EXPLAINED:

MELTDOWN & SPECTRE

Jens Neuhalfen

https://github.com/neuhalje/presentation_meltdown_spectre

EXPLAINED:

MELTDOWN & SPECTRE

for normal people

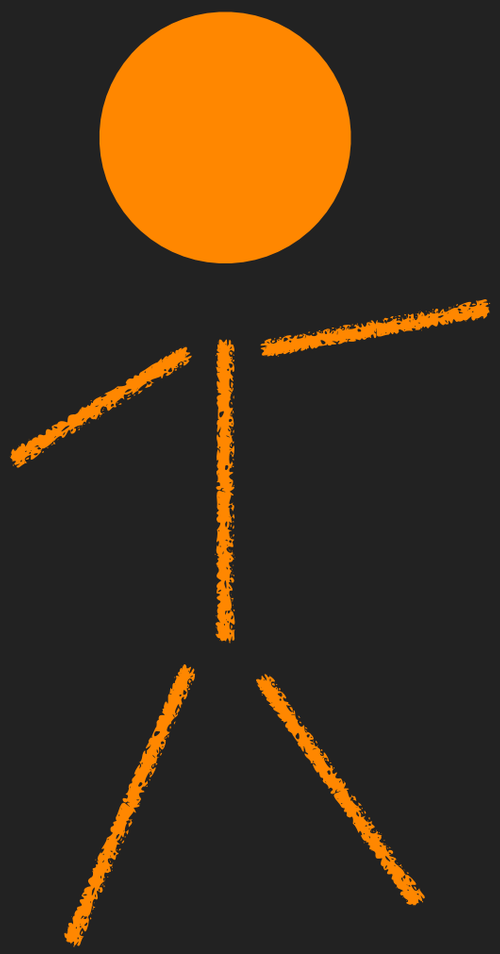
https://github.com/neuhalje/presentation_meltdown_spectre

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

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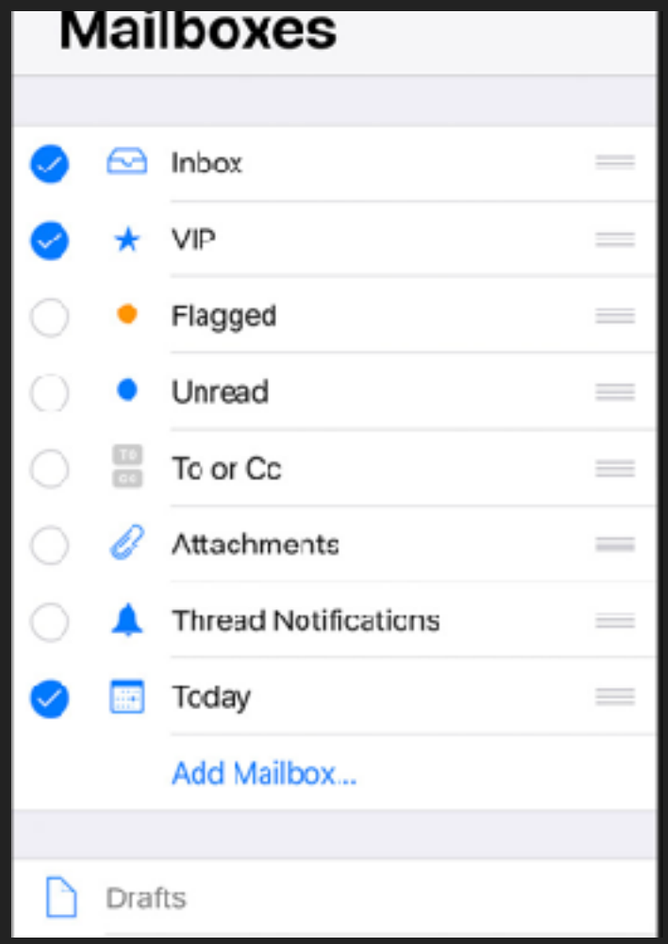
You don’t want
this

