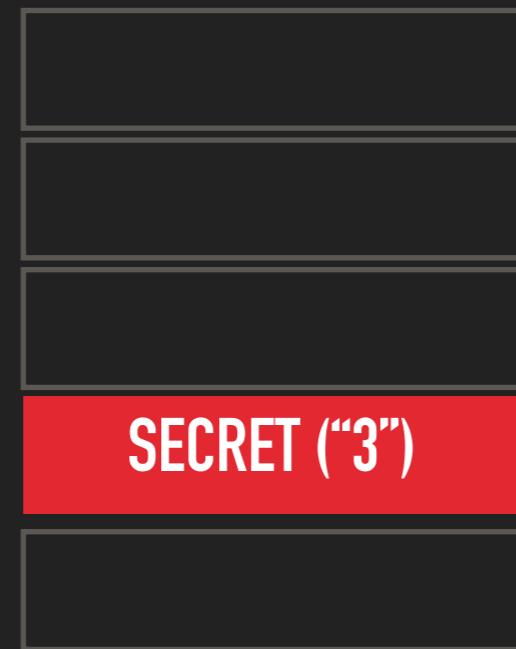
MELTDOWN: THE ATTACK

110011010
010111010
111100100
000101101
100110010

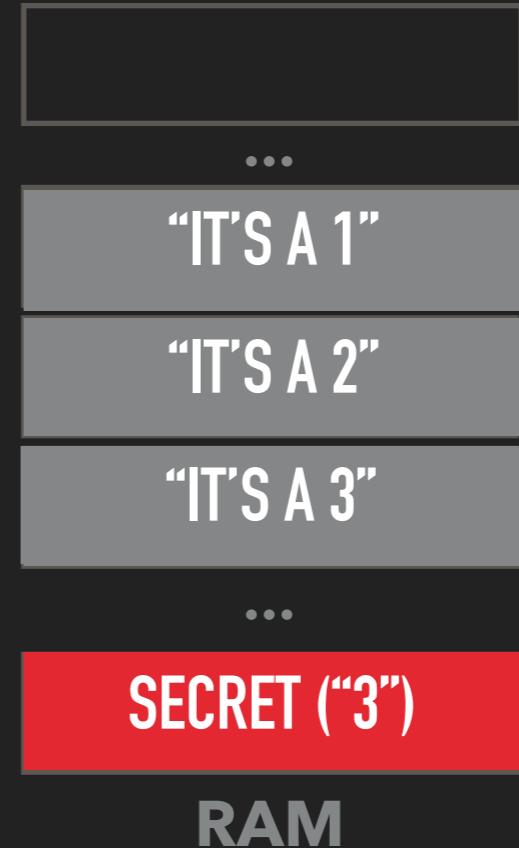
Spy

110011010
010111010
111100100
000101101
100110010

Collector



Cache



RAM





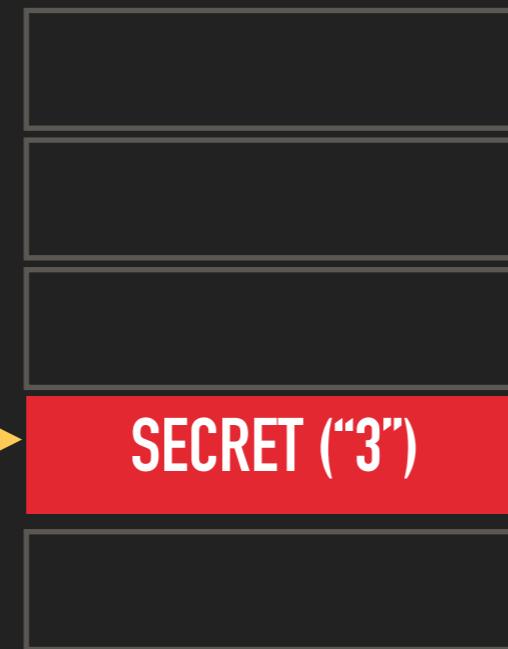
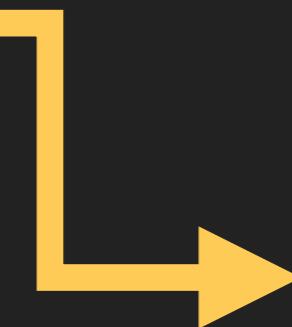
MELTDOWN: THE ATTACK

110011010
010111010
111100100
000101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



Cache



RAM

- 2 1. Spy will read the **secret**

MELTDOWN: THE ATTACK

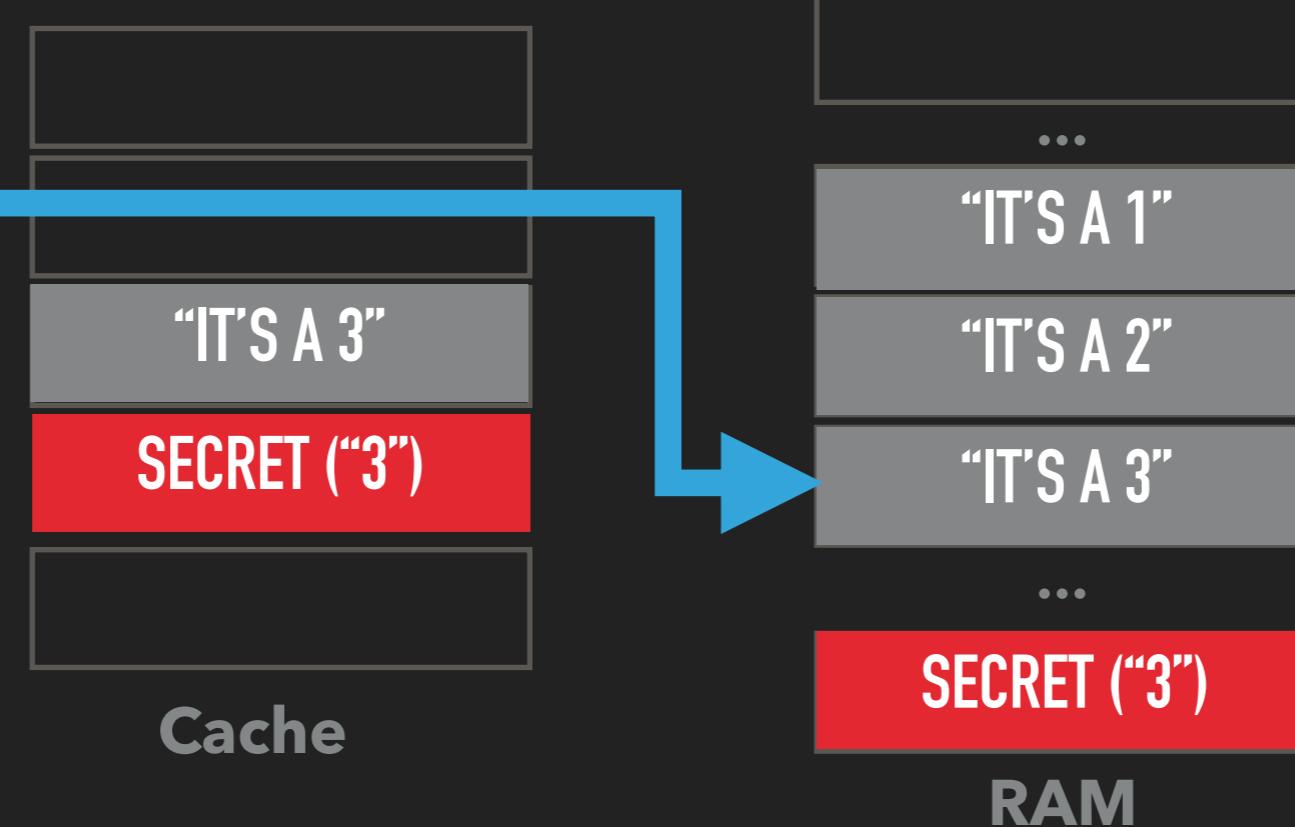


110011010
010111010
111100100
000101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



- 2 1. Spy will read the **secret**
2. Depending on the **value**, Spy will cache a grey block¹

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses

MELTDOWN: THE ATTACK

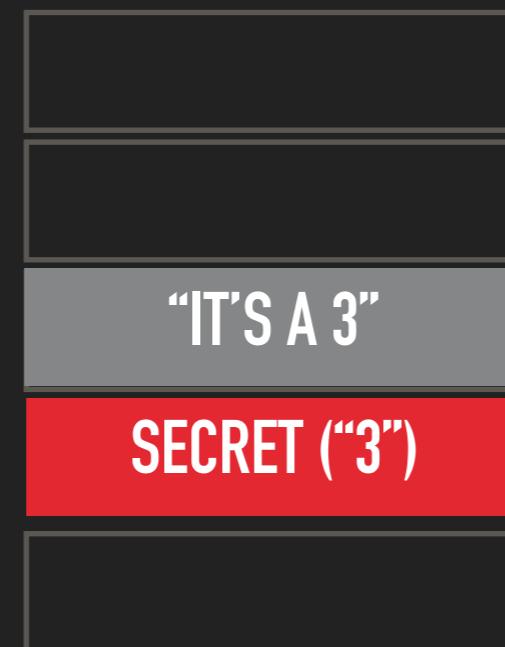


110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



- 2 1. **Spy** will read the **secret**
- 2 2. Depending on the **value**, **Spy** will cache a grey block¹
- 1 3. CPU detects **Spys** access validation and terminates **Spy**

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses

MELTDOWN: THE ATTACK



110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

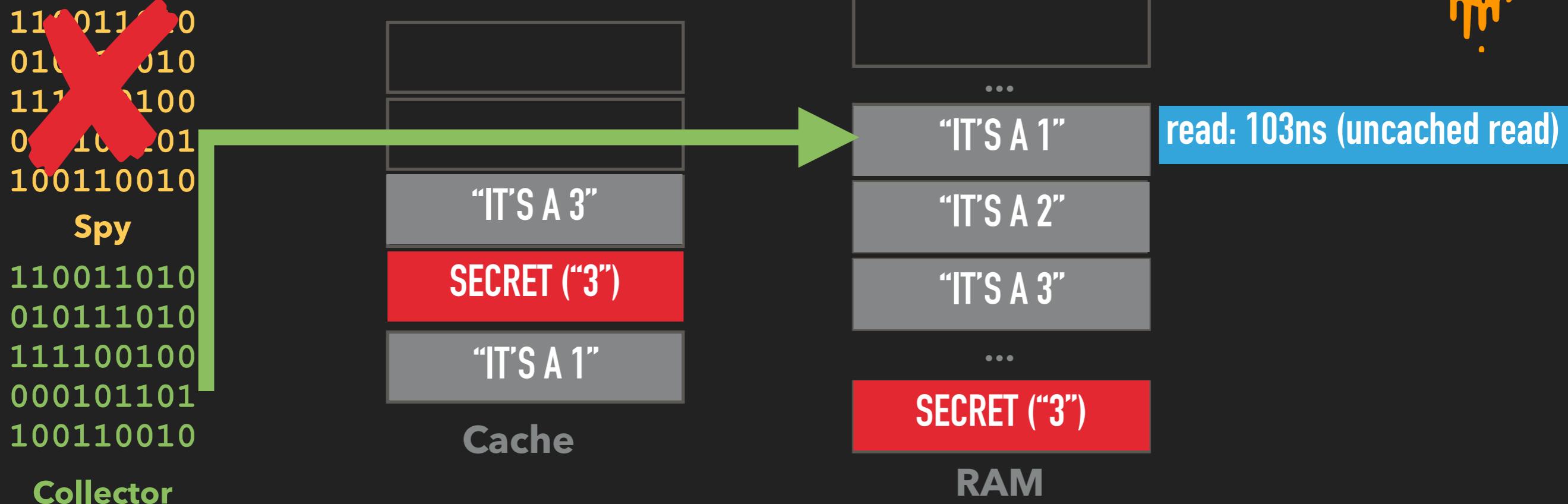
Collector



- 2 1. **Spy** will read the **secret**
- 2 2. Depending on the **value**, **Spy** will cache a grey block¹
- 1 3. CPU detects **Spys** access validation and terminates **Spy**
4. **Collector** now reads all grey blocks and stops the time

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses

MELTDOWN: THE ATTACK



Collector

- 2 1. Spy will read the secret
- 2 2. Depending on the value, Spy will cache a grey block¹
- 1 3. CPU detects Spys access validation and terminates Spy
4. Collector now reads all grey blocks and stops the time

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses



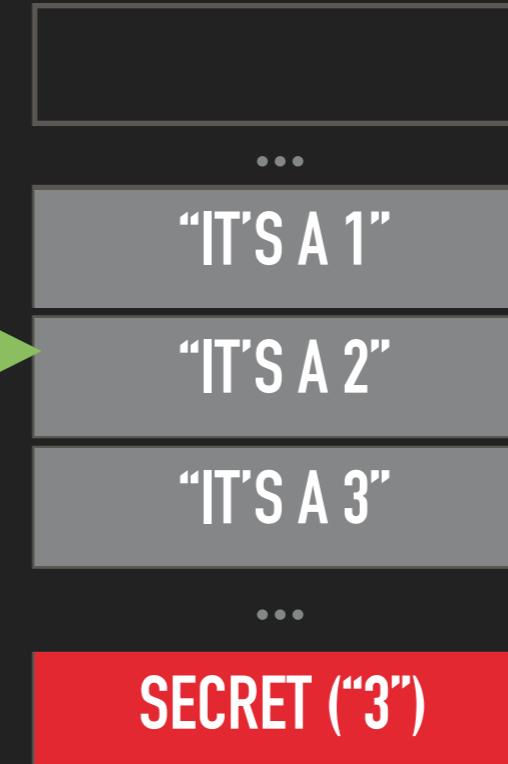
MELTDOWN: THE ATTACK

110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



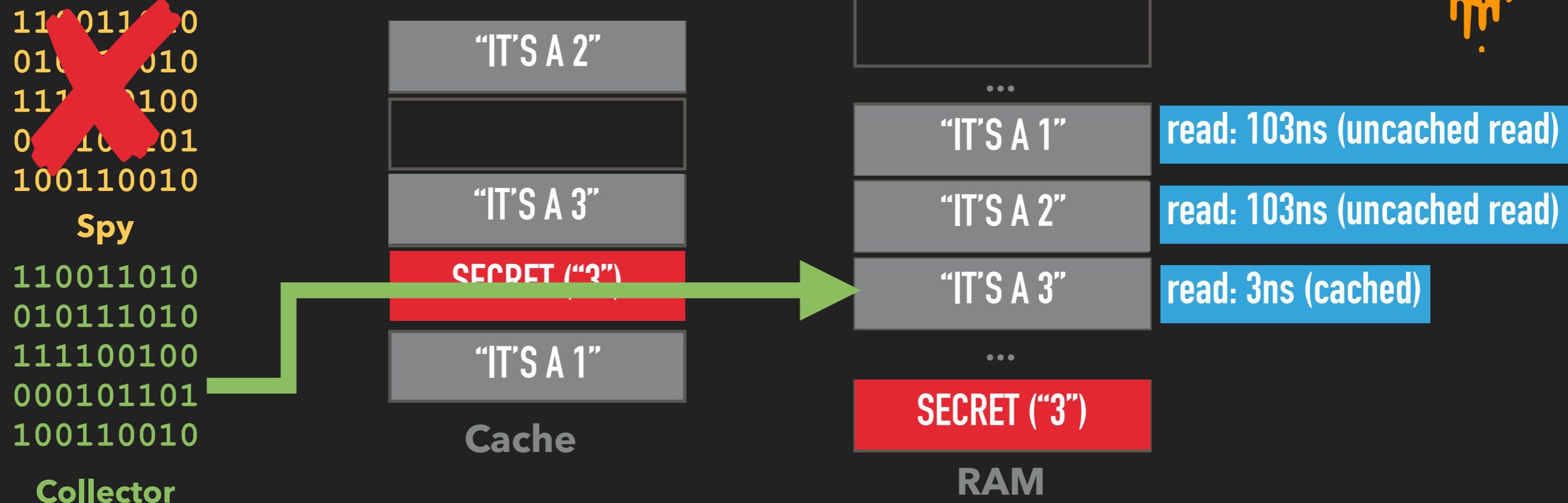
read: 103ns (uncached read)
read: 103ns (uncached read)

- 2 1. **Spy** will read the **secret**
- 2 2. Depending on the **value**, **Spy** will cache a grey block¹
- 1 3. CPU detects **Spys** access validation and terminates **Spy**
4. **Collector** now reads all grey blocks and stops the time

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses



MELTDOWN: THE ATTACK



- 2** 1. **Spy** will read the **secret**
- 2** 2. Depending on the **value**, **Spy** will cache a grey block¹
- 1** 3. CPU detects **Spys** access validation and terminates **Spy**
- 4** 4. **Collector** now reads all grey blocks and stops the time

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses

MELTDOWN: THE ATTACK

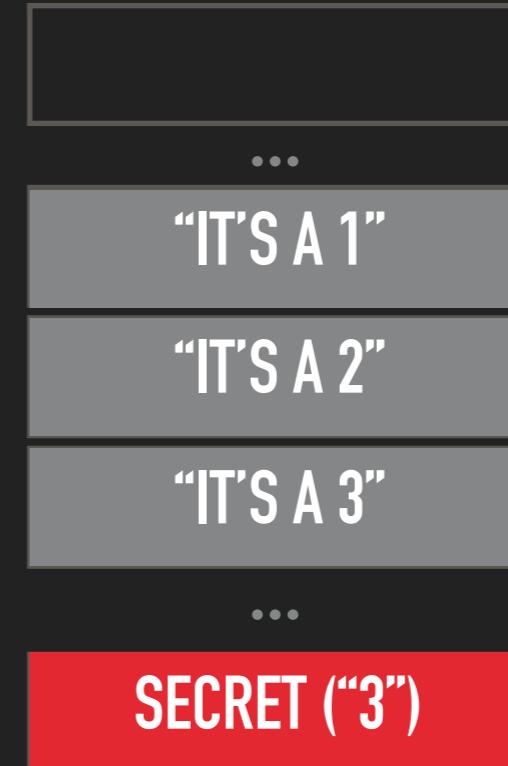
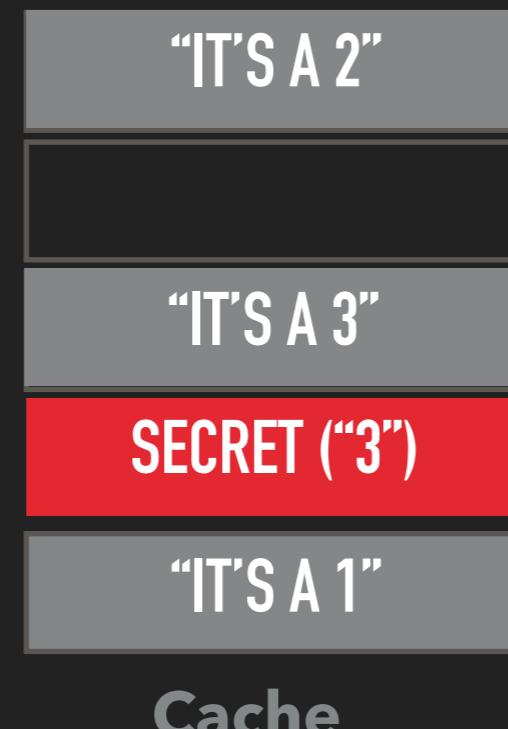


110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



read: 103ns (uncached read)
read: 103ns (uncached read)
read: 3ns (cached)

- 2 1. Spy will read the **secret**
- 2 2. Depending on the **value**, Spy will cache a grey block¹
- 1 3. CPU detects **Spys** access validation and terminates **Spy**
4. **Collector** now reads all grey blocks and stops the time
1. Block "It's a 3" will be the block read the fastest

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses



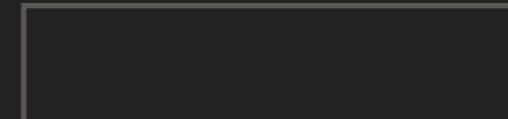
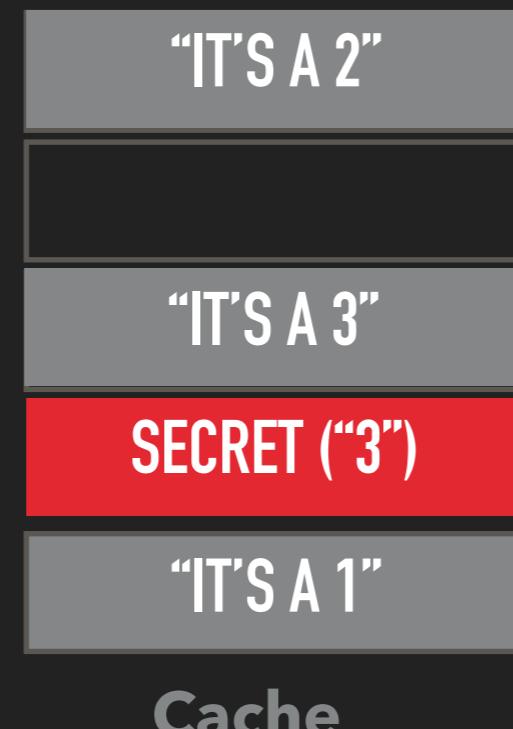
MELTDOWN: THE ATTACK

110011010
010111010
111100100
00101101
100110010

Spy

110011010
010111010
111100100
000101101
100110010

Collector



...



read: 103ns (uncached read)



read: 103ns (uncached read)



read: 3ns (cached)

...