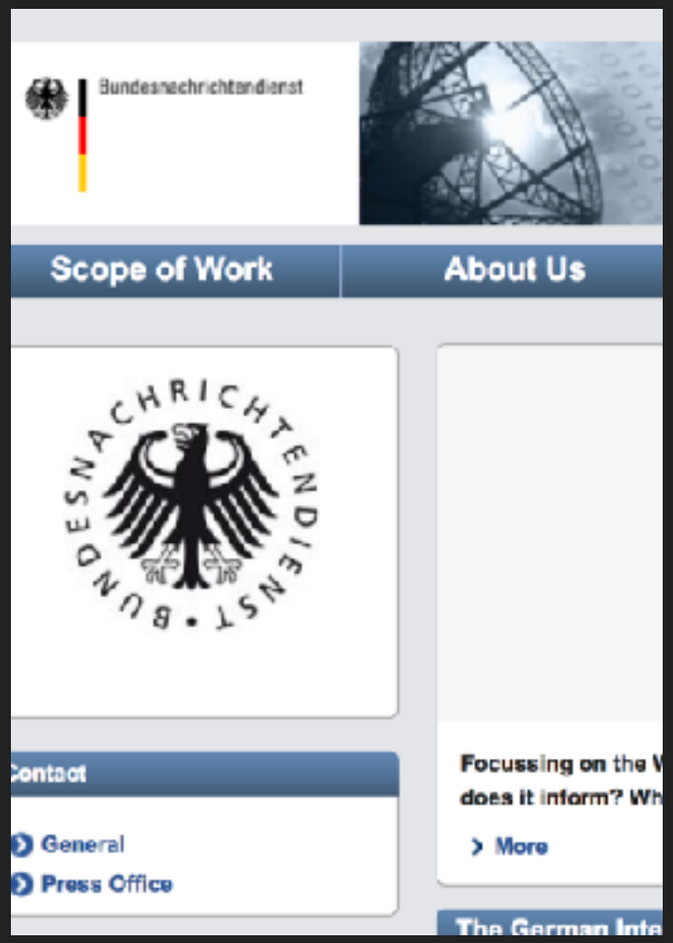
SECURITY GOALS: APP ISOLATION

You don't want
this



To read
that

SECURITY GOALS: BROWSER TAB ISOLATION



You don’t want *this*

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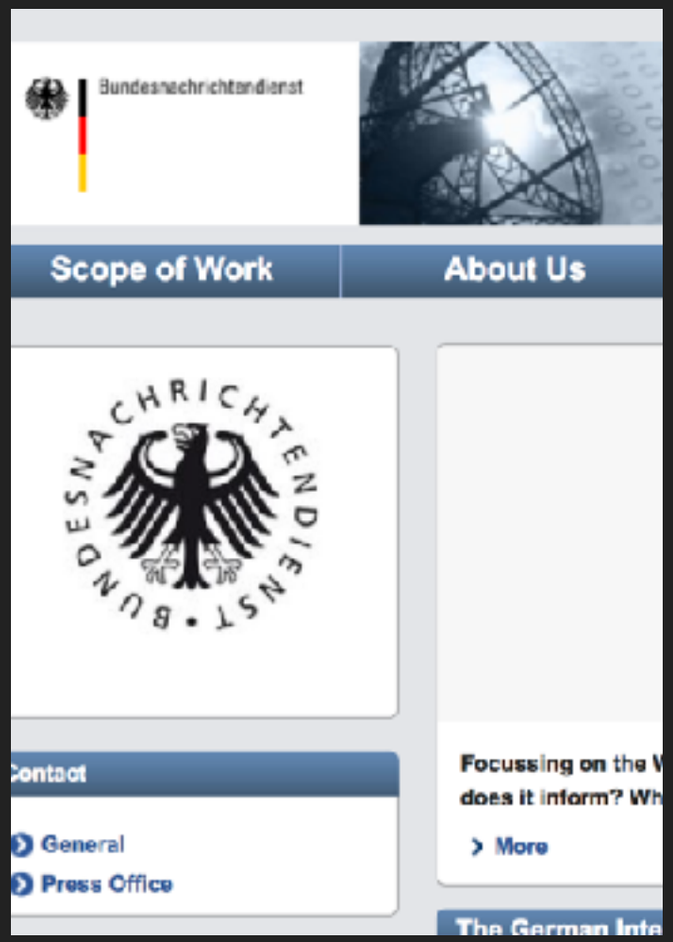

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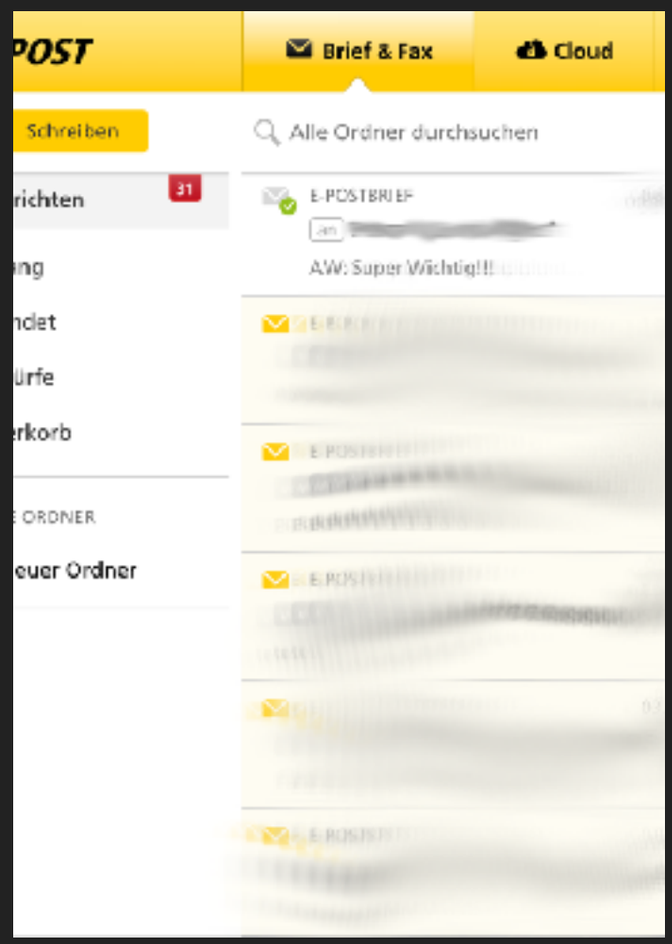


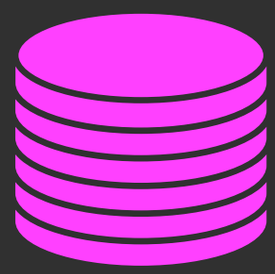
To read *that*

SECURITY GOALS: CLOUD ISOLATION

You don’t want

this

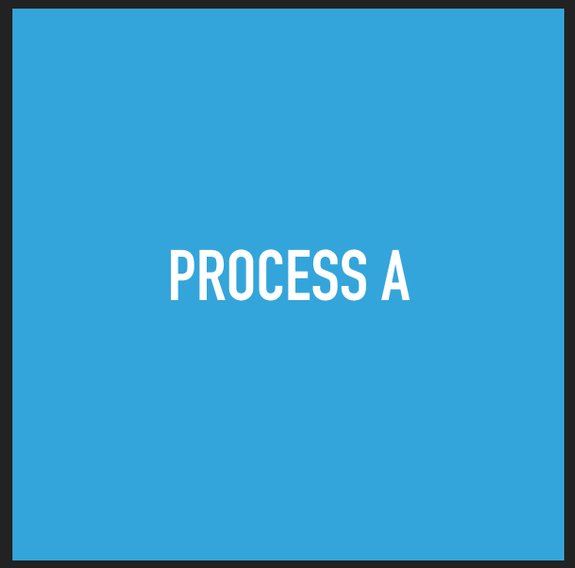
SECURITY GOALS: CLOUD ISOLATION



You don't want
this

To read
that

SECURITY GOALS: MEMORY ISOLATION



You don’t want

this

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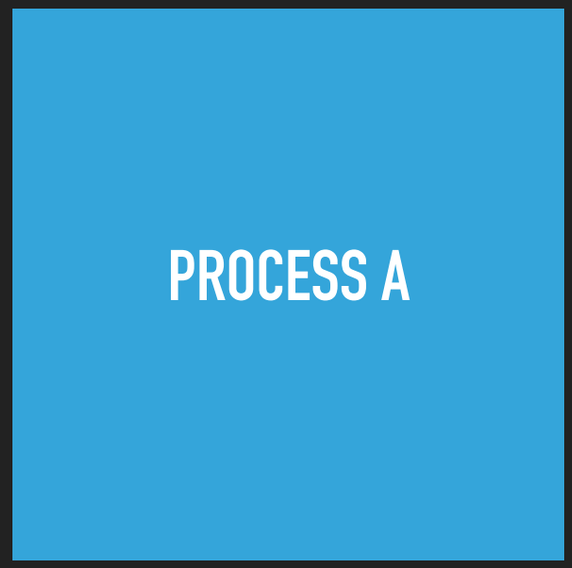

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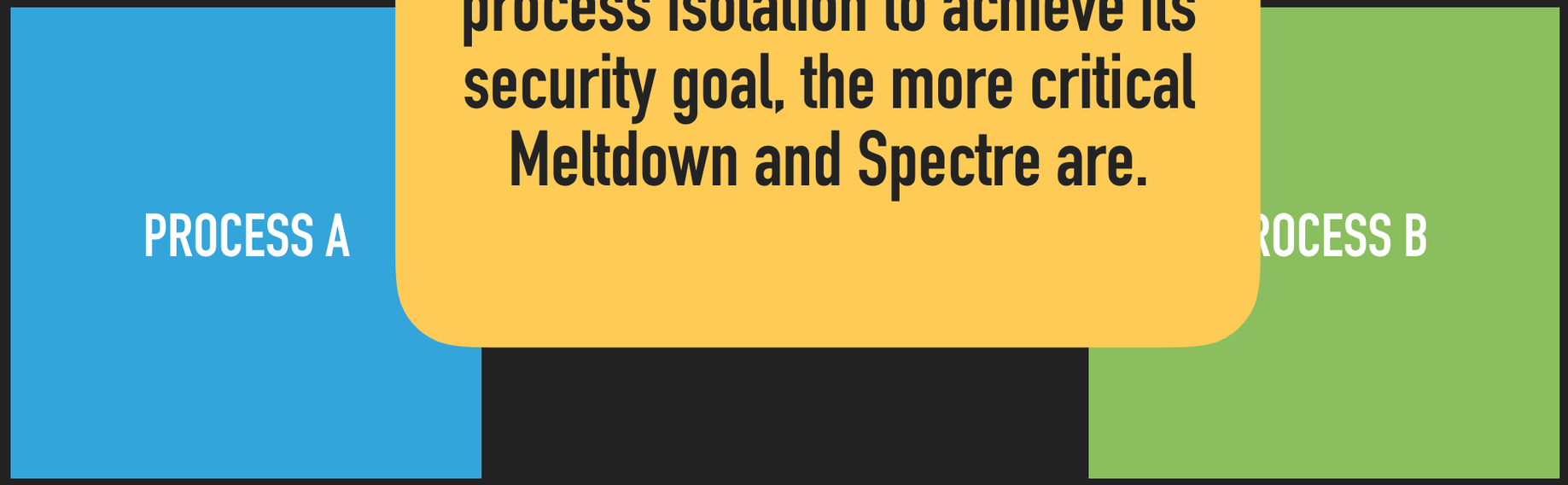
SECURITY GOALS: MEMORY ISOLATION

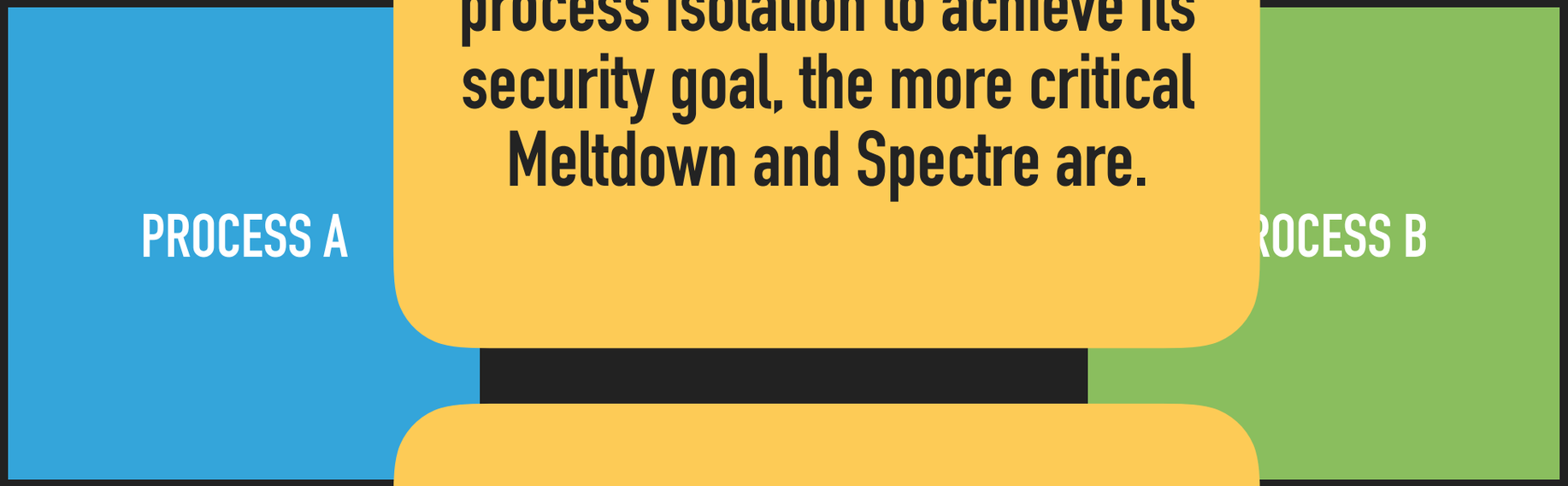


The more a system relies on process isolation to achieve its security goal, the more critical Meltdown and Spectre are.

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.

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

You don't read *this* *hat*

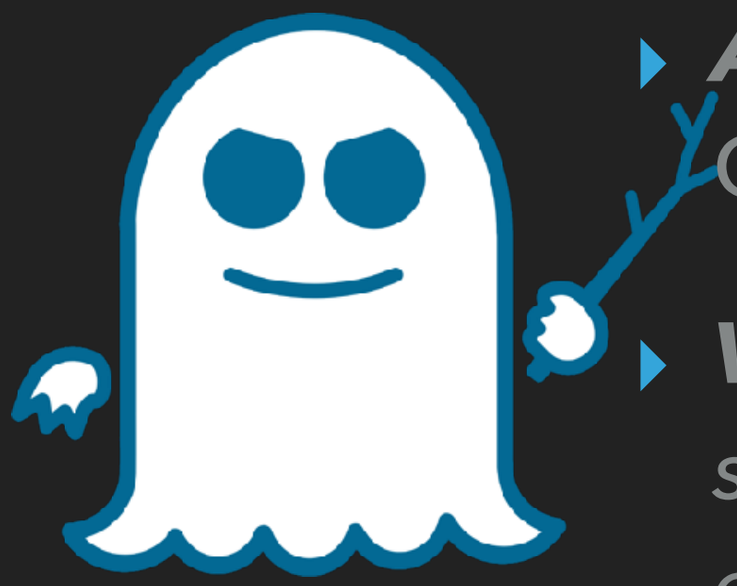
MELTDOWN AND SPECTRE

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	MEDIUM RISK	HIGH RISK
Exploit unlikely or running untrusted code already worst case	Exploit possible but needs another successful attack to run attackers code	Exploit possible and runs untrusted code “by design”