RAM

2 1. **Spy** will read the **secret**

2 Depending on the **value**, **Spy** will cache a grey block¹

1 3. CPU detects **Spys** access validation and terminates **Spy**

4. **Collector** now reads all grey blocks and stops the time

1. Block "It's a 3" will be the block read the fastest

¹ Actually Spy will cache the address of block #3 and Collector will read the blocks addresses

MELTDOWN



Meltdown exploits two properties of modern CPUs

- ▶ *Out of order execution* of OPs and μ OPs
- ▶ Timing side channels for the cache

This allows an attacker to

- ▶ Read all memory mapped¹ in a process
- ▶ This often includes all other processes memory
- ▶ This does NOT allow reading “outside of a VM²”

¹ Virtual vs. physical memory is a subject for another time ² For fully virtualised VMs



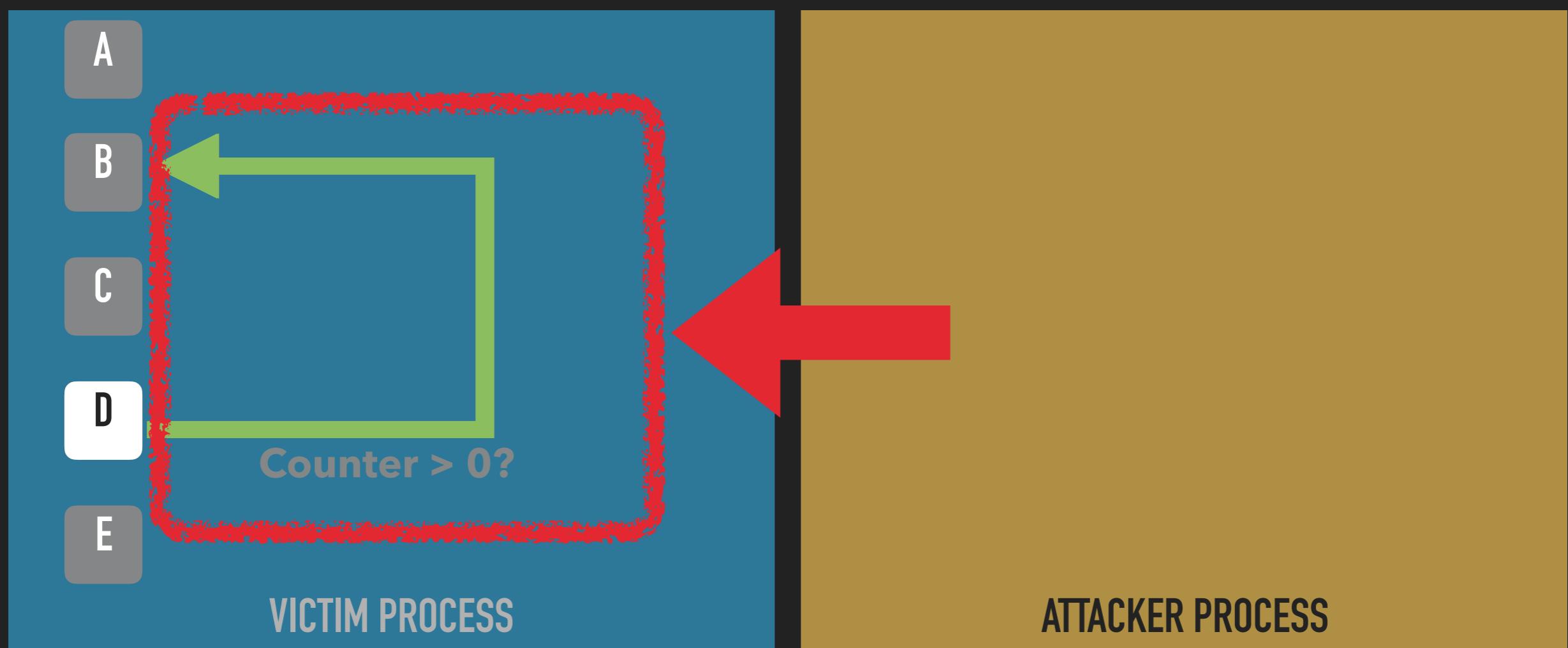
SPECULATIVE
EXECUTION

SPECTRE

SPECTRE



Spectre attacks other processes by forcing them to *speculatively* run other code paths



SPECTRE



Spectre works like this:

- force victim to leak secret
- stash away secret
- retrieve secret

SPECTRE



Spectre works like this:

- force victim to leak secret
- stash away secret
- retrieve secret

- and ■ *basically* work like in Meltdown

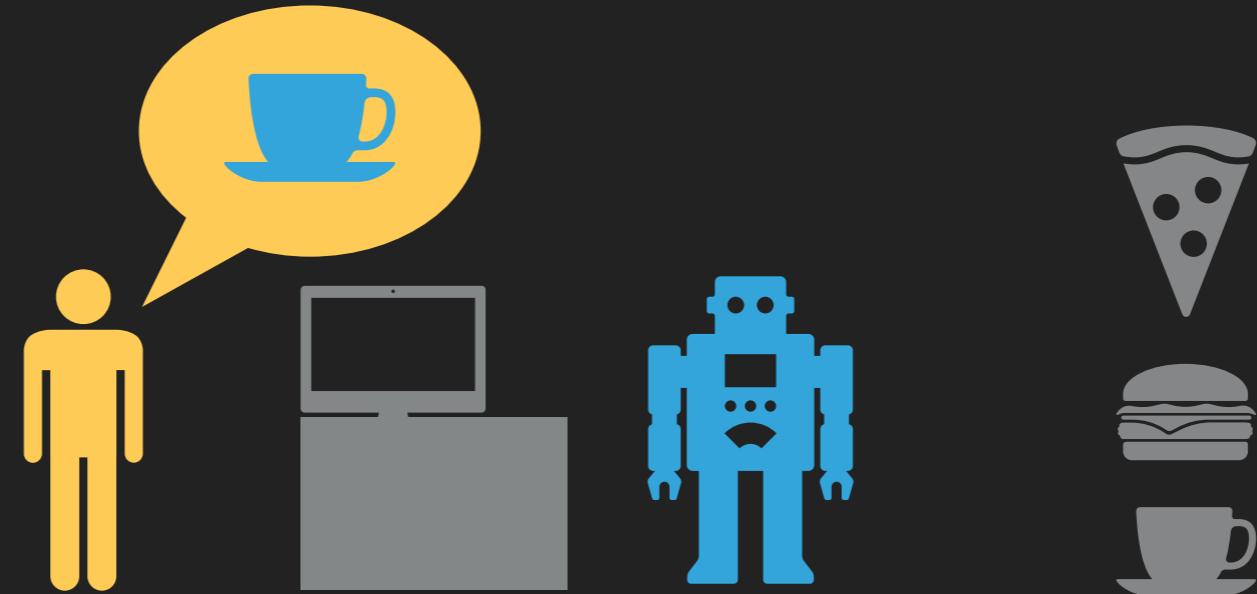
SPECTRE



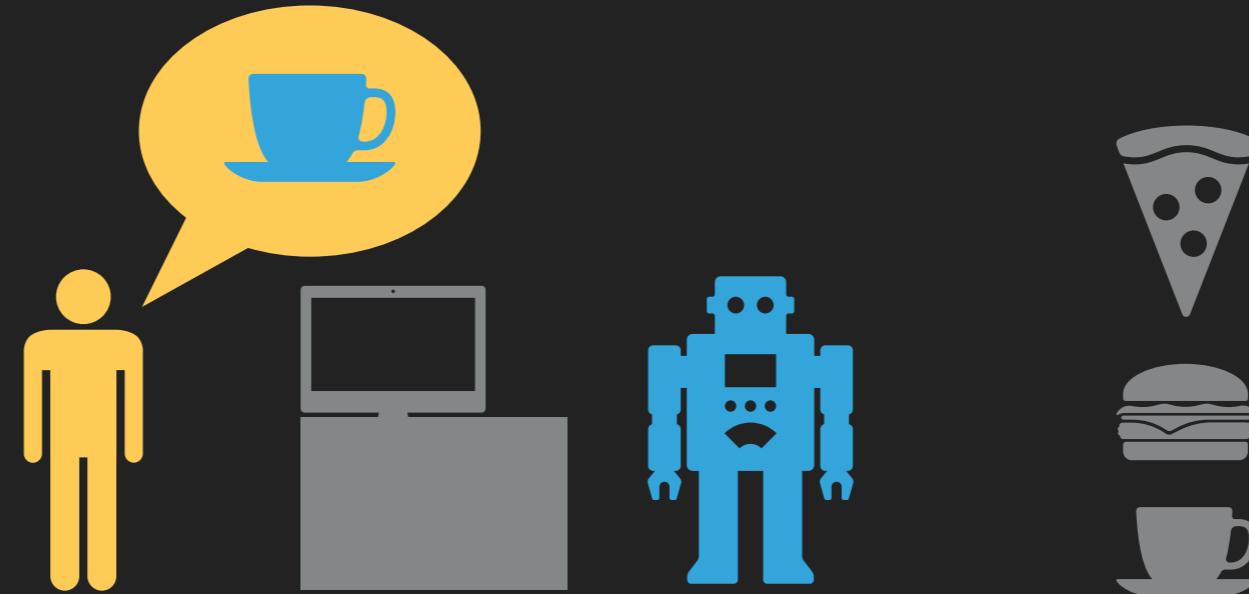
Spectre works like this:

- force victim to leak secret
- stash away secret
- retrieve secret
- and ■ *basically work like in Meltdown*
- works by manipulating the *branch prediction* of the CPU

SPECTRE: BRANCH PREDICTION



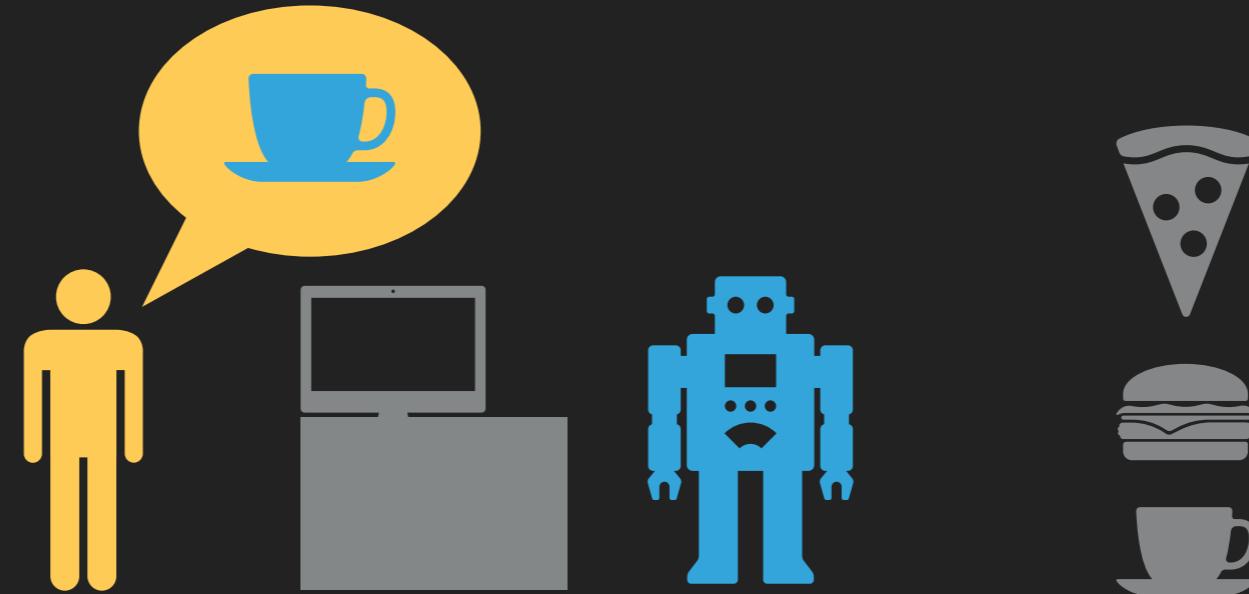
SPECTRE: BRANCH PREDICTION



Monday

A yellow speech bubble containing a blue coffee cup icon, followed by the word "Monday" in a stylized script font.

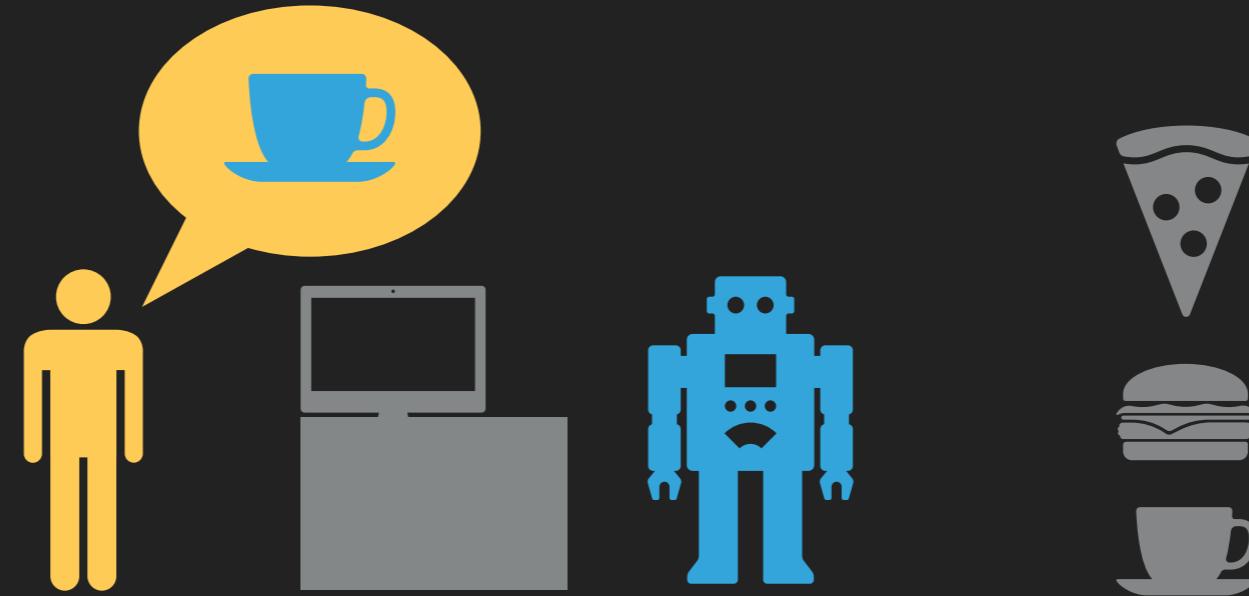
SPECTRE: BRANCH PREDICTION



 *Monday*

 *Tuesday*

SPECTRE: BRANCH PREDICTION

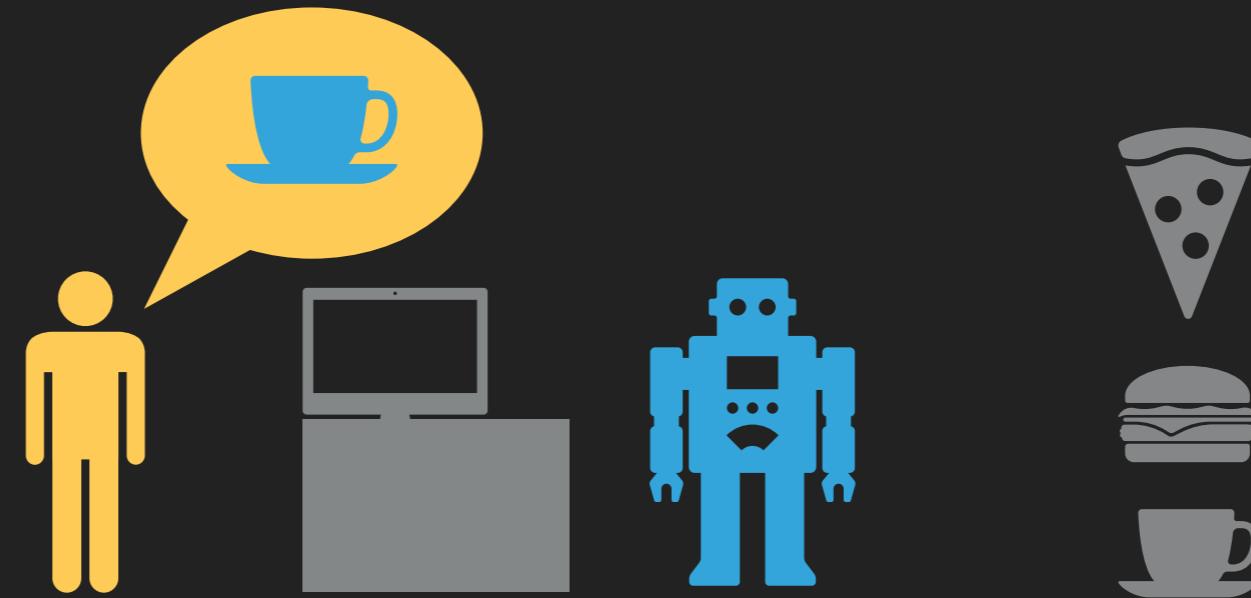


 *Monday*

 *Tuesday*

 *Wednesday*

SPECTRE: BRANCH PREDICTION



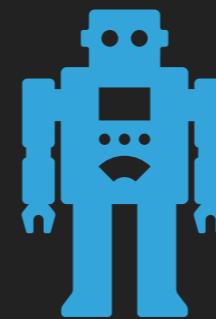
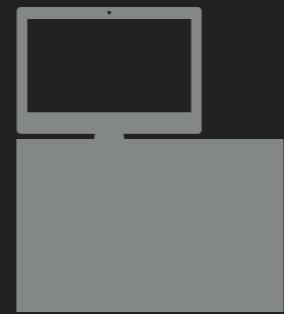
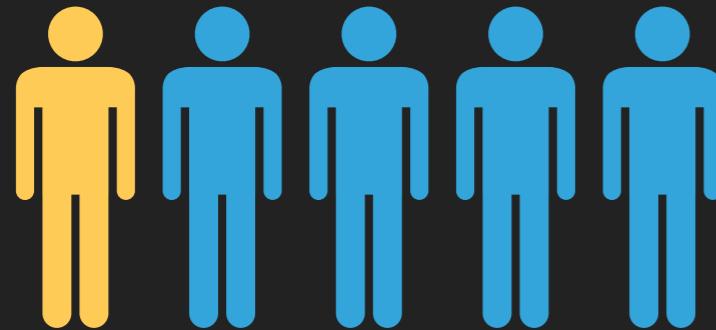
 *Monday*

 *Tuesday*

 *Wednesday*

...

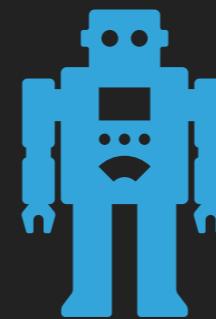
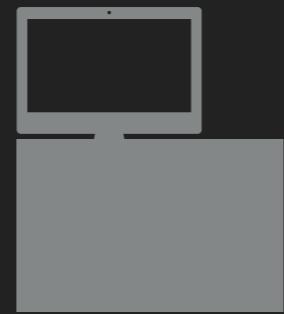
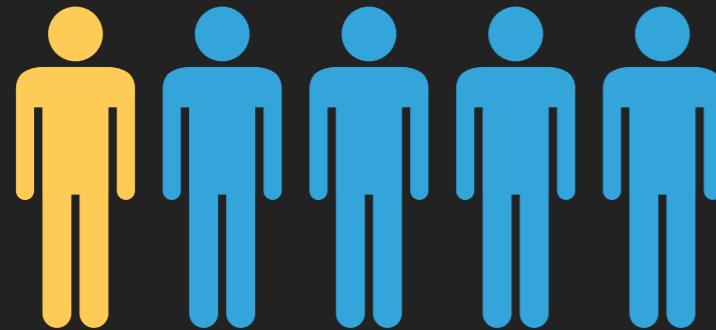
SPECTRE: SPECULATIVE EXECUTION



The CPU can improve the coffee machine utilisation by
speculatively brewing the coffee for 

This is very similar to the effect seen in Meltdown.

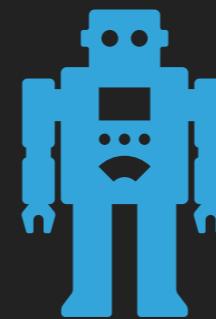
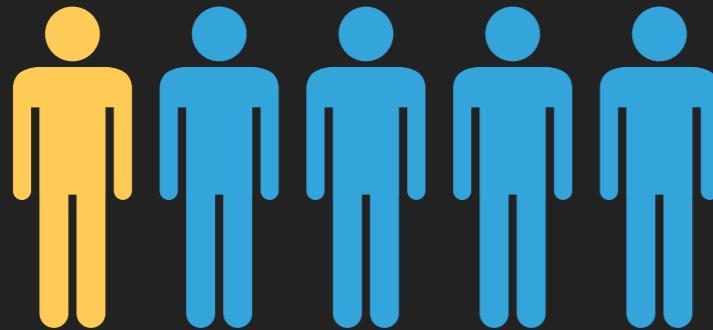
SPECTRE: SPECULATIVE EXECUTION



The CPU can improve the coffee machine utilisation by
speculatively brewing the coffee for 

This is very similar to the effect seen in Meltdown.

SPECTRE: SPECULATIVE EXECUTION

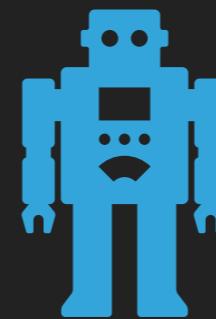
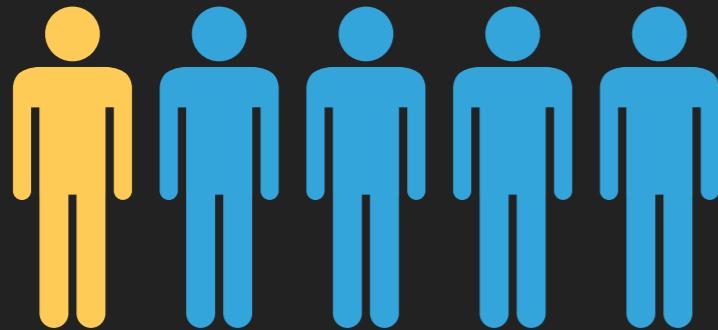


The CPU can improve the coffee machine utilisation by *speculatively* brewing the coffee for 

This is very similar to the effect seen in Meltdown.

- ▶ In the **Meltdown** attack the CPU knows the next instruction (order) and asynchronously checks the permissions

SPECTRE: SPECULATIVE EXECUTION

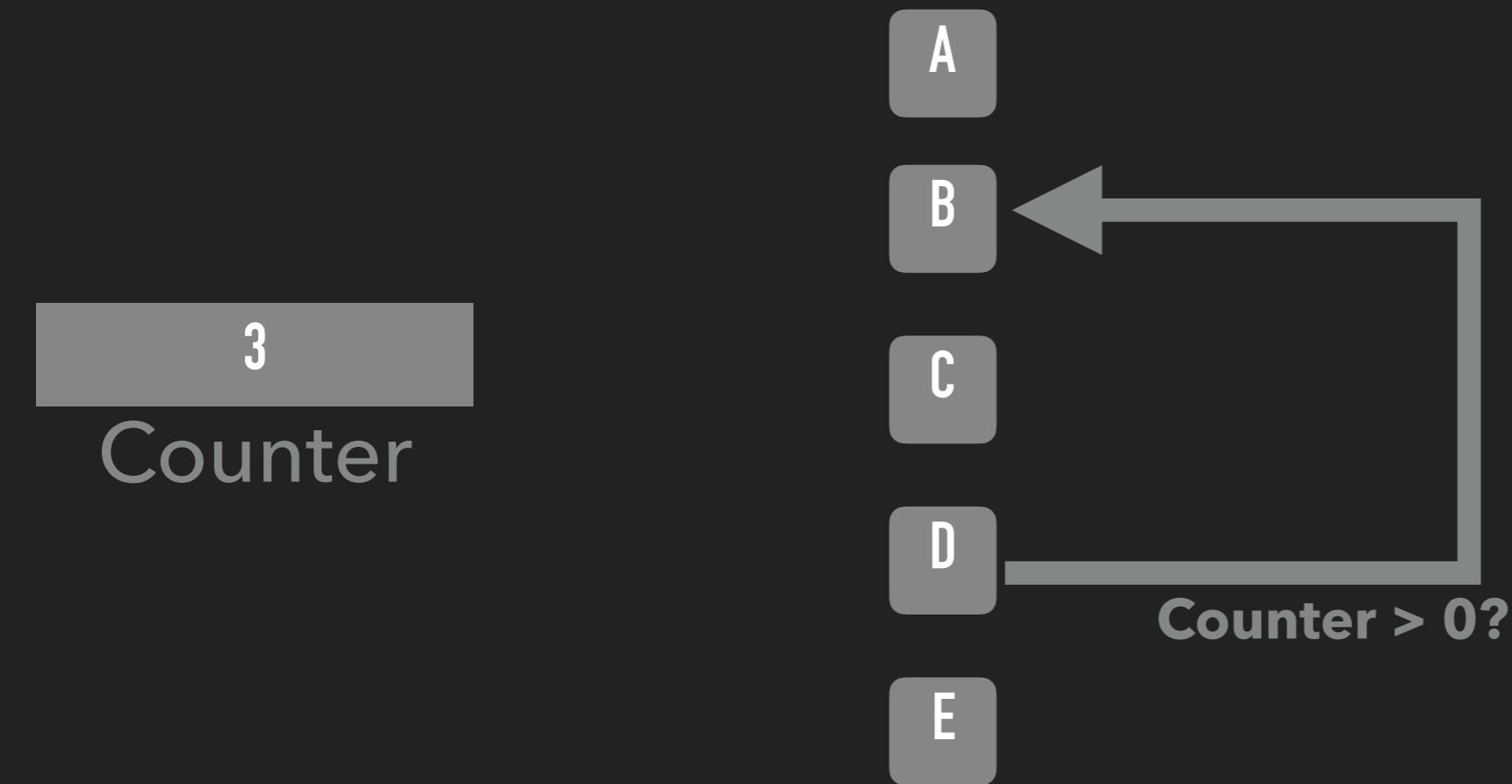


The CPU can improve the coffee machine utilisation by *speculatively* brewing the coffee for 

This is very similar to the effect seen in Meltdown.

- ▶ In the **Meltdown** attack the CPU knows the next instruction (order) and asynchronously checks the permissions
- ▶ In **Spectre** the CPU guesses the next instructions based on heuristics (brew coffee without knowing the order)