THREAT-O-METER

LOW RISK

Exploit unlikely or running untrusted code already worst case

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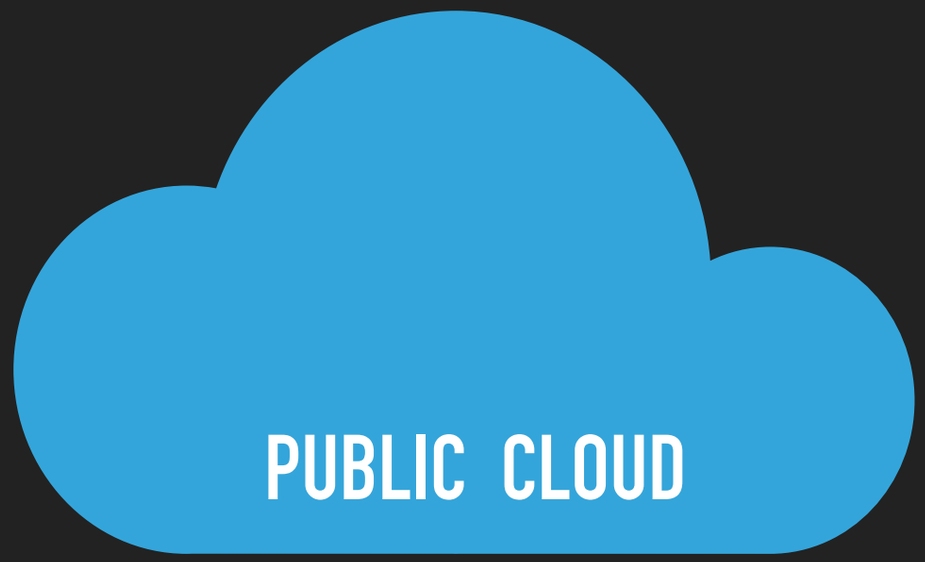
THREAT-O-METER



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THREAT-O-METER

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

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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

DATABASE SERVER

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

LOW RISK

Exploit unlikely or running untrusted code already worst case

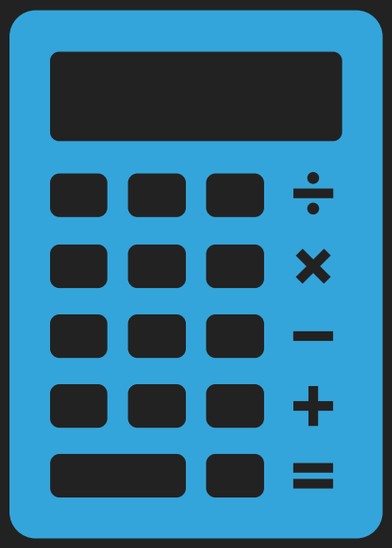
MEDIUM RISK

Exploit possibl needs anoth 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

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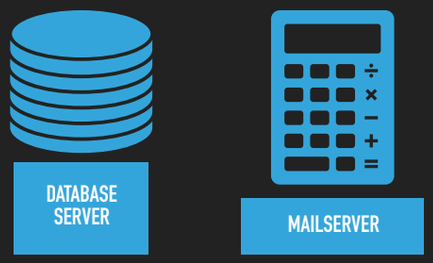
THREAT-O-METER



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HIGH RISK

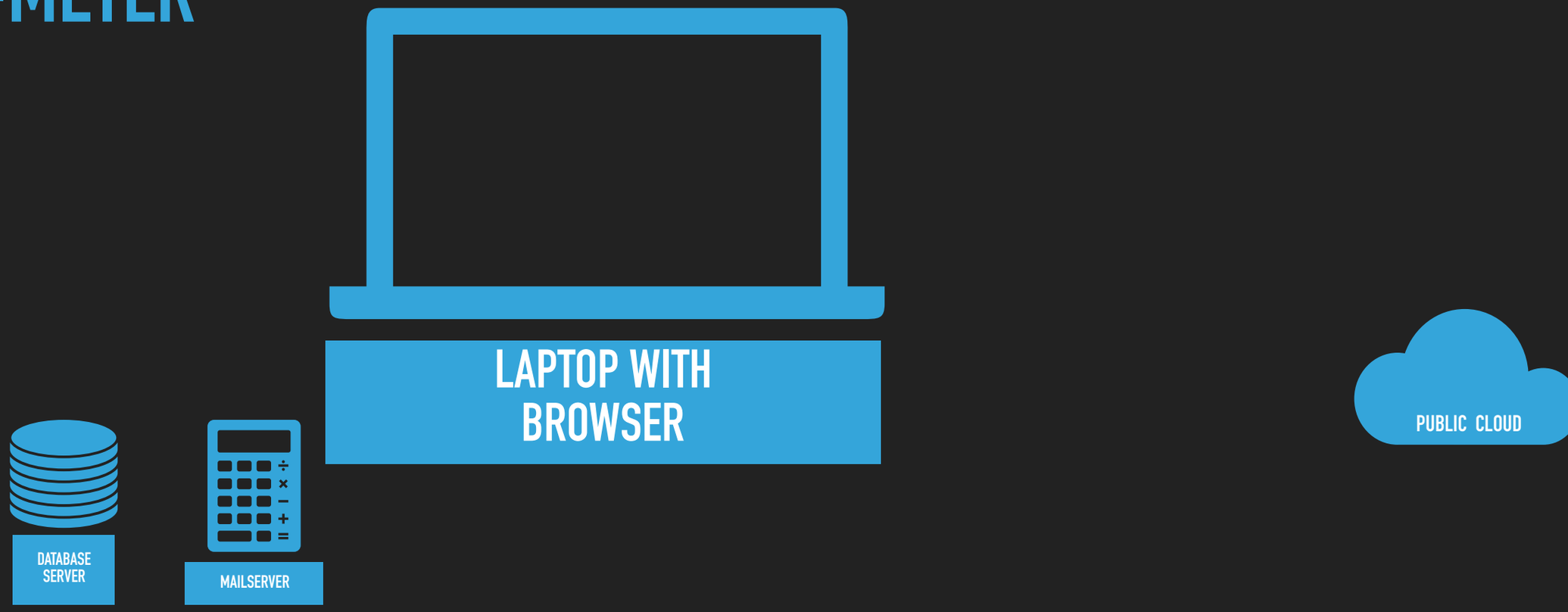
design”

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.

THREAT-O-METER



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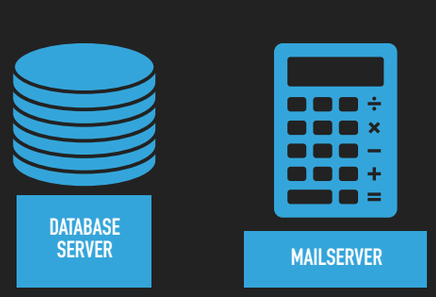
Exploit possible and runs untrusted code “by design”

THREAT-O-METER

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



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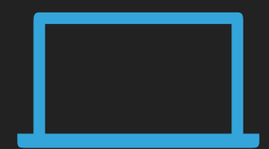

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THREAT-O-METER

Mobile phones run apps and websites (JavaScript).