SPECTRE: SPECULATIVE EXECUTION



COUNTER

A B ... E

A

←

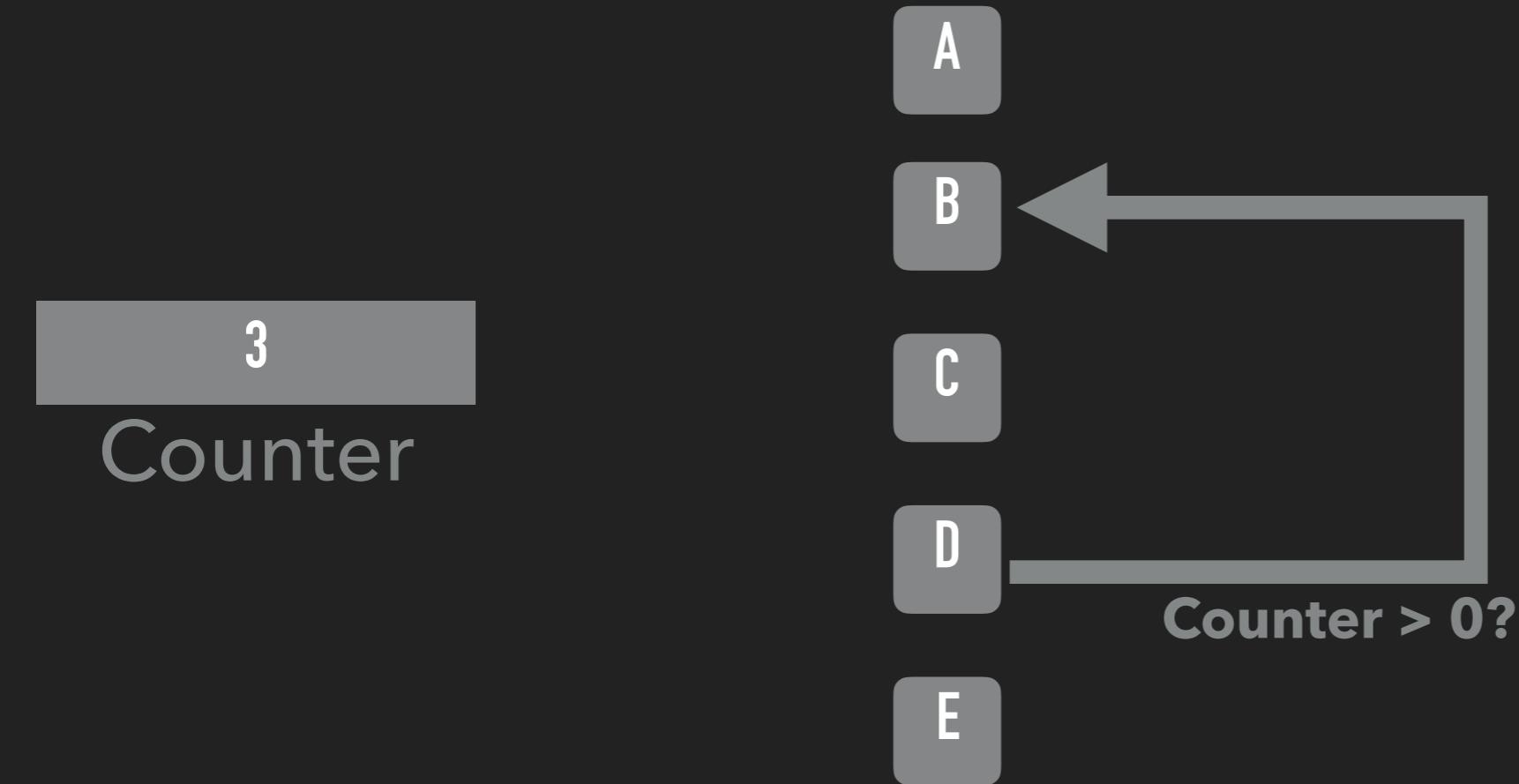
Some variable used in branch

Instructions

Currently active instruction

Conditional branch

SPECTRE: SPECULATIVE EXECUTION



COUNTER

A B ... E

A

←

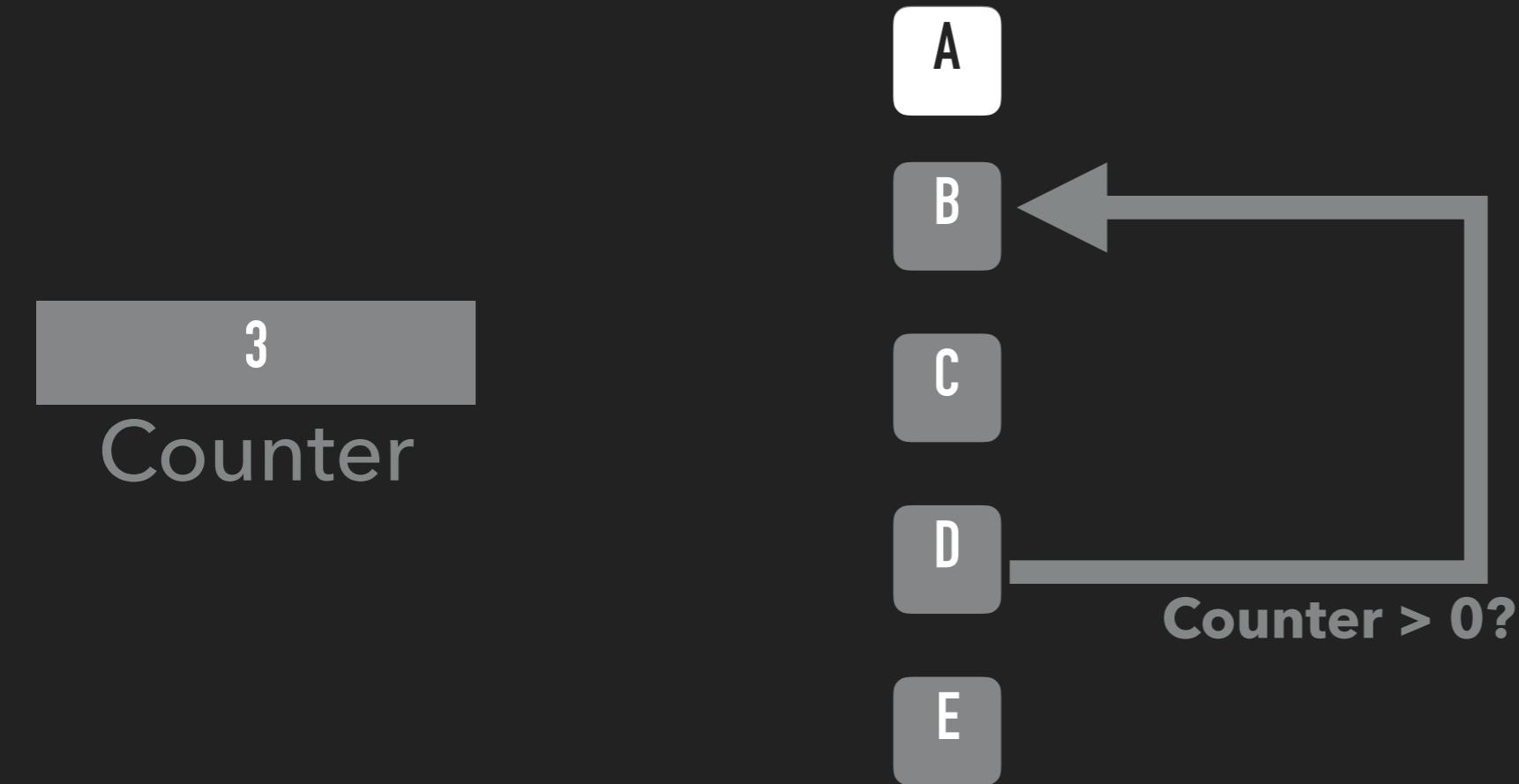
Some variable used in branch

Instructions

Currently active instruction

Conditional branch

SPECTRE: SPECULATIVE EXECUTION



COUNTER

Some variable used in branch

A B ... E

Instructions

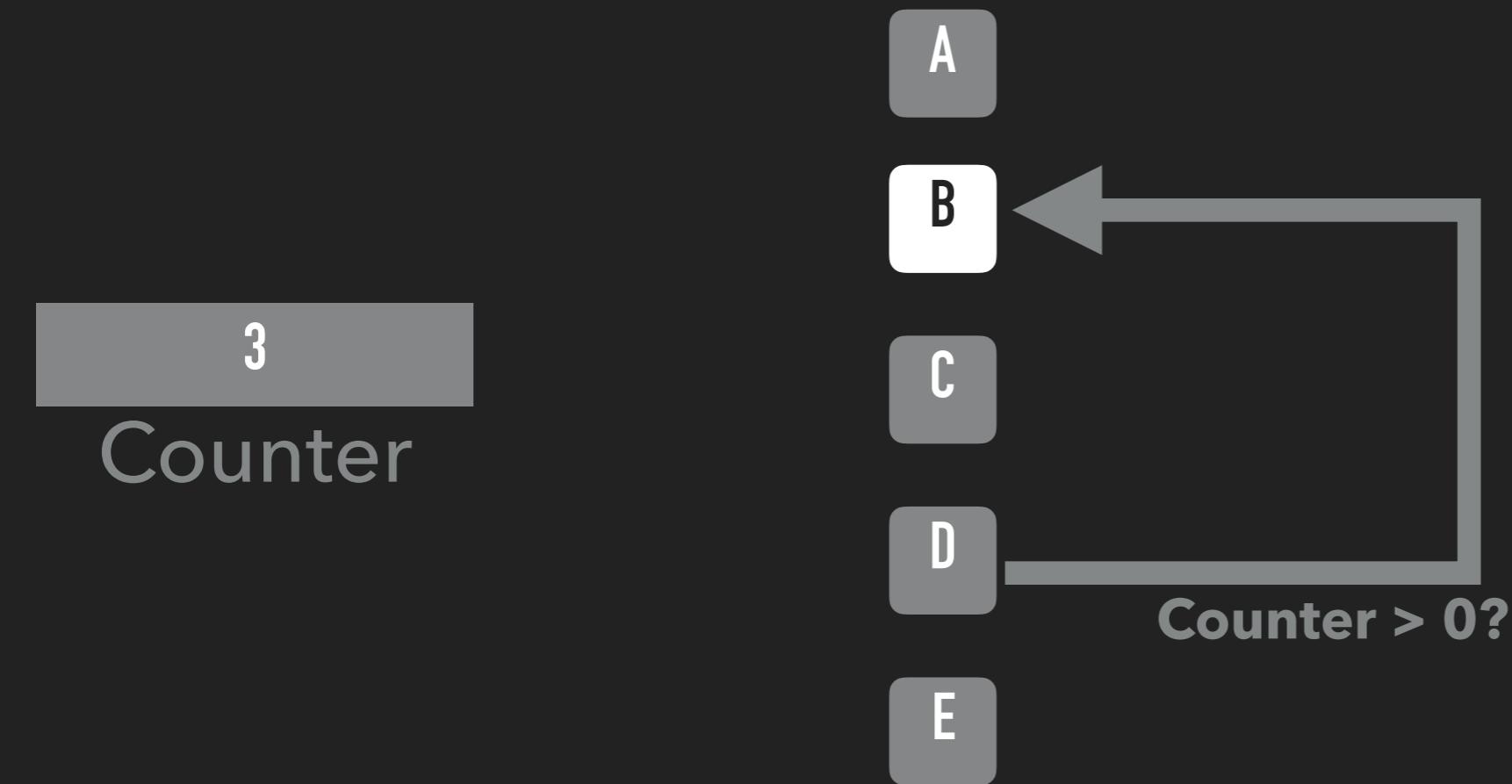
A

Currently active instruction



Conditional branch

SPECTRE: SPECULATIVE EXECUTION



COUNTER

A B ... E

A

←

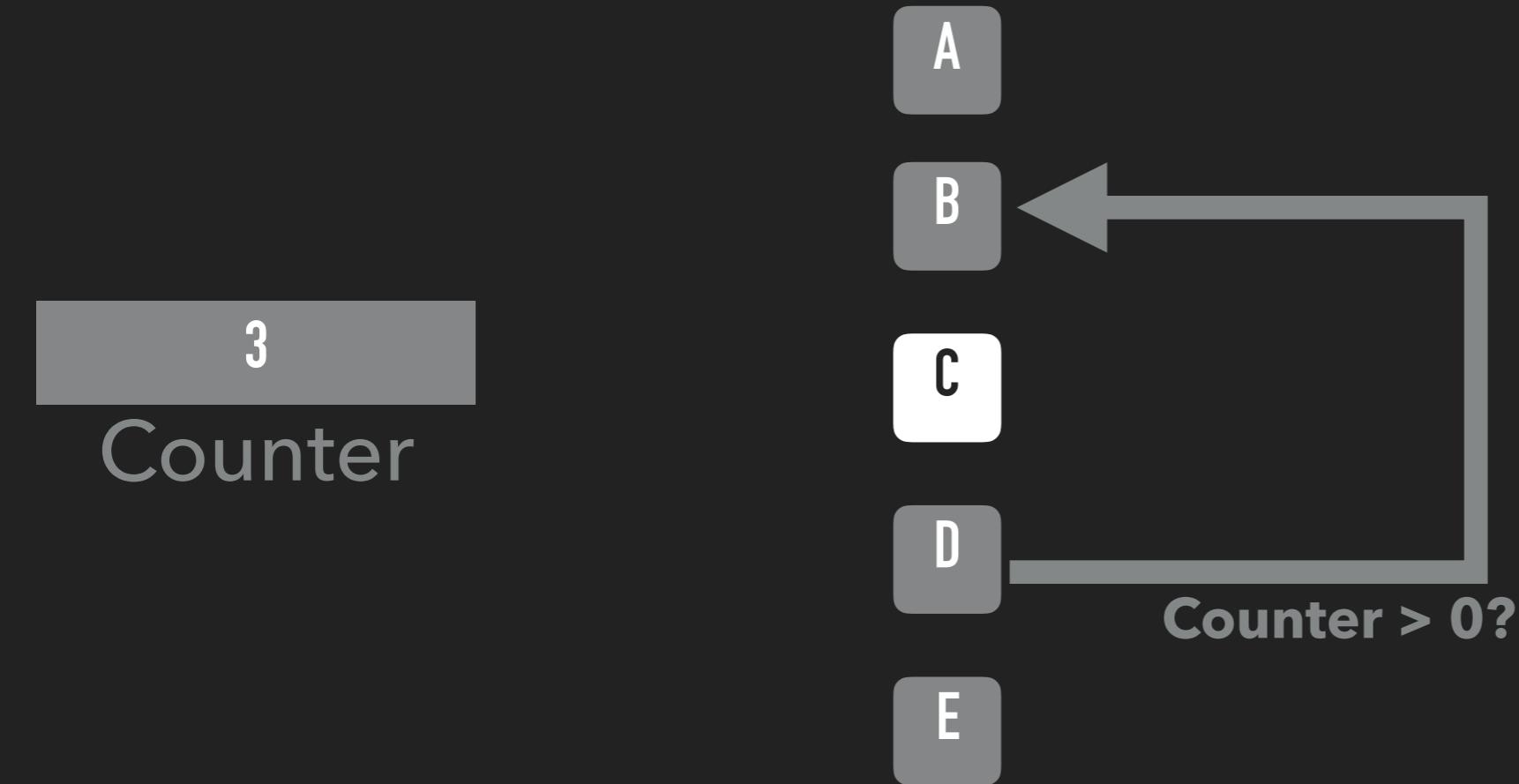
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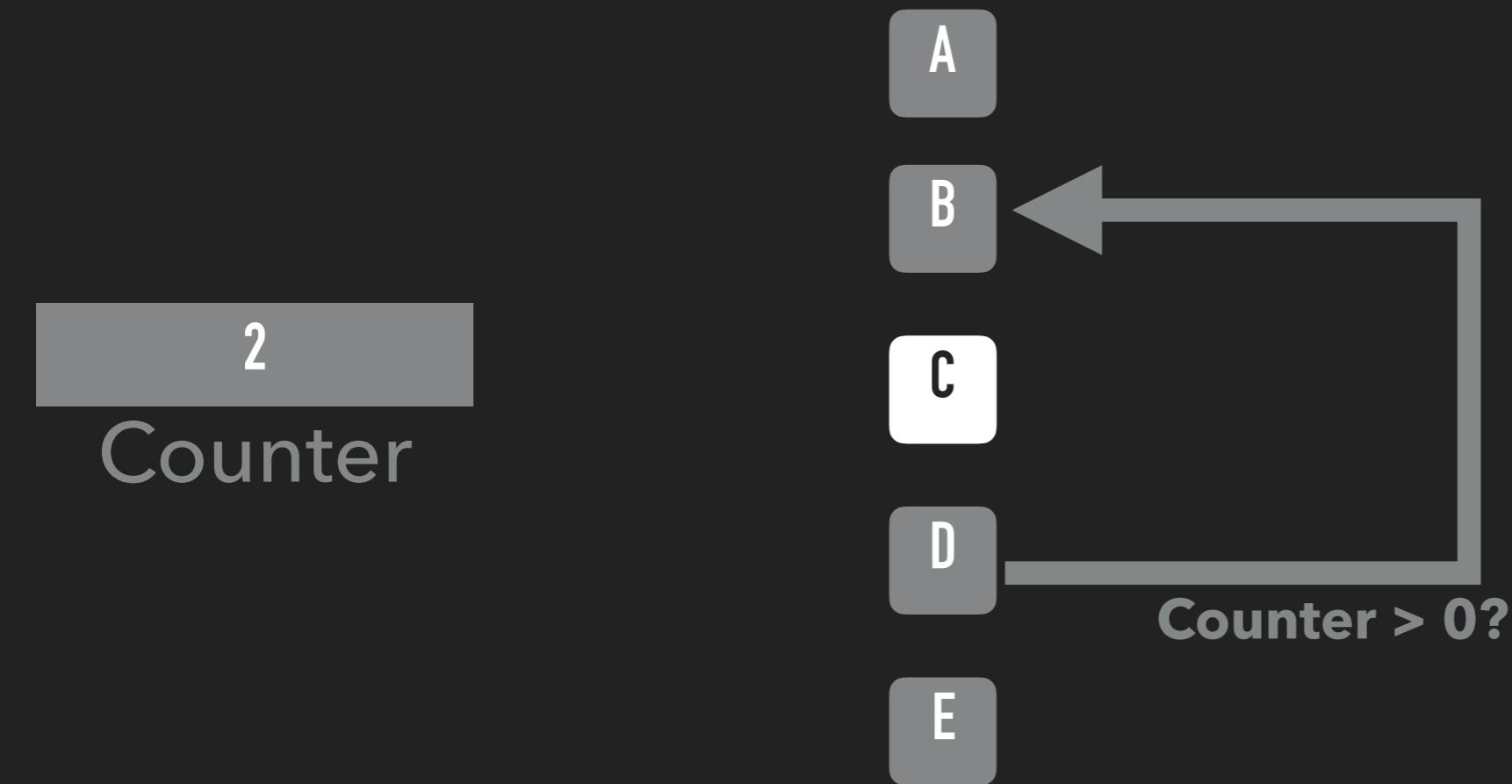
COUNTER Some variable used in branch

A B ... E Instructions

A Currently active instruction

Conditional branch

SPECTRE: SPECULATIVE EXECUTION



COUNTER

A B ... E

A

←

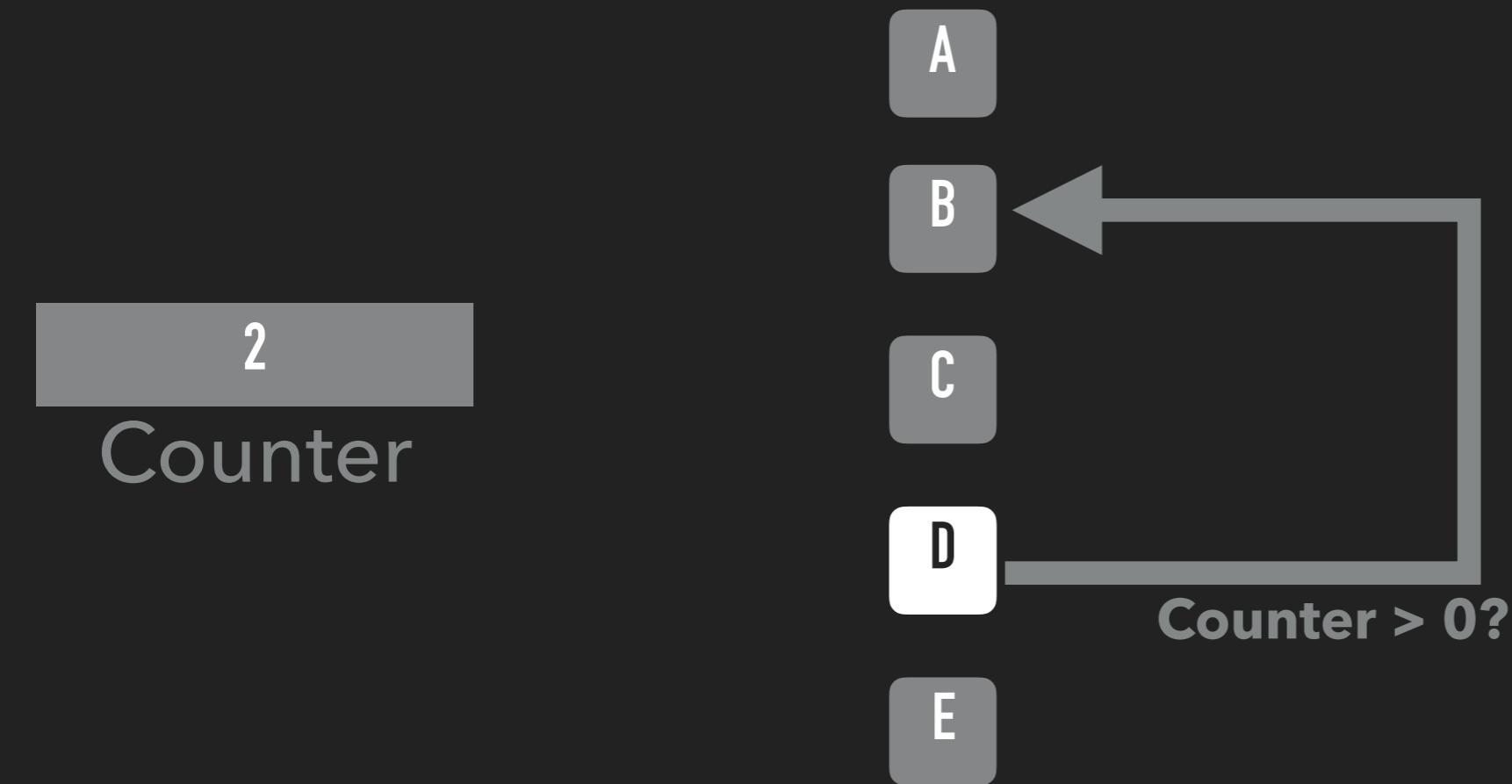
Some variable used in branch

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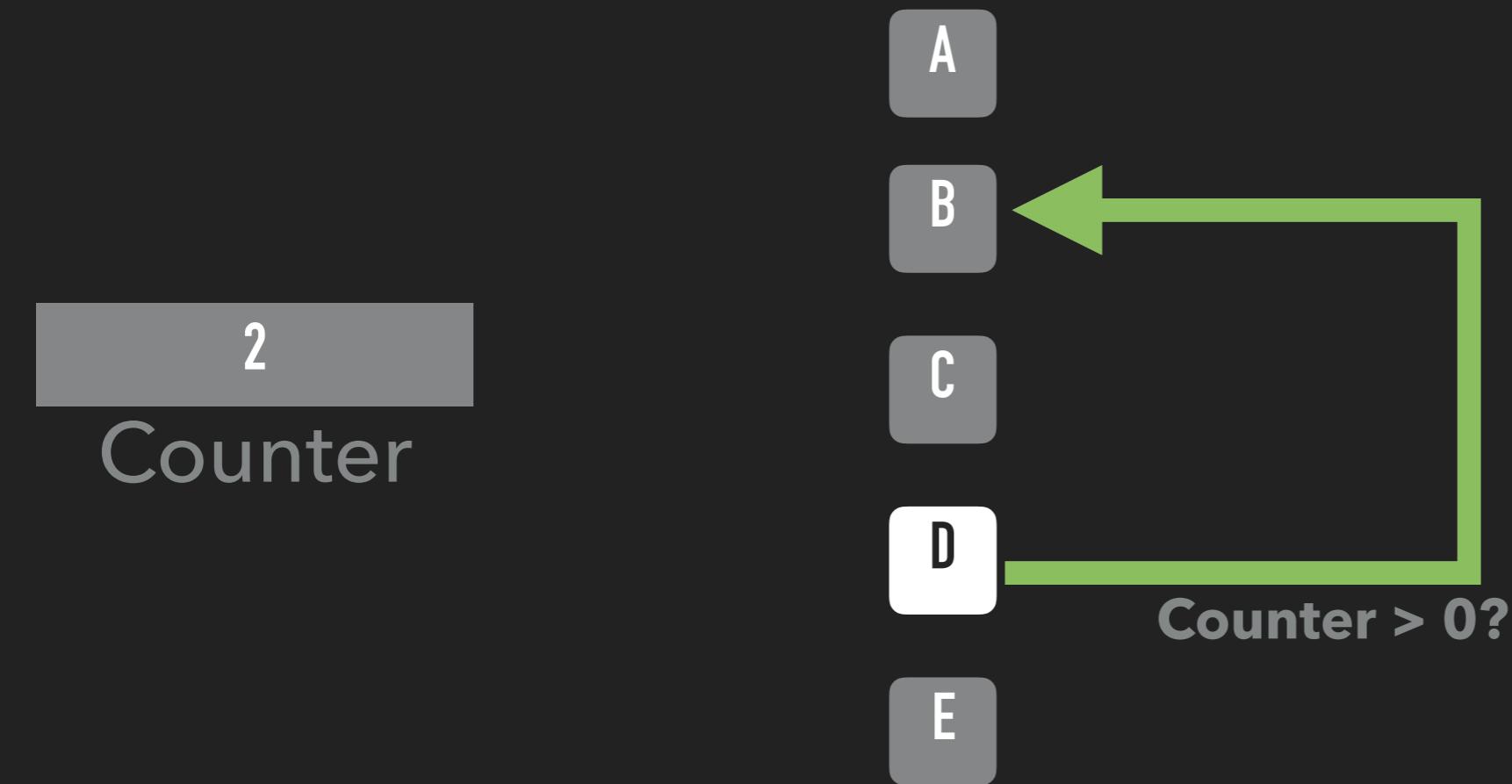
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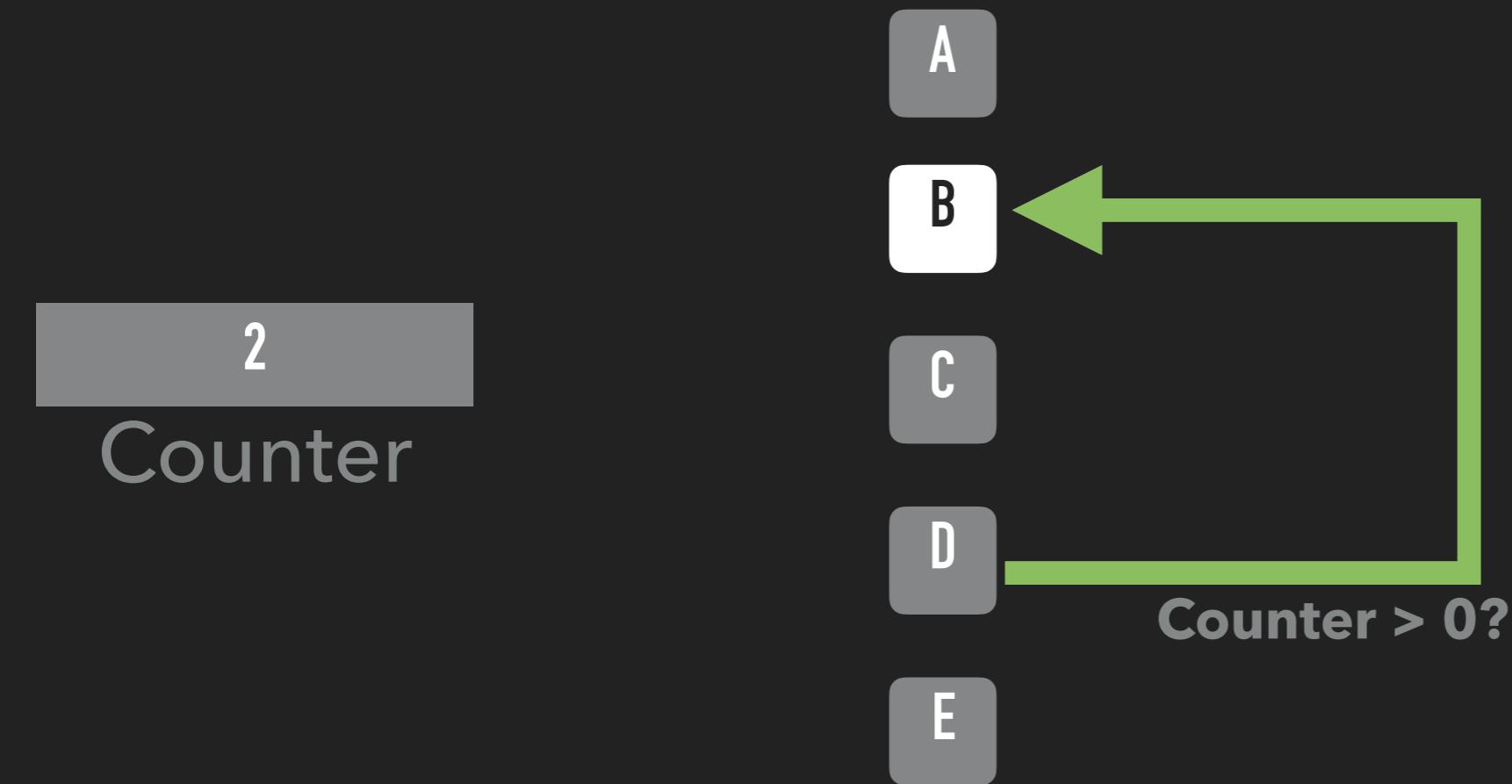
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Currently active instruction