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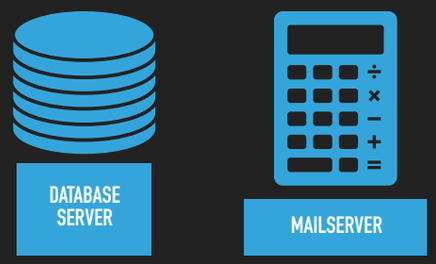

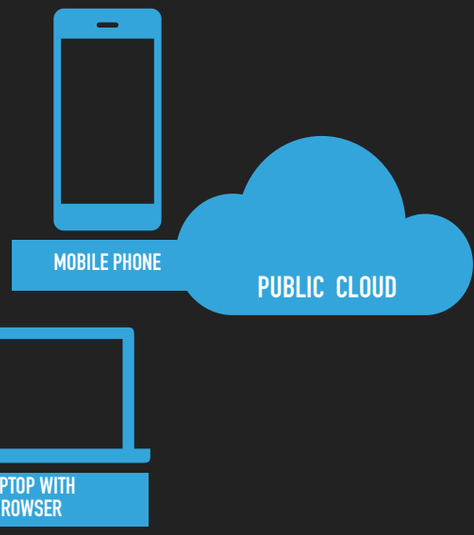

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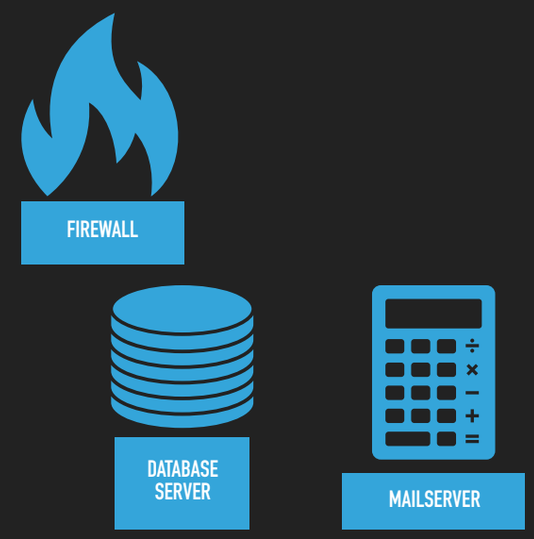

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MEDIUM RISK

Exploit possibl needs anoth successful attack attackers co

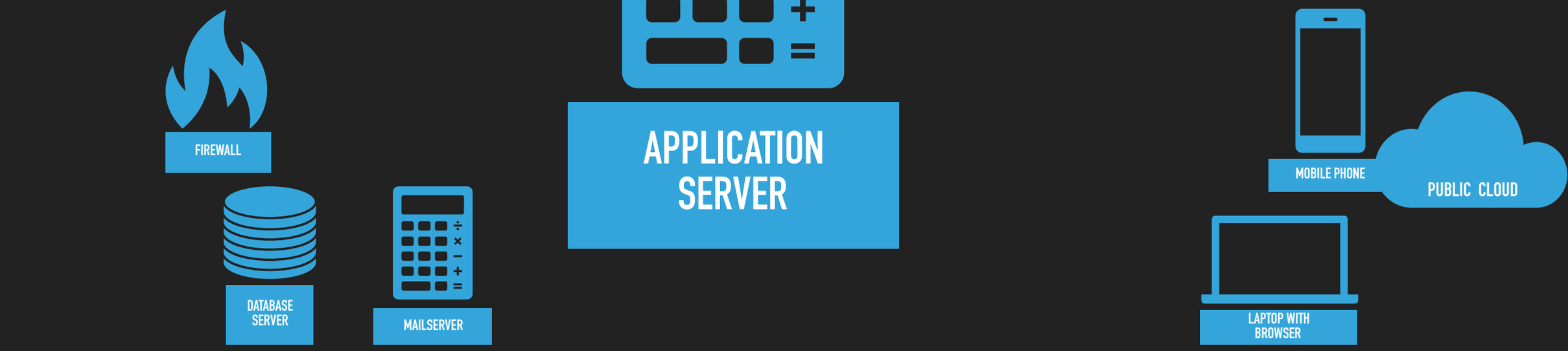
Firewalls and switches (normally) do not expose an attackable surface to the external network.

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



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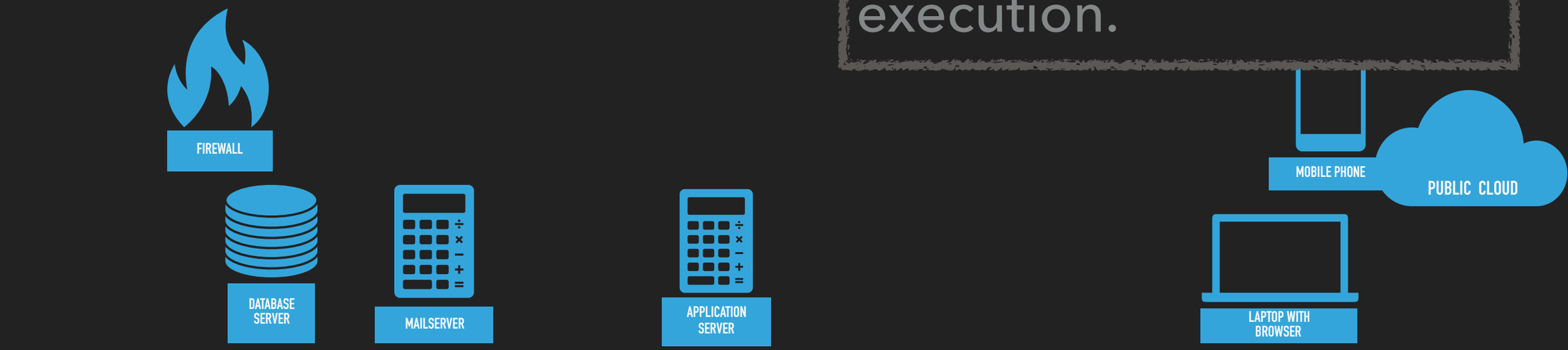
THREAT-O-METER

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



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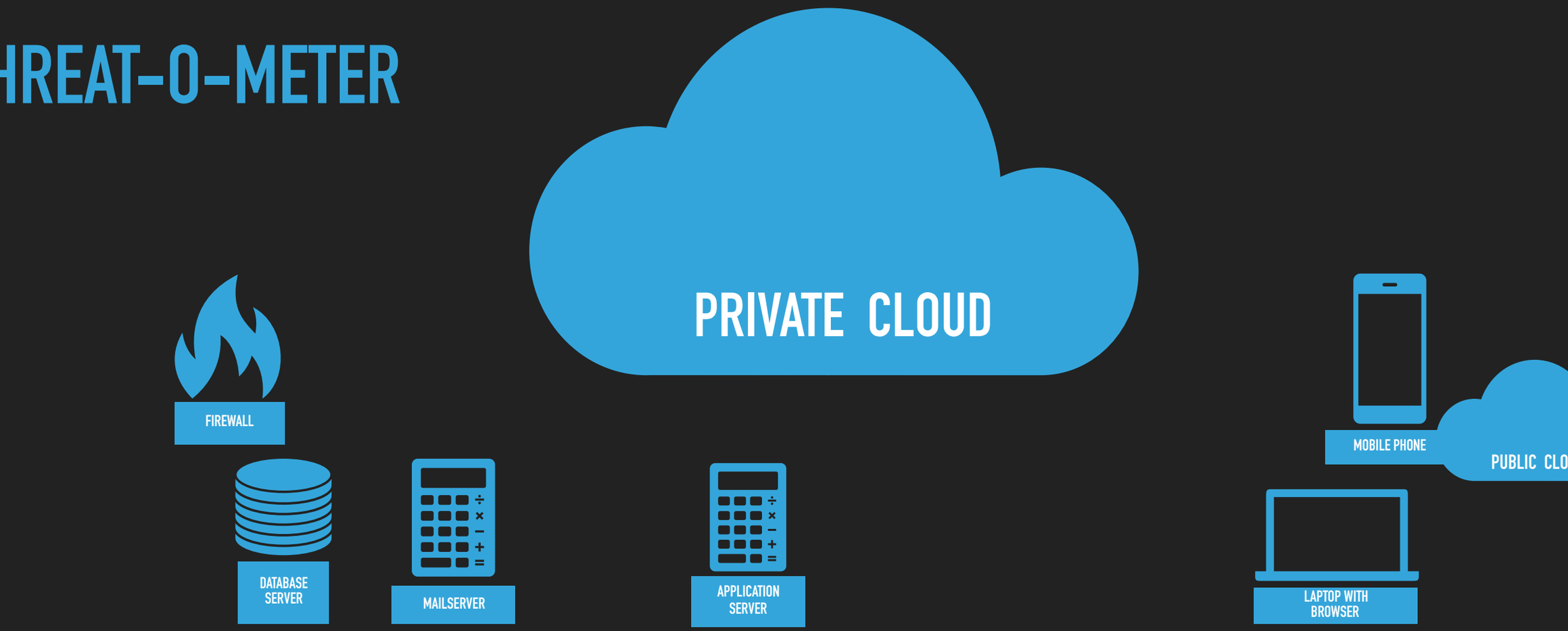

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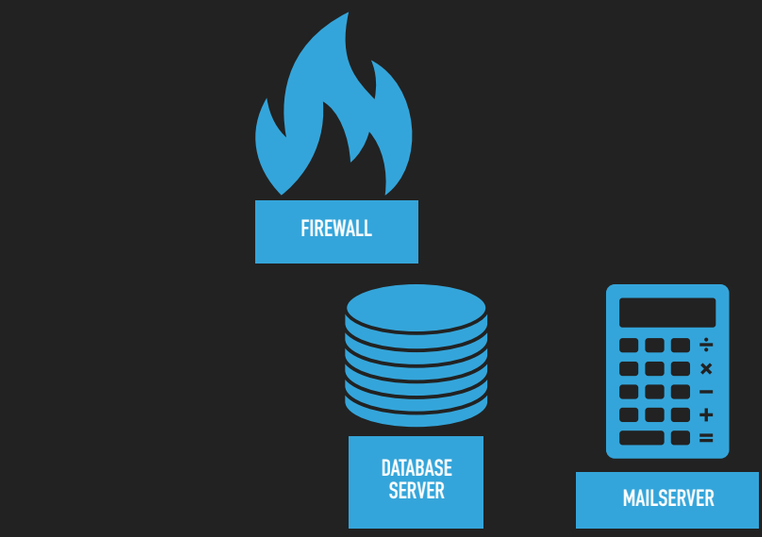

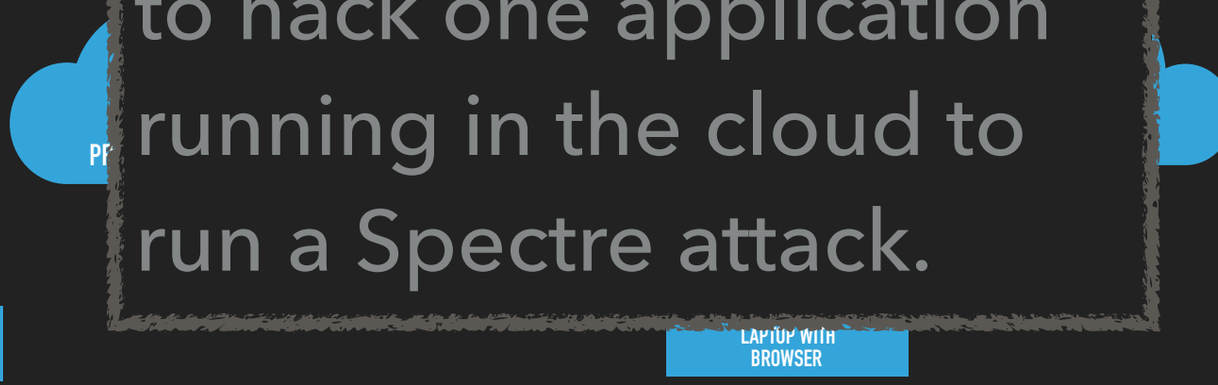

Private clouds run many different workloads but they are all trusted.

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

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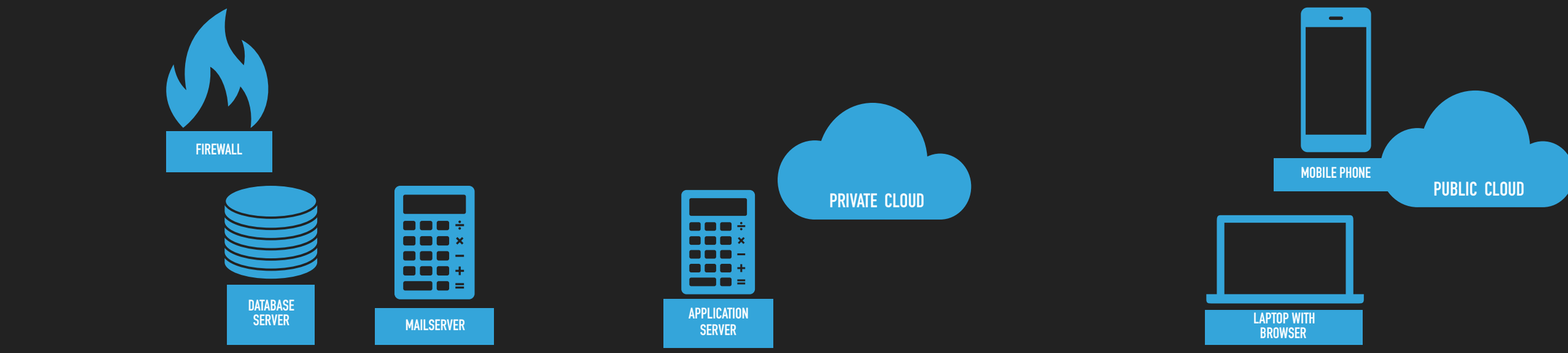