←

Conditional branch

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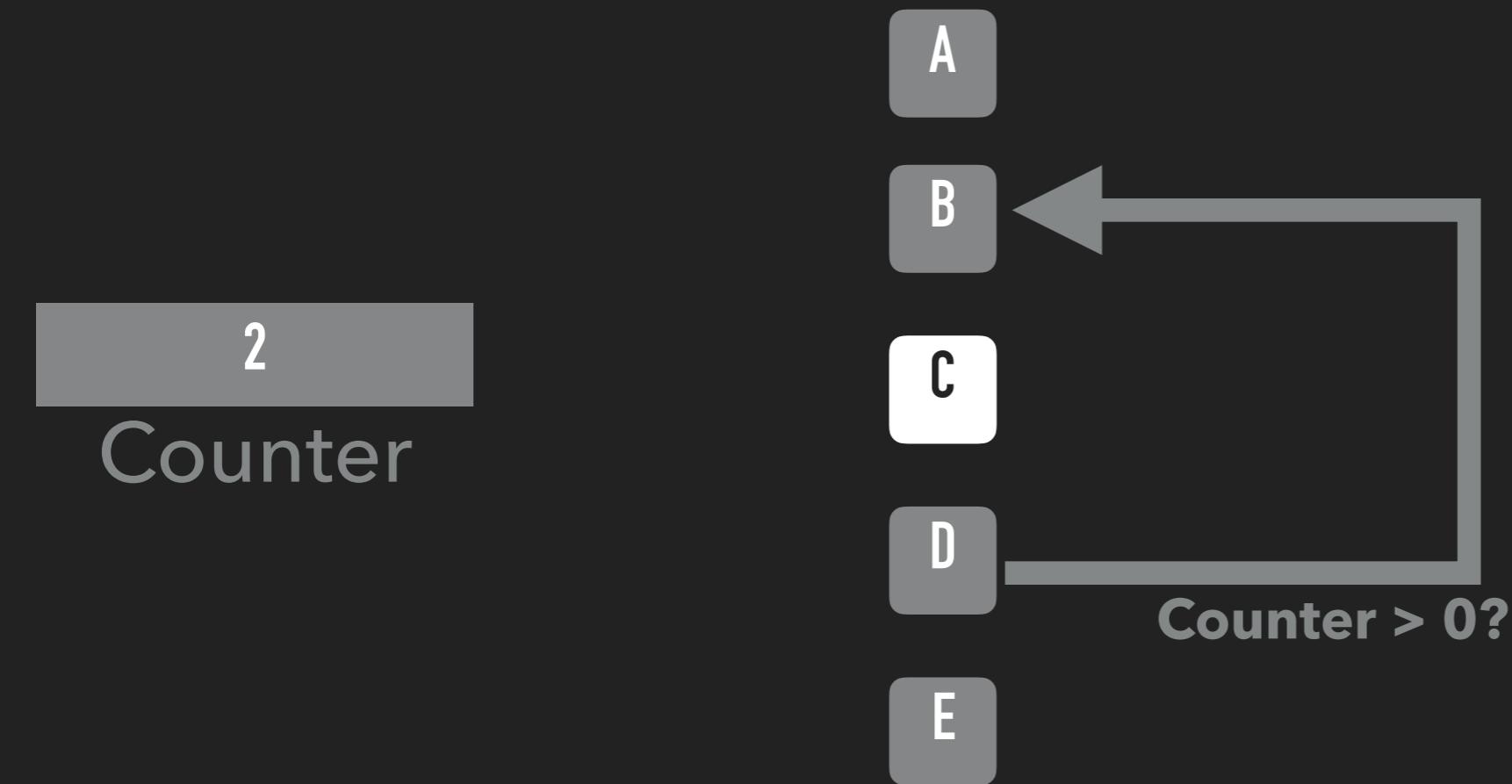
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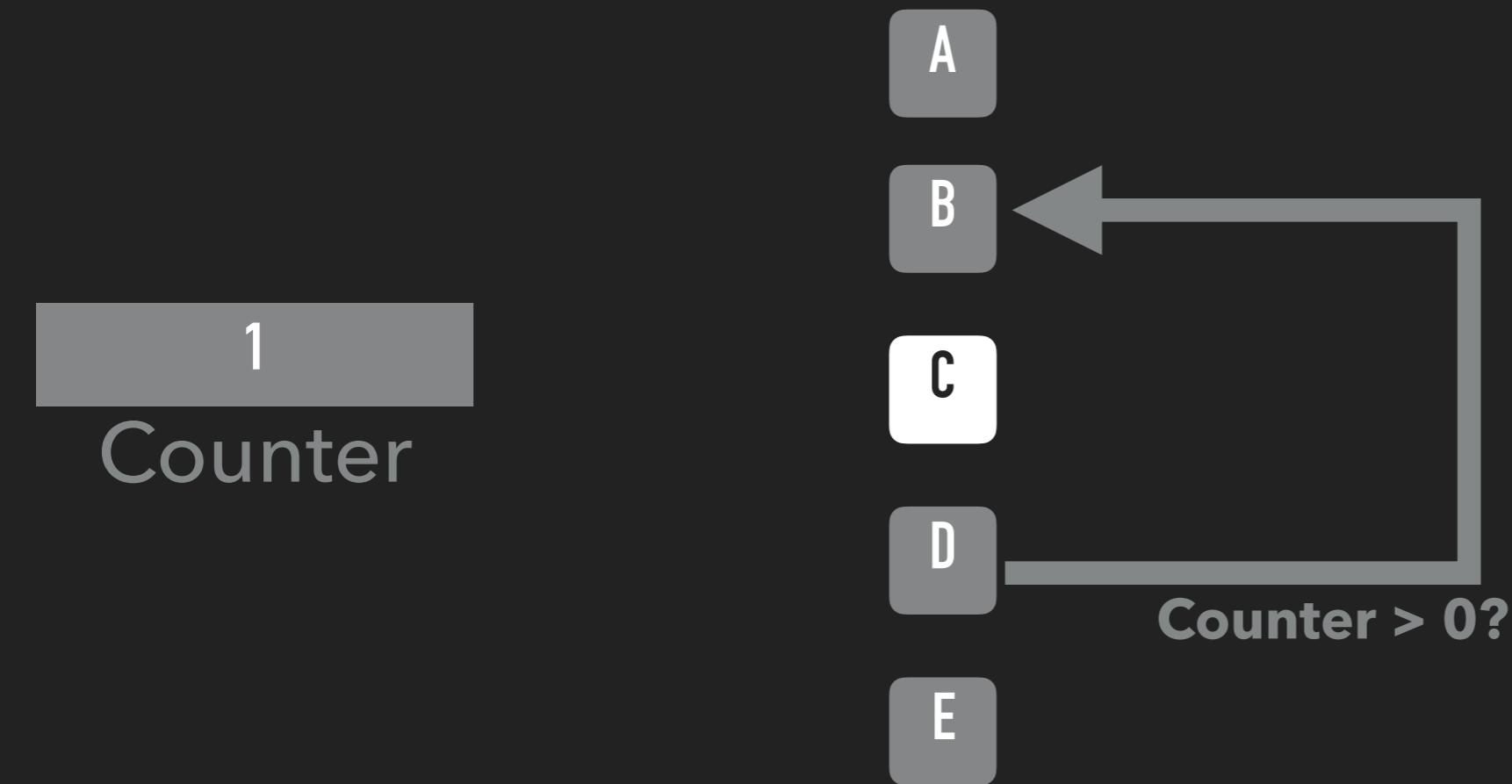
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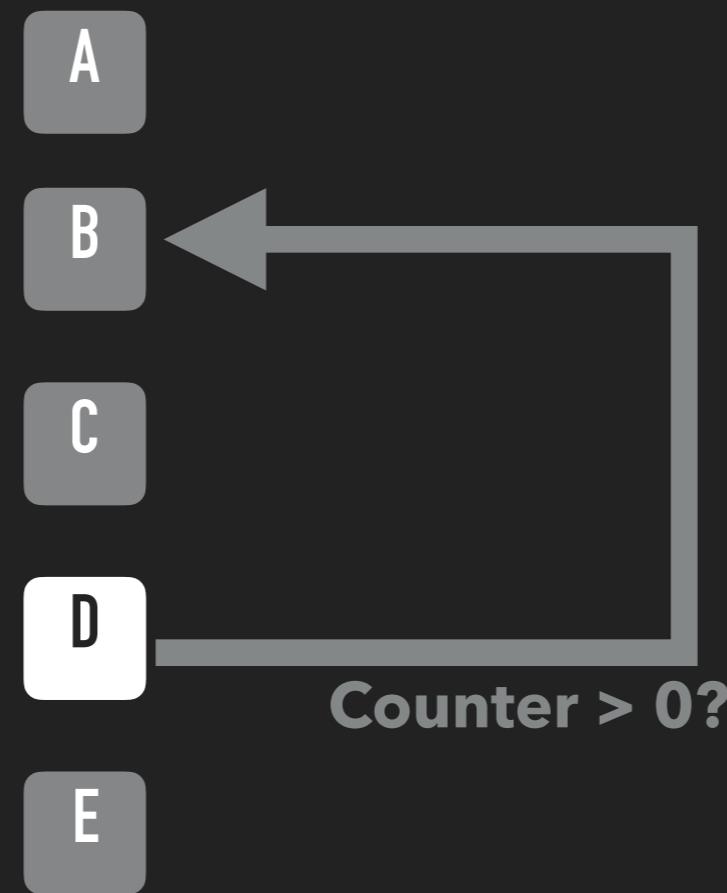
Currently active instruction

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1
Counter



COUNTER

A B ... E

A



Some variable used in branch

Instructions

A

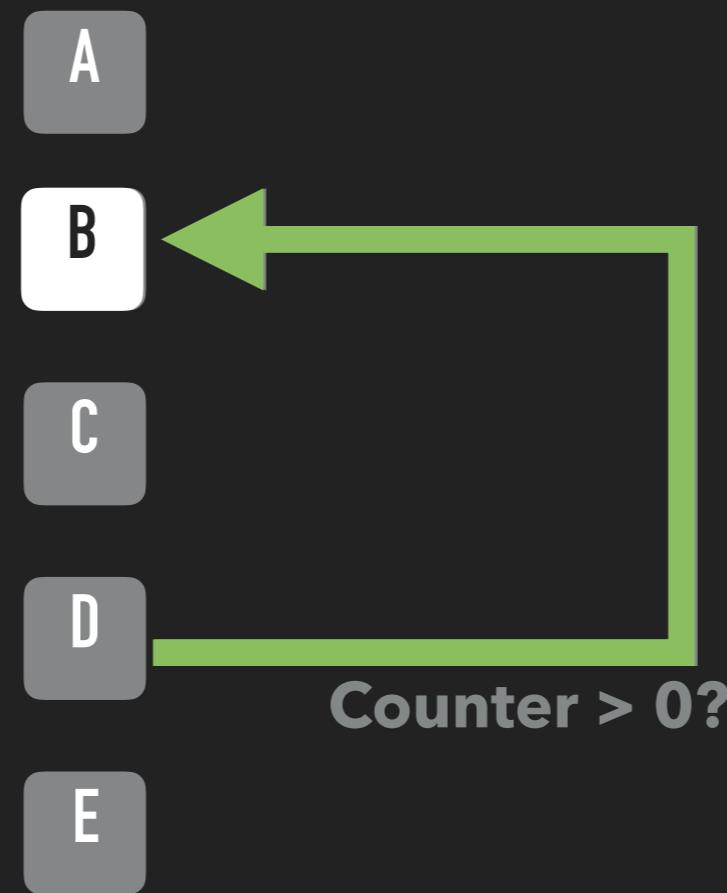
Currently active instruction

Conditional branch

SPECTRE: SPECULATIVE EXECUTION



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COUNTER

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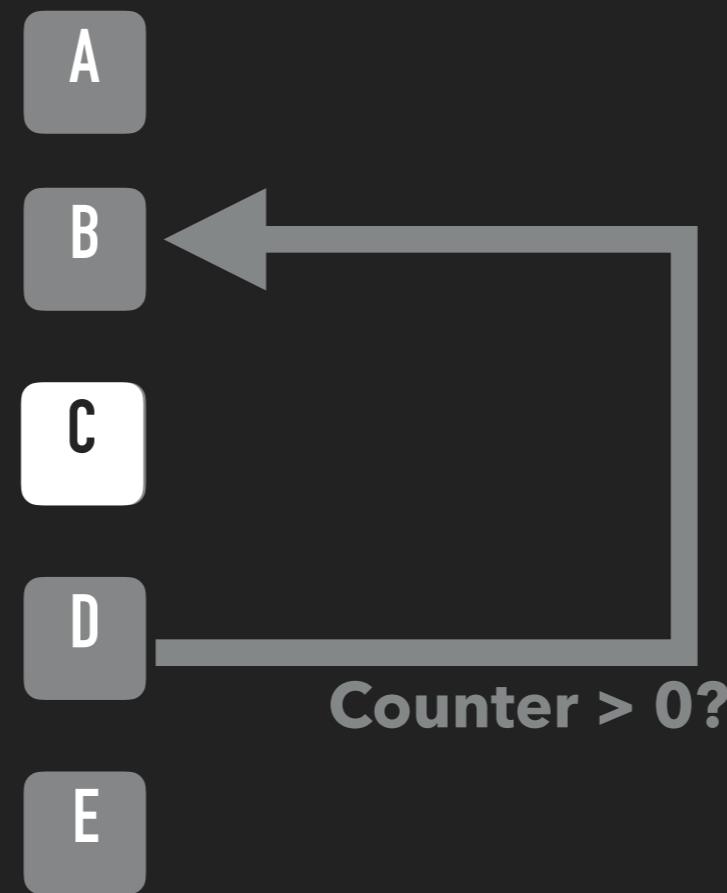
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COUNTER

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A

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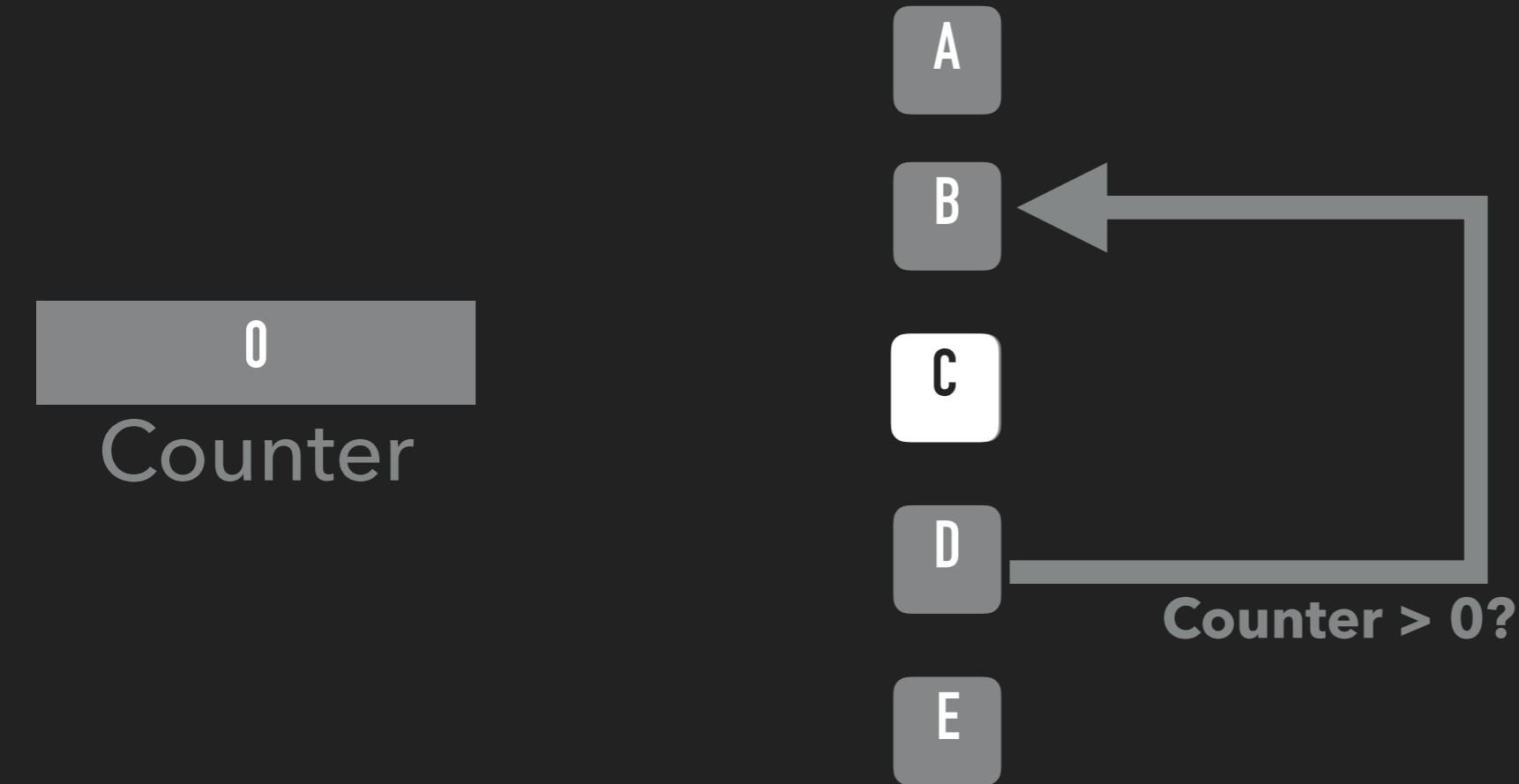
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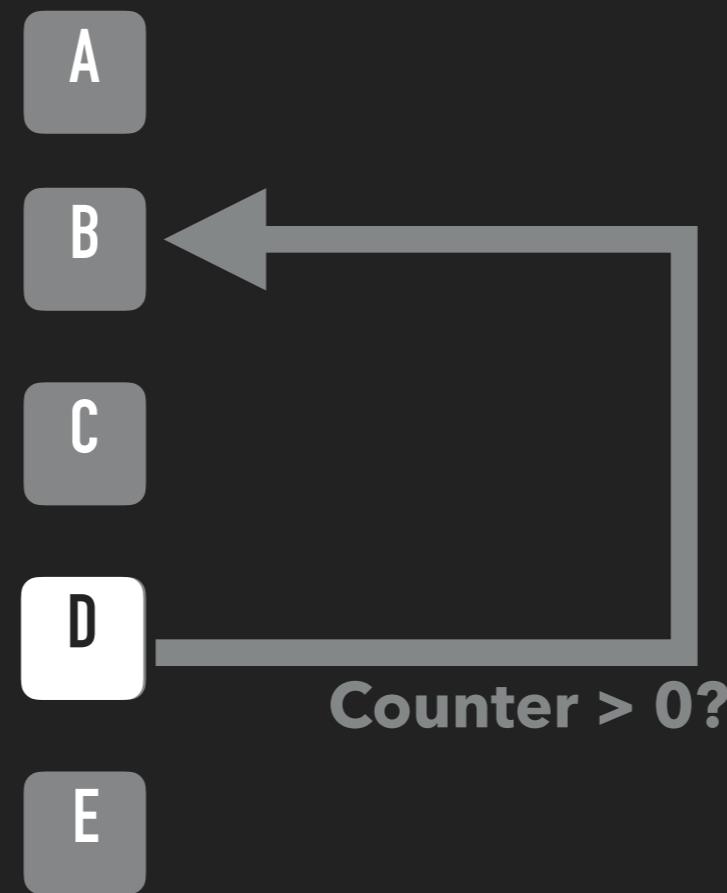
Currently active instruction

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SPECTRE: SPECULATIVE EXECUTION