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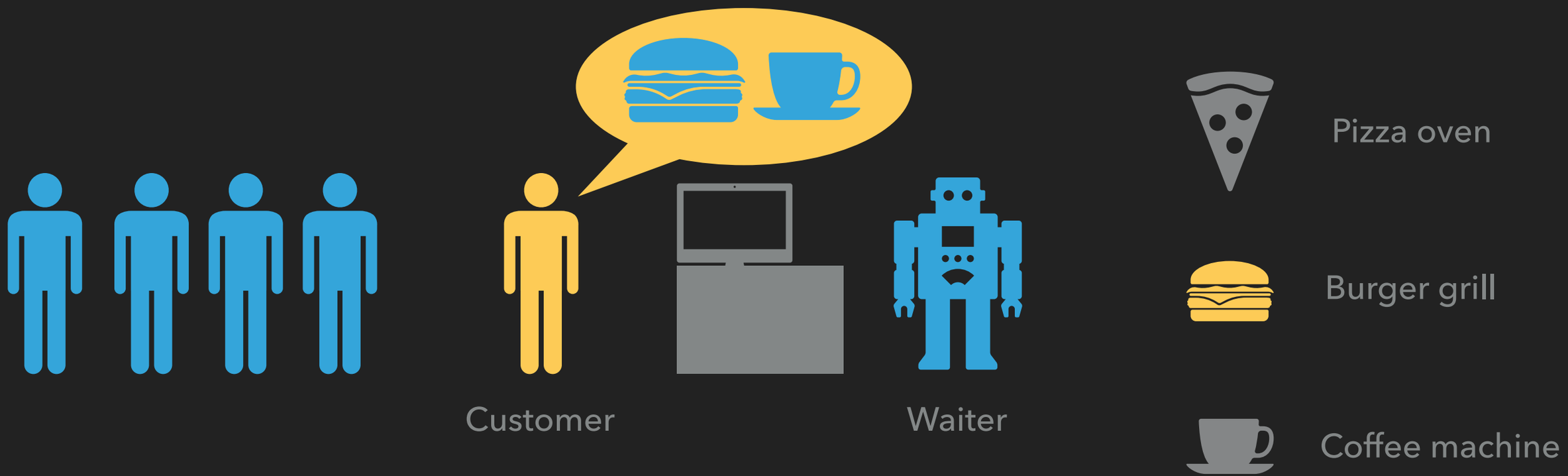
ACCIDENT, MALICE, INCOMPETENCE?

WHY DID IT HAPPEN?

CONFIDENTIAL BURGERS INC.

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



Grand Opening Today

CONFIDENTIAL BURGERS INC.

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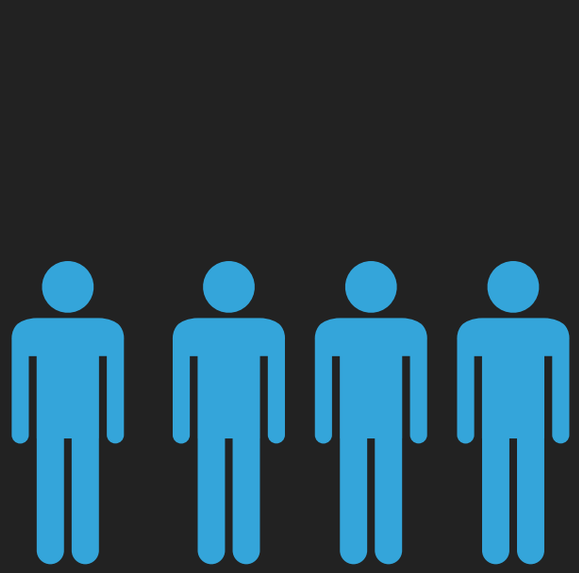
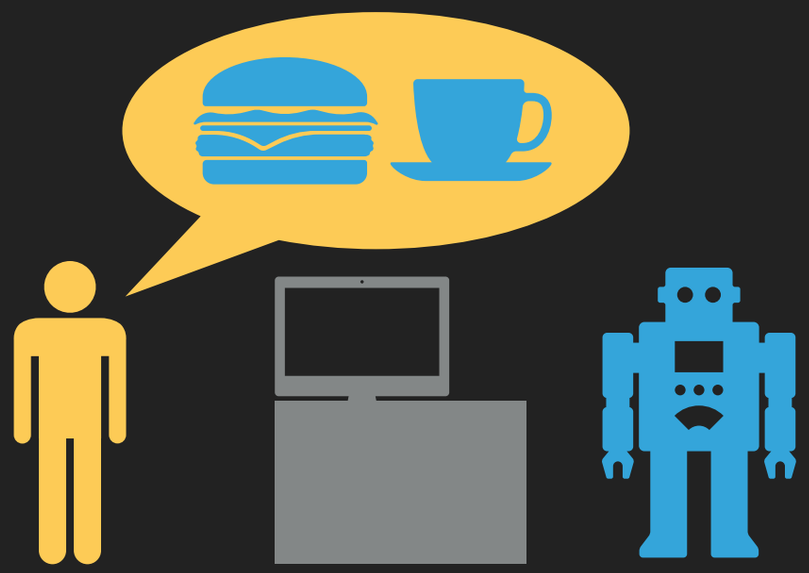


The waiter (CPU) will



Customer

Waiter

Pizza oven

Burger grill

Coffee machine

CONFIDENTIAL BURGERS INC.