0
Counter



COUNTER

A B ... E

A

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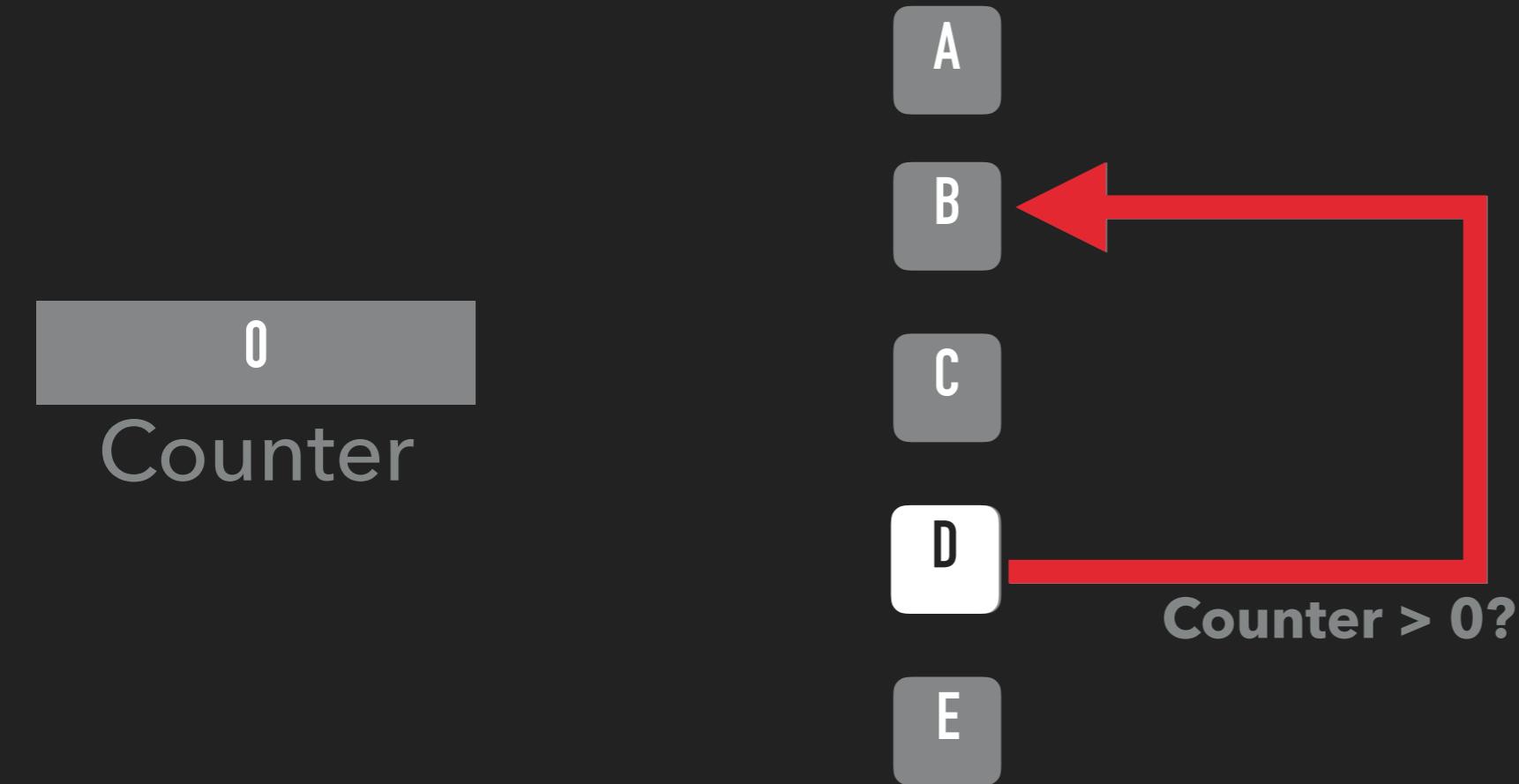
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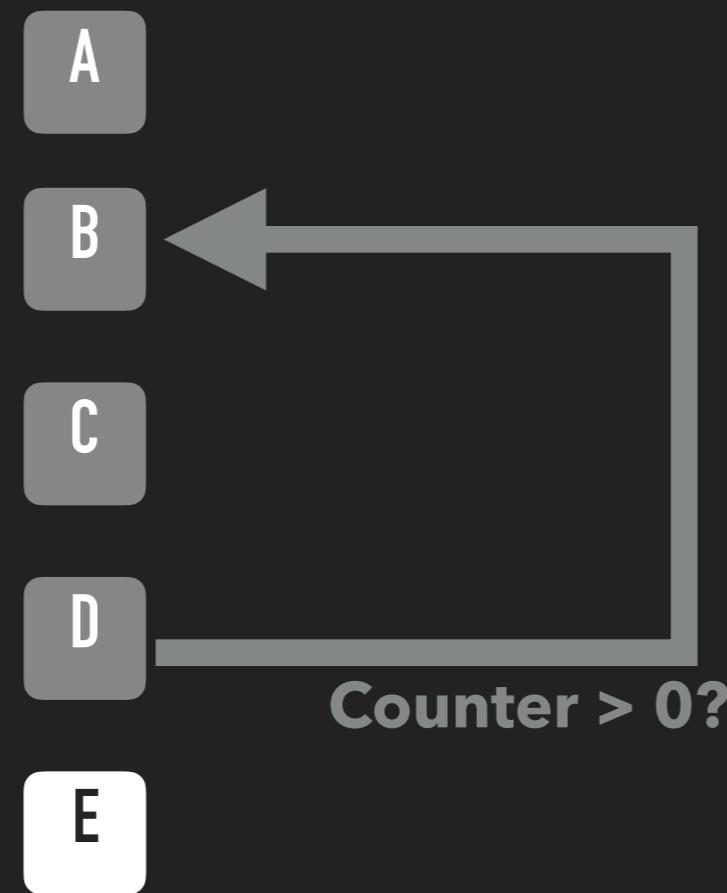
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Some variable used in branch

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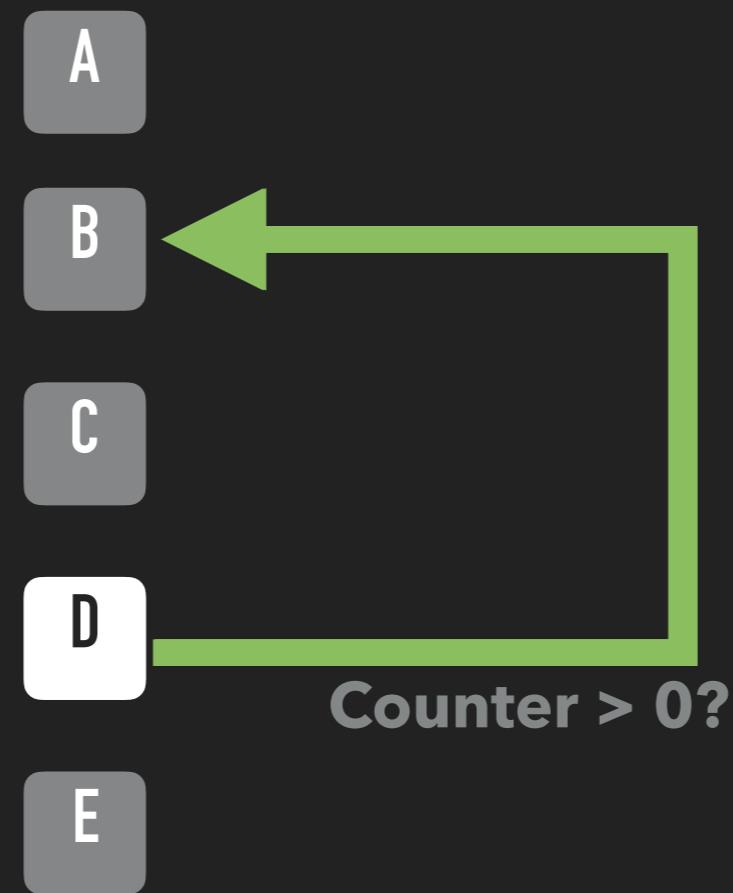
Currently active instruction

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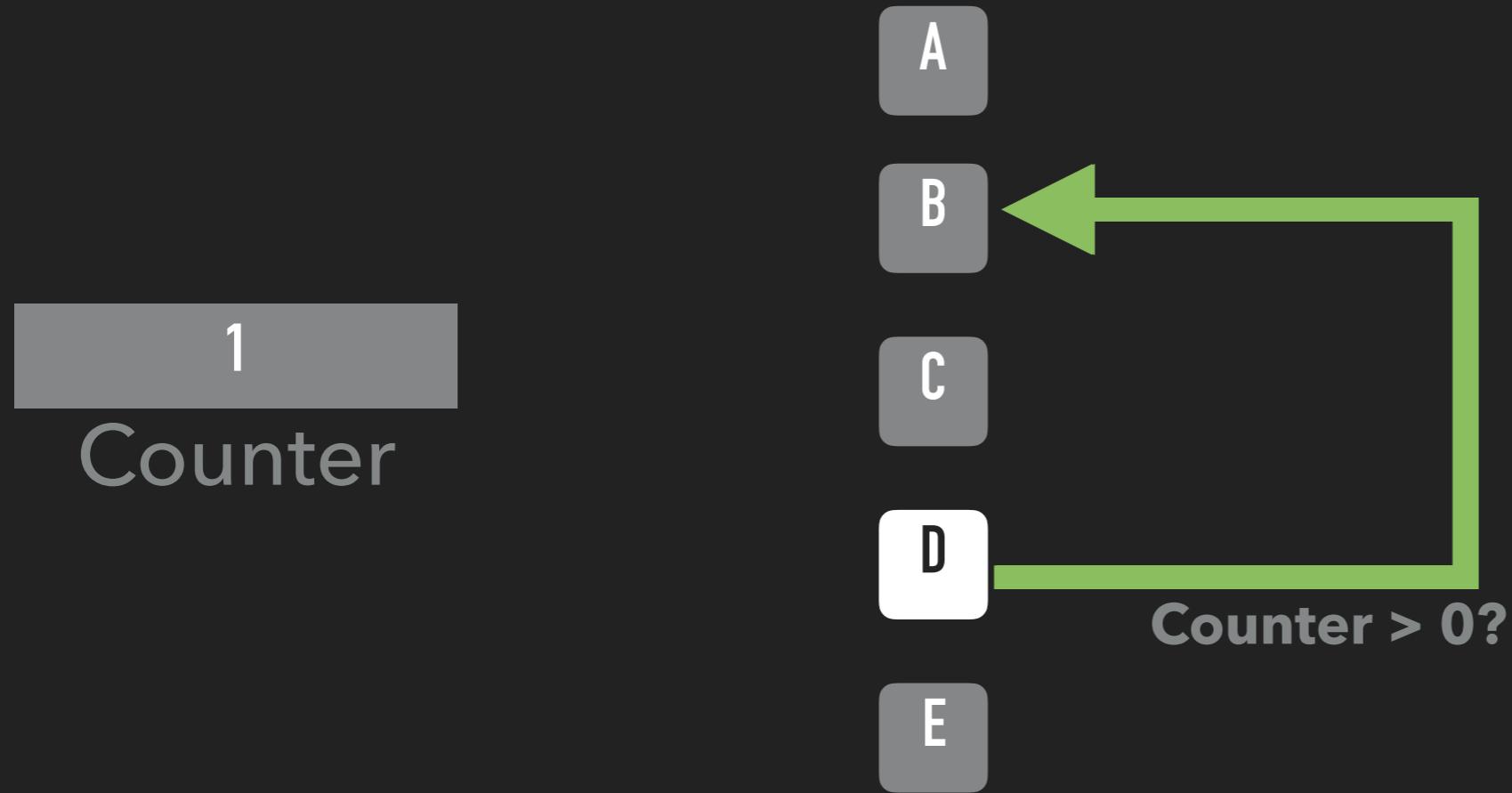
SPECTRE: SPECULATIVE EXECUTION



1
Counter

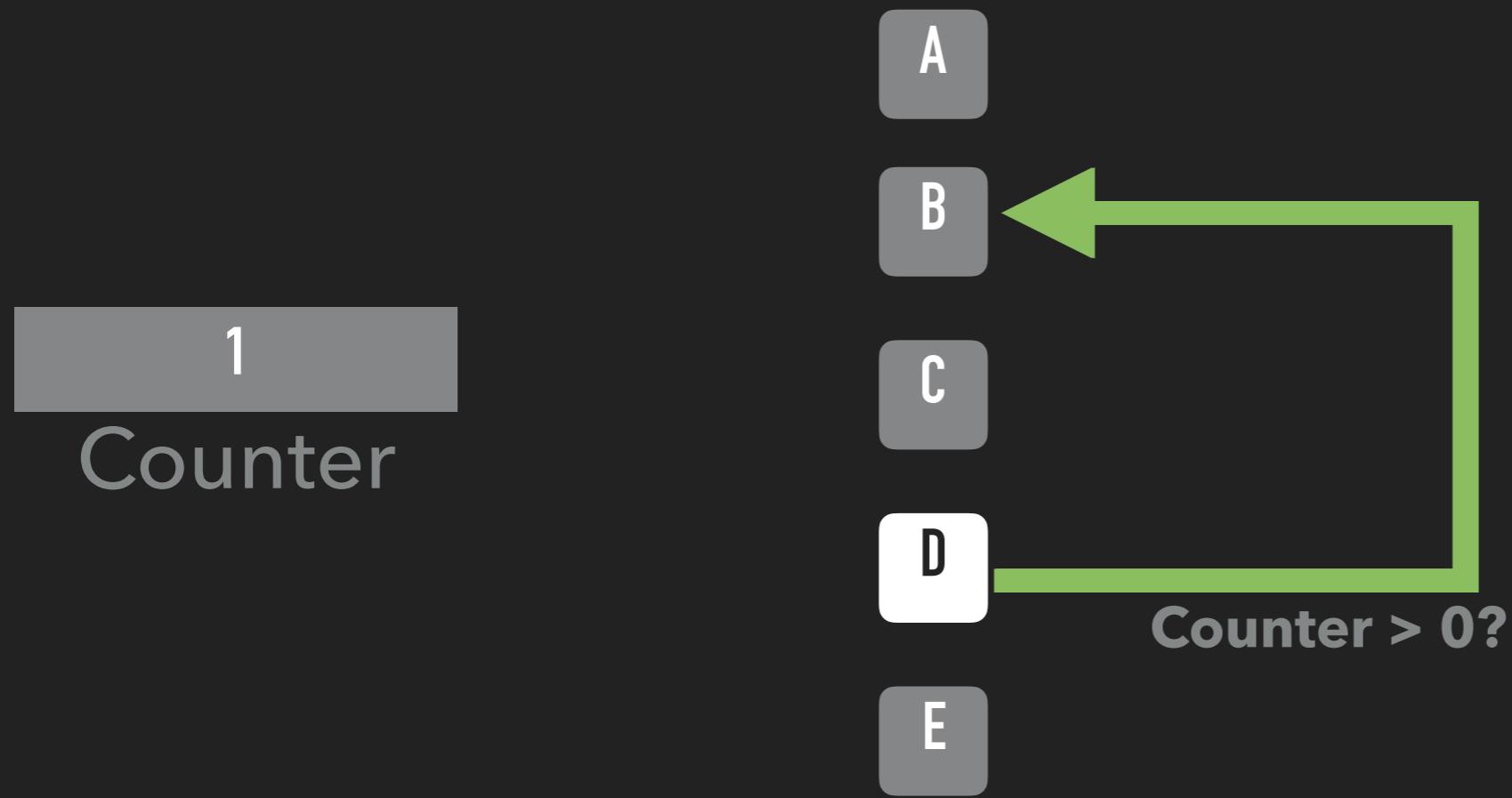


SPECTRE: SPECULATIVE EXECUTION



The CPU has learned that Counter *probably* is > 0

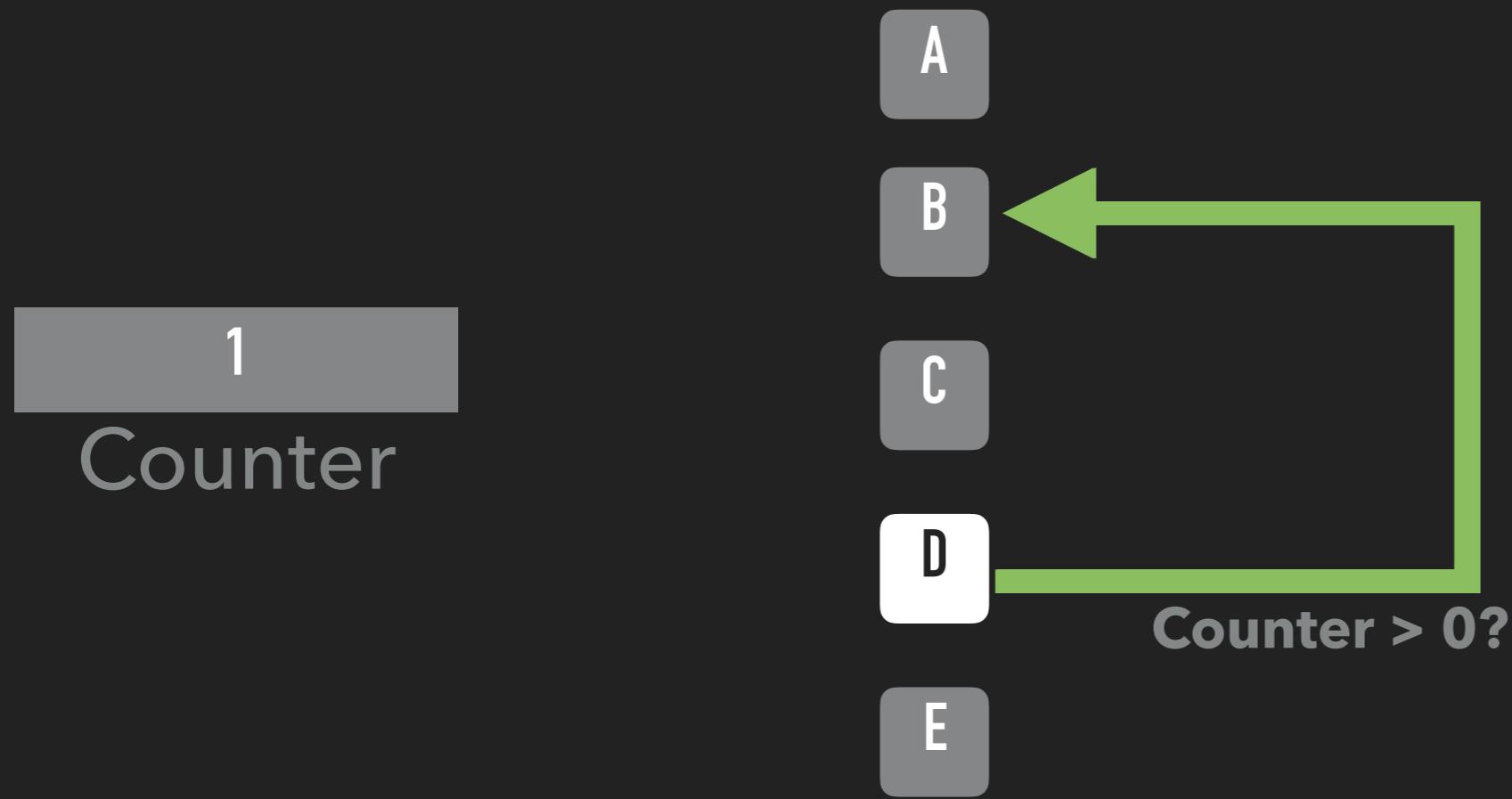
SPECTRE: SPECULATIVE EXECUTION



The CPU has learned that Counter *probably* is > 0

Reading Counter from memory is very slow

SPECTRE: SPECULATIVE EXECUTION

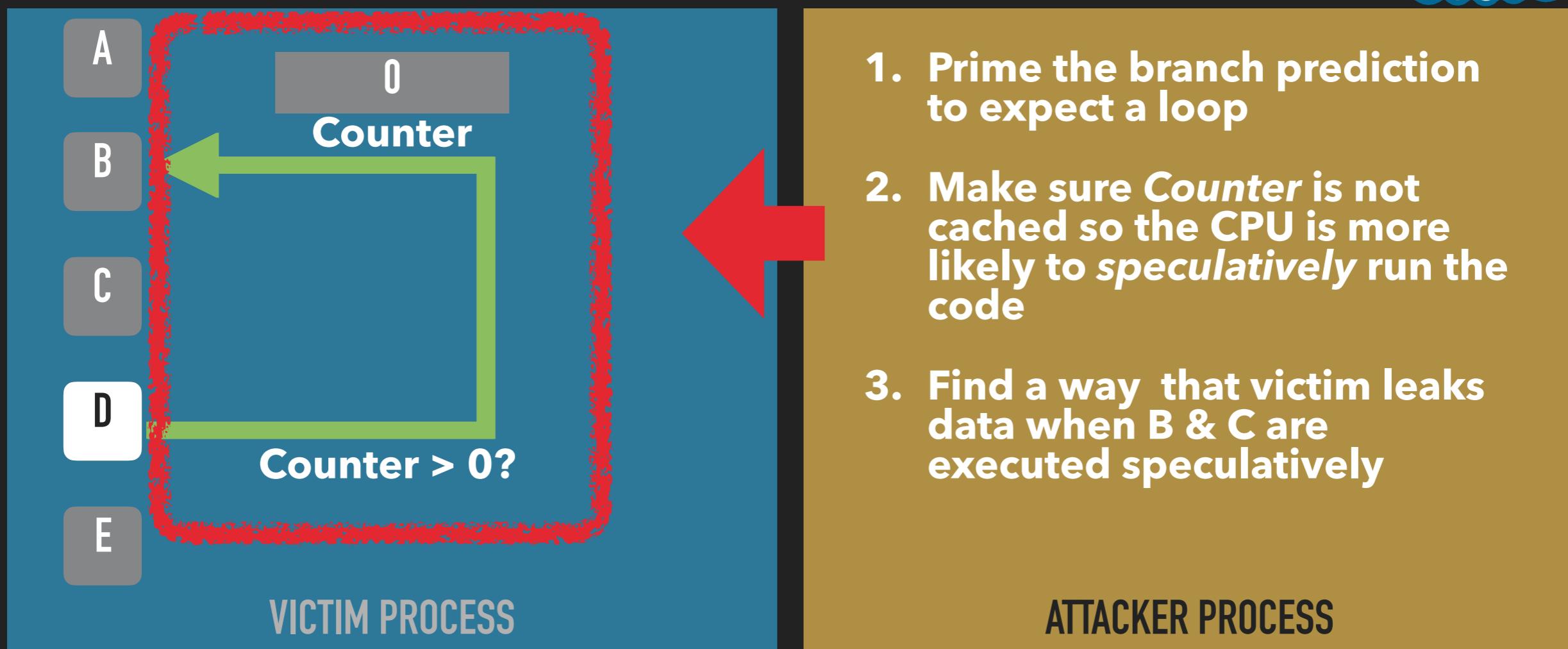


The CPU has learned that Counter *probably* is > 0

Reading Counter from memory is very slow

The CPU *speculatively* executes B C to improve performance

SPECTRE: SPECULATIVE EXECUTION



Attacker can influence the CPUs branch prediction of victim.

Making the victim *speculatively* execute “wrong” code.

E.g. loop even when Counter is == 0.

SPECTRE: VARIANT 1 (CVE-2017-5753)



```
if (x < array1_size)
    y = array2[array1[x] * 256];
```

- ▶ This is code of the victim
- ▶ x is controlled by the attacker
- ▶ attacker wants to read array1[x] out of bounds
- ▶ array2 is used to leak the value of y (like in Meltdown)

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1. Attacker manipulates branch prediction
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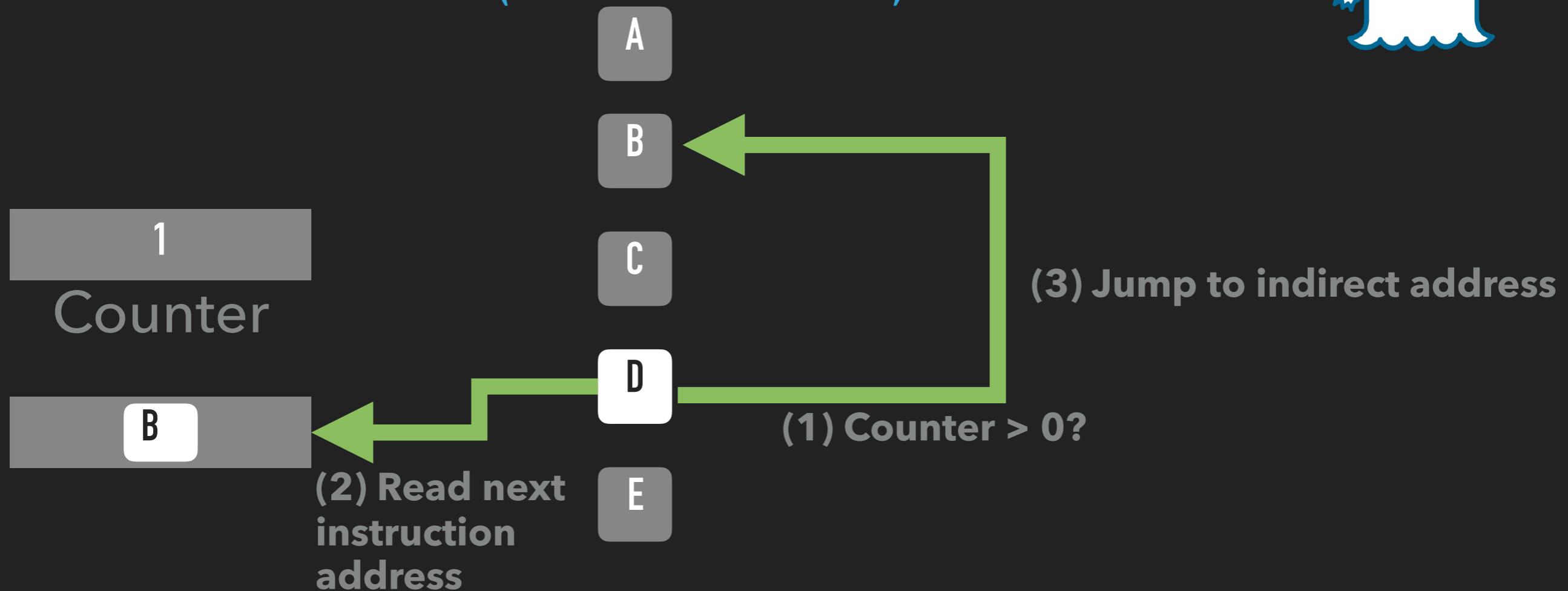
SPECTRE: VARIANT 1 (CVE-2017-5753)



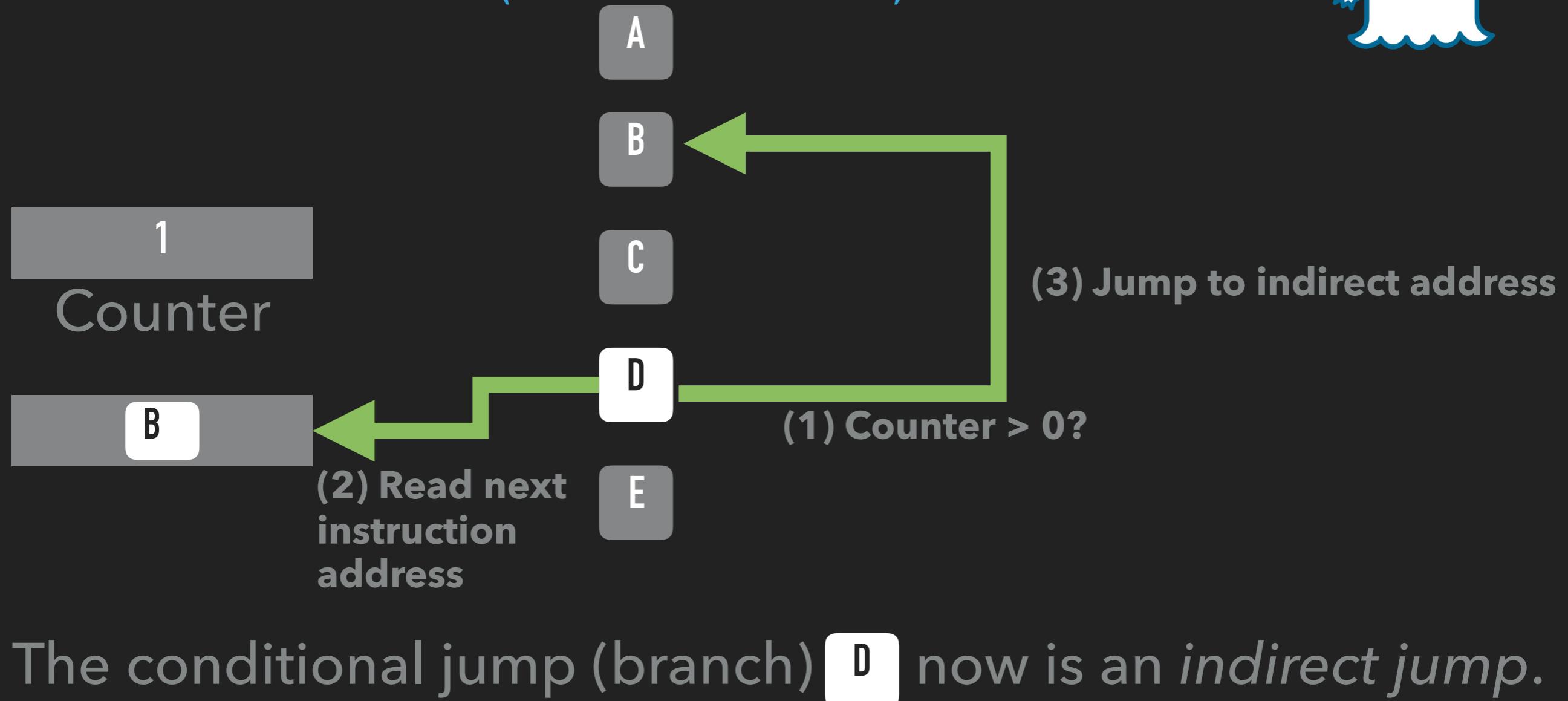
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1. Attacker manipulates branch prediction
 2. Speculatively runs even when `x > array1_size`
 3. The cache timing of `array2[..]` leaks the value `array1[x]`

SPECTRE: VARIANT 2 (CVE-2017-5715)

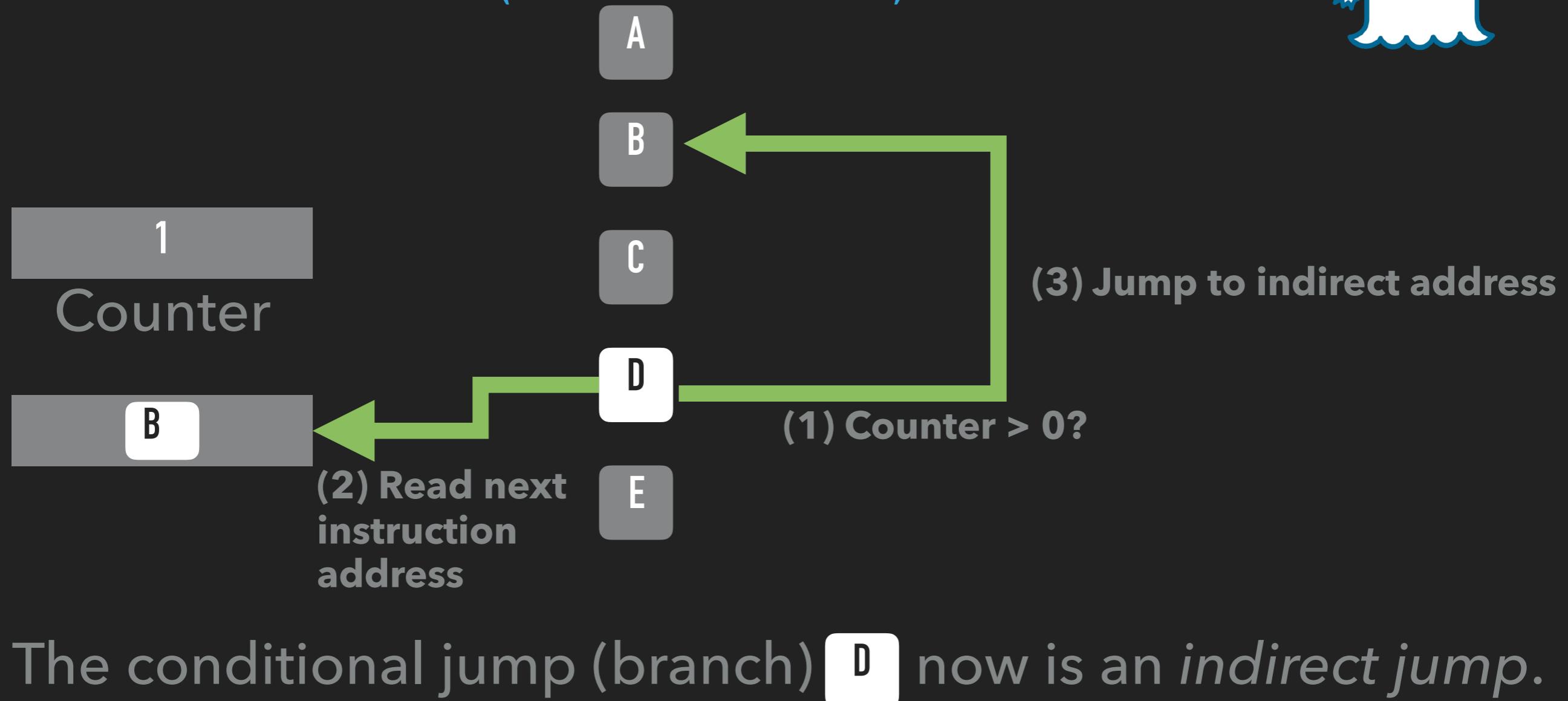


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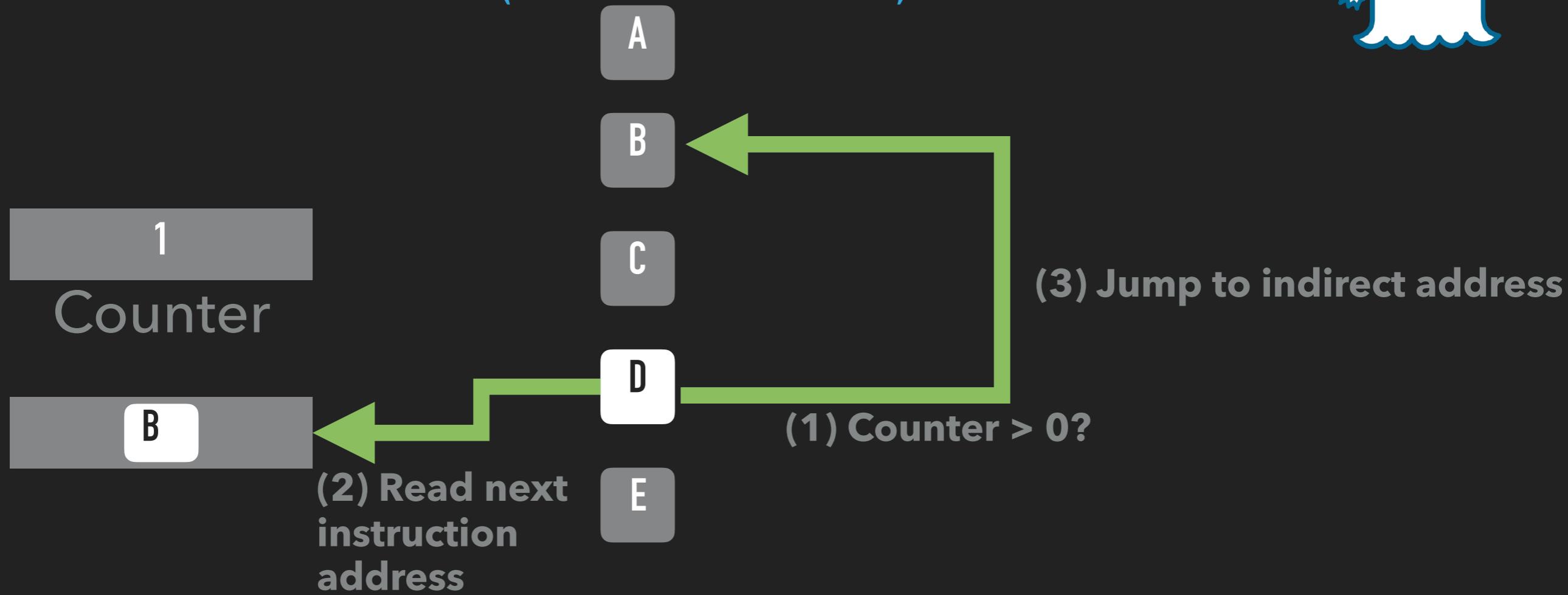


- ▶ The conditional jump (branch) **D** now is an *indirect jump*.

SPECTRE: VARIANT 2 (CVE-2017-5715)

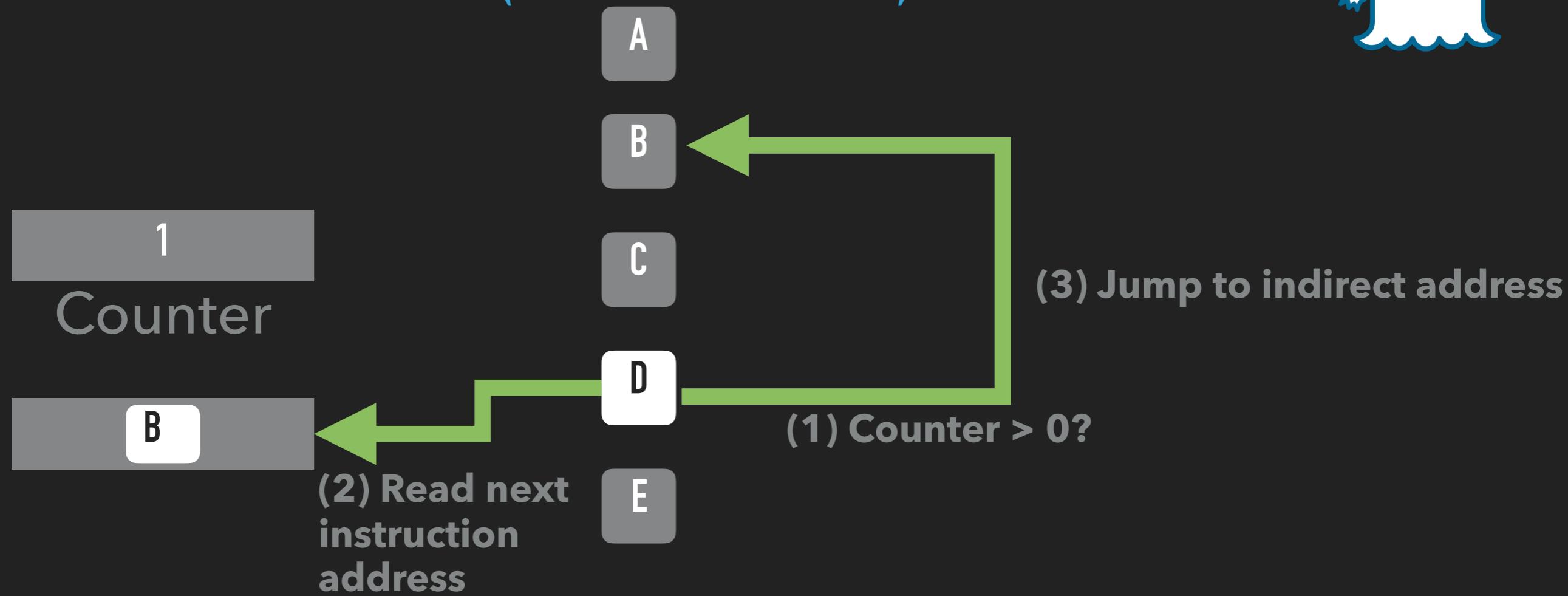


SPECTRE: VARIANT 2 (CVE-2017-5715)



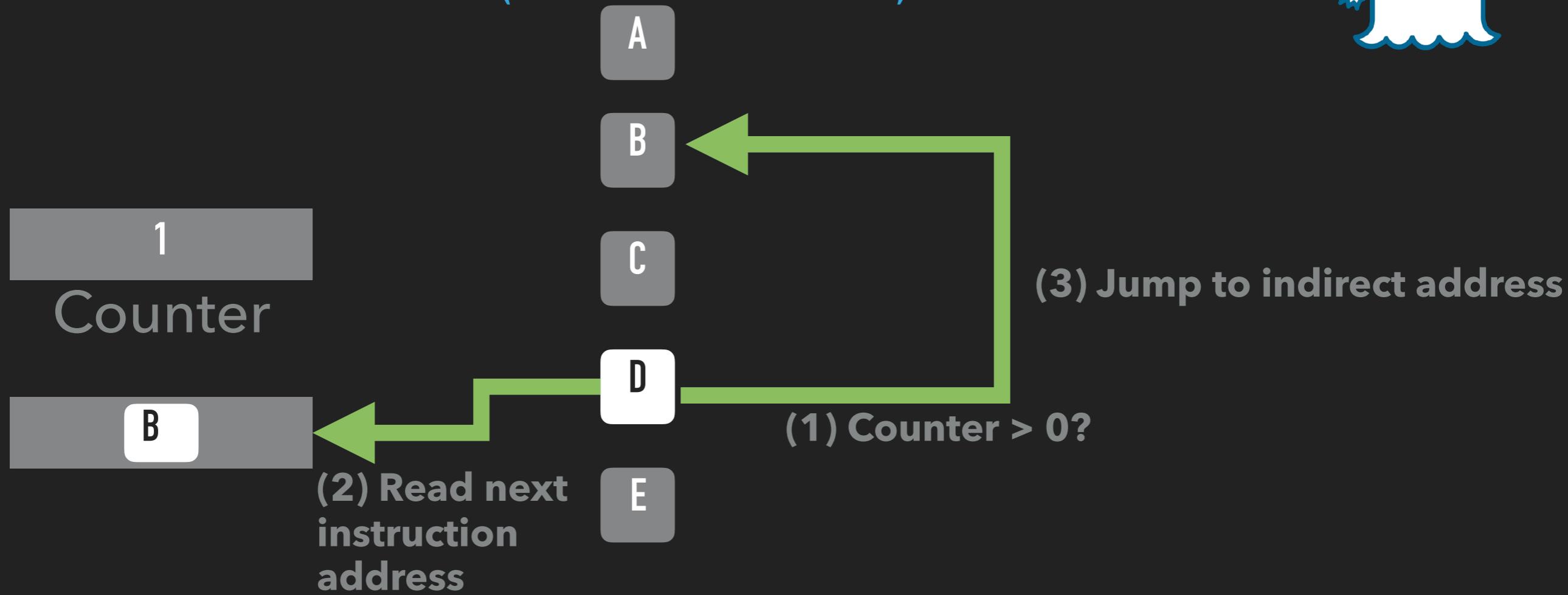
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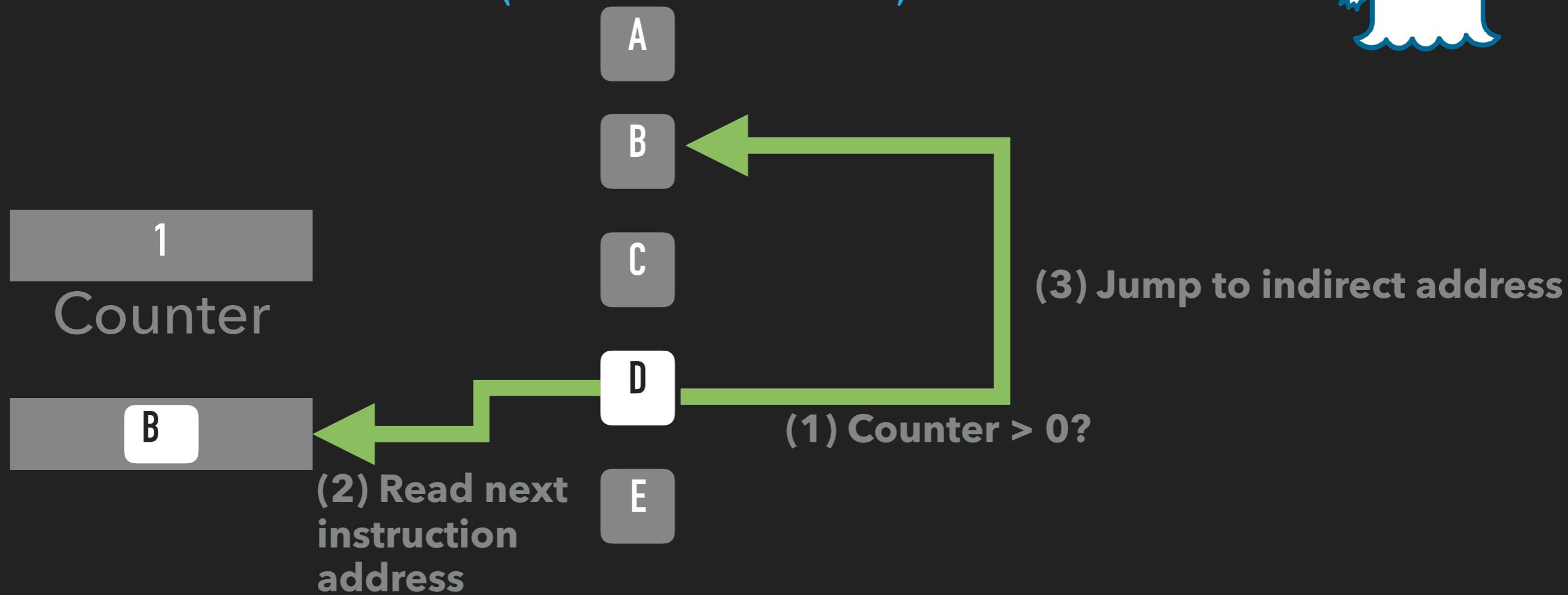
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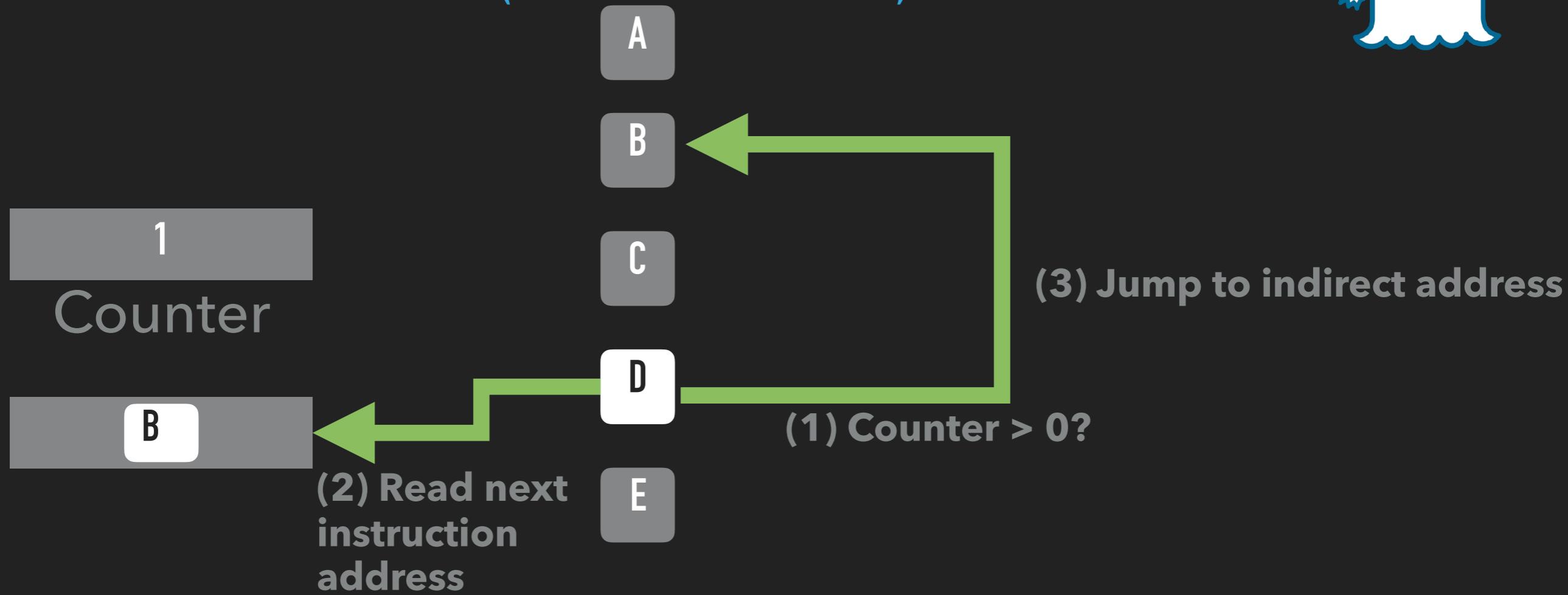
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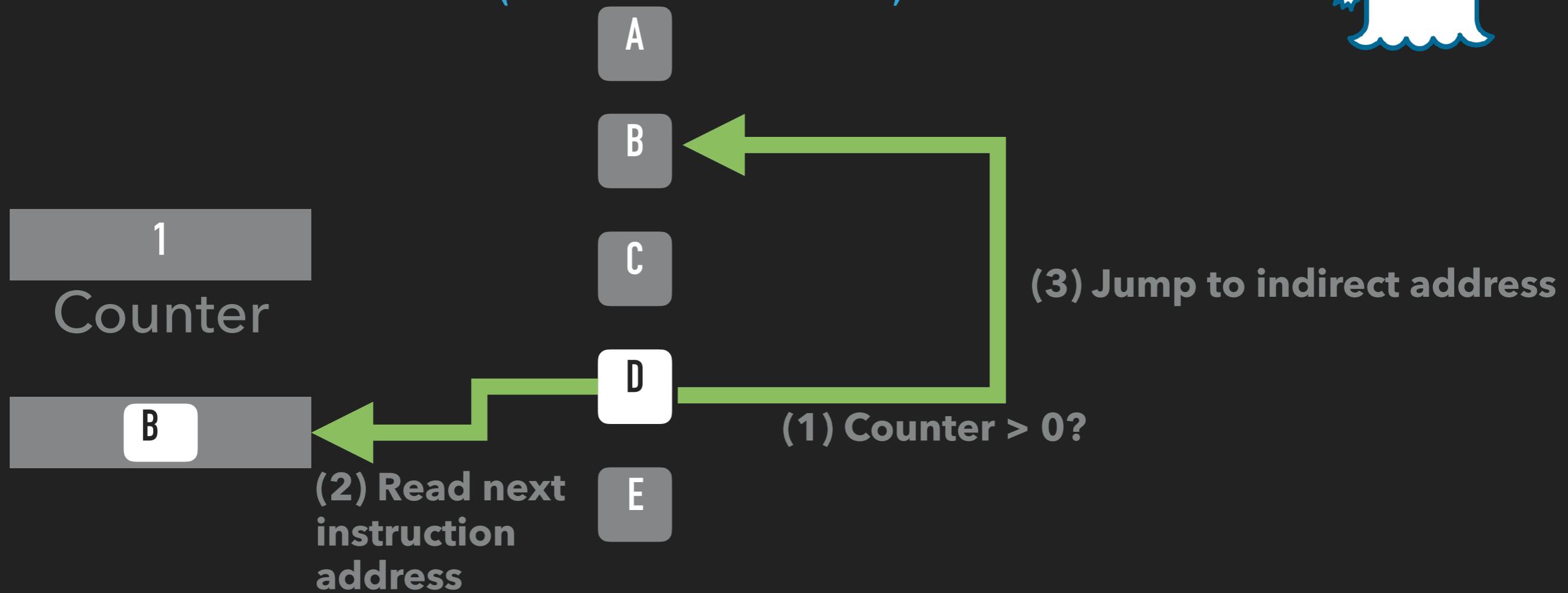
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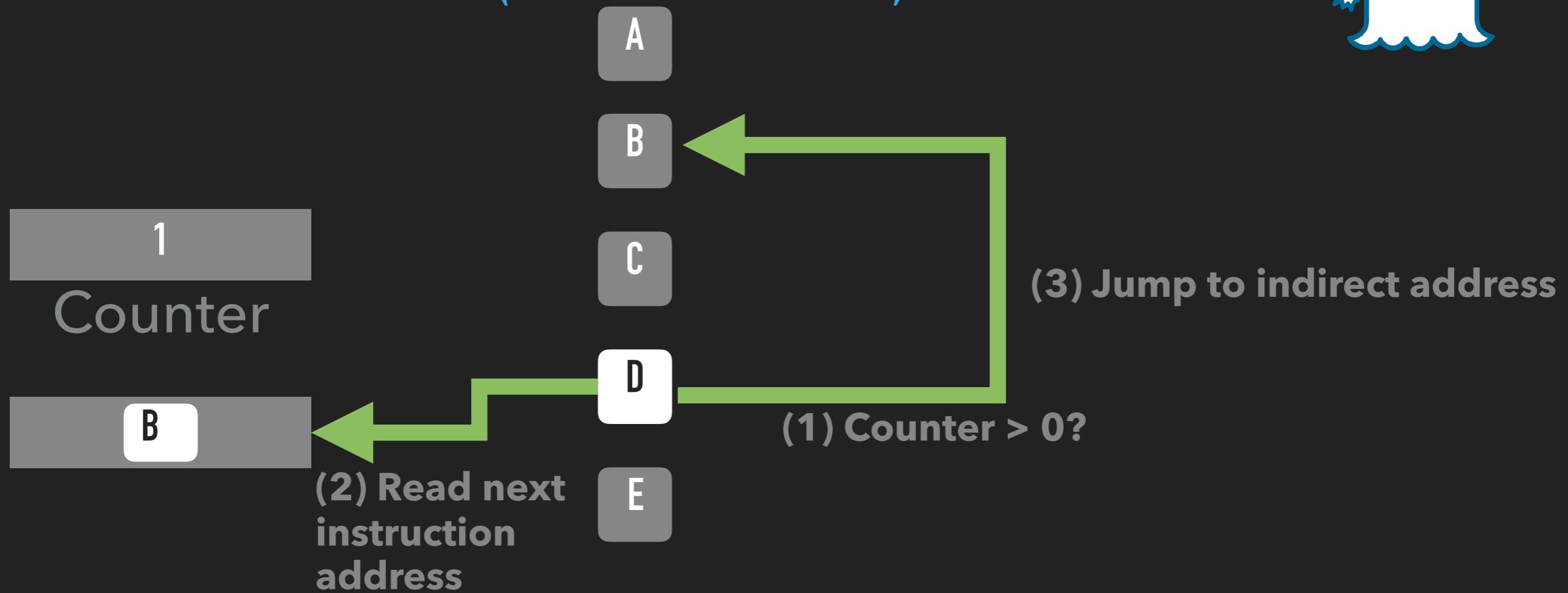
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- ▶ This can also be used to *speculatively* execute any code found in the target process (kernel).

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MELTDOWN AND
SPECTRE

CONCLUSION

THREAT-O-METER

LOW RISK

Exploit unlikely or
running
untrusted code already
worst case

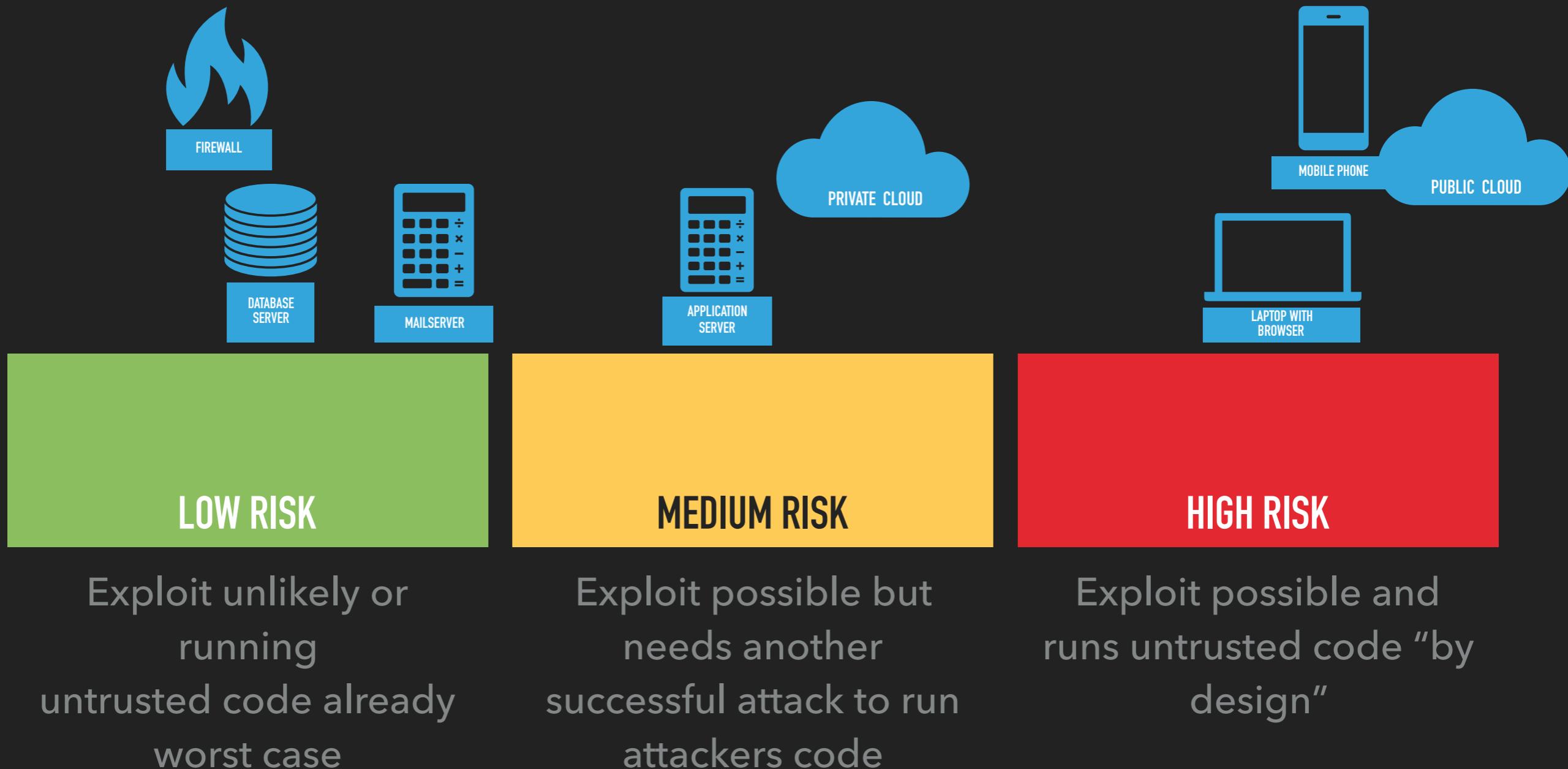
MEDIUM RISK

Exploit possible but
needs another
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attackers code

HIGH RISK

Exploit possible and
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design"

THREAT-O-METER



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Meltdown and Spectre exploit side effects of modern CPU architectures.



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THREAT-O-METER

Meltdown and Spectre exploit side effects of modern CPU architectures.

The *exploitability* very much depends on the field of application of the system.

Expect new “bugs” of this type!

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MELTDOWN

THREAT-

Melt
CPU

The
appl

Expe

Exclusive: Spectre-NG - Multiple new Intel CPU flaws revealed, several serious



TRENDS & NEWS | C'T DECKT AUF

Jürgen Schmidt

03.05.2018

Intel Core i, Meltdown und Spectre, Prozessoren, Sicherheitslücken, Spectre

New flaws and even more patches - "Spectre Next Generation" is just around the corner. According to information exclusively available to c't, researchers have already found eight new security holes in Intel processors.

untrusted code already
worst case

successful attack to run
attackers code

design"

Knock knock

Branch prediction

Who's there?

Q & A



Something missing?

Boring?

Awesome?

Feedback helps!

FEEDBACK

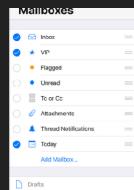




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[HTTPS://SPECTREATTACK.COM/](https://spectreattack.com/)



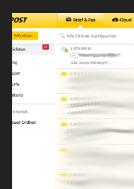
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[HTTPS://PORTAL.E-POST.DE](https://portal.e-post.de)



[HEISE.DE](#)
<https://www.heise.de/ct/artikel/Exclusive-Spectre-NG-Multiple-new-Intel-CPU-flaws-revealed-several-serious-4040648.html>

ASSETS

ABANDONED SLIDES