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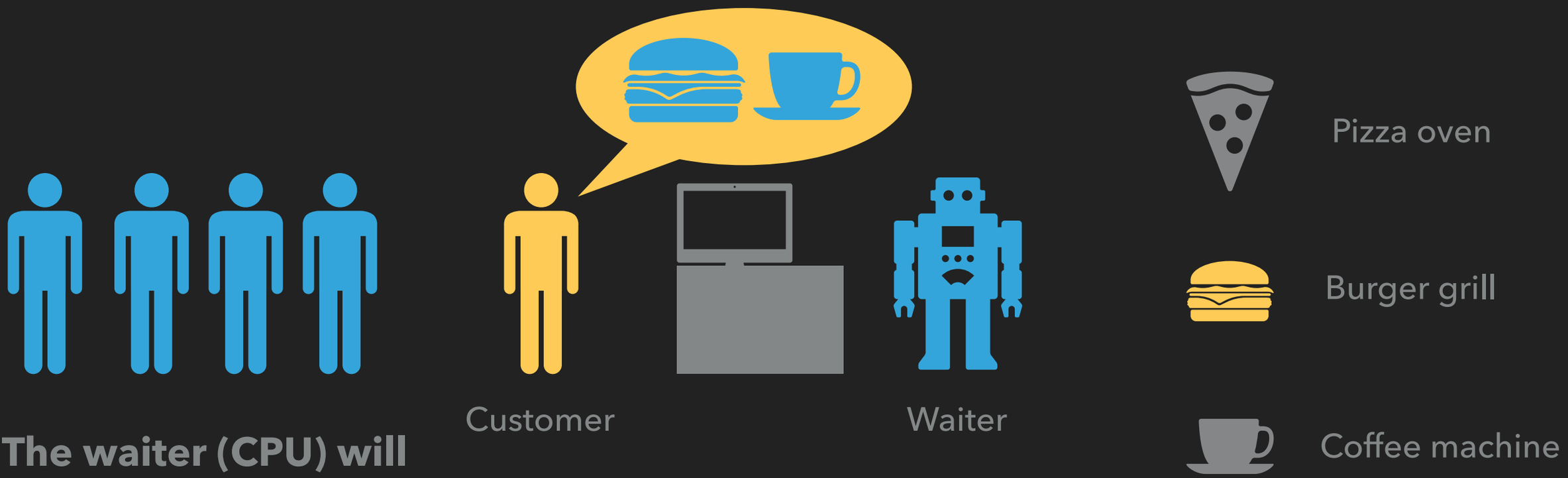

The waiter (CPU) will

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

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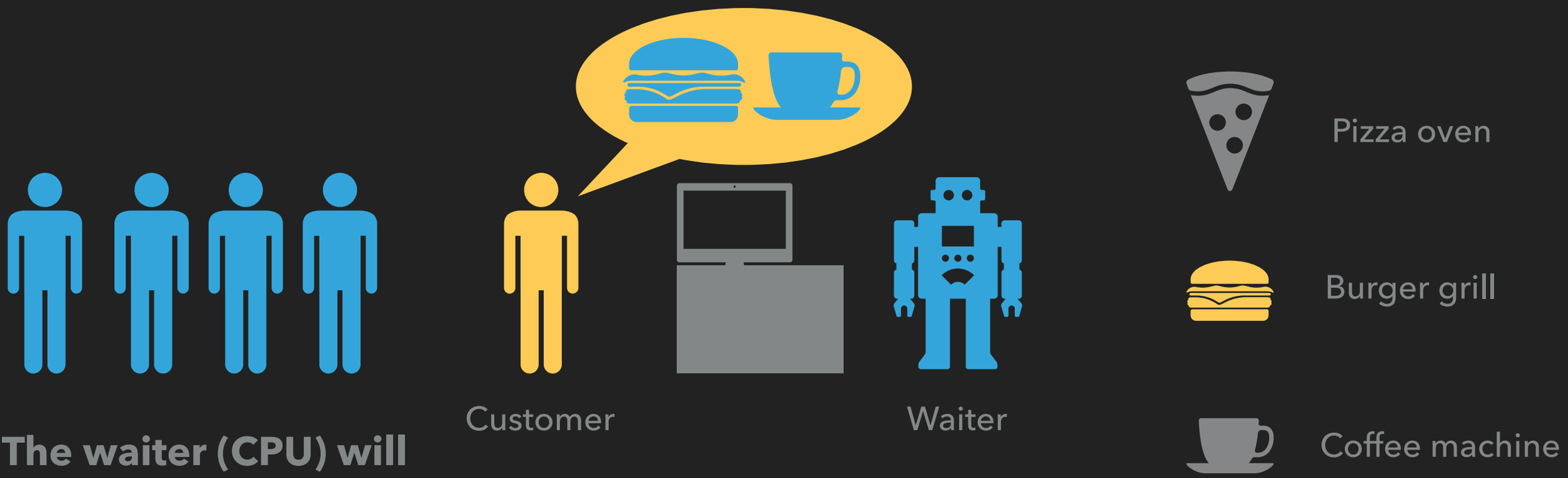

The waiter (CPU) will

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

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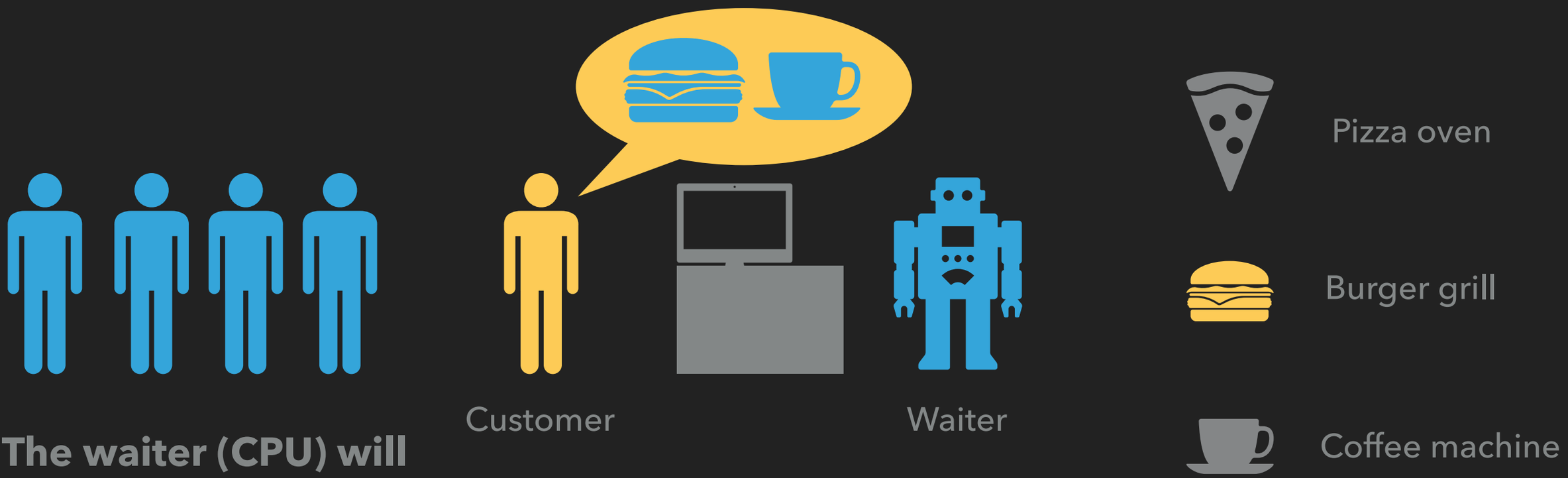

The waiter (CPU) will

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

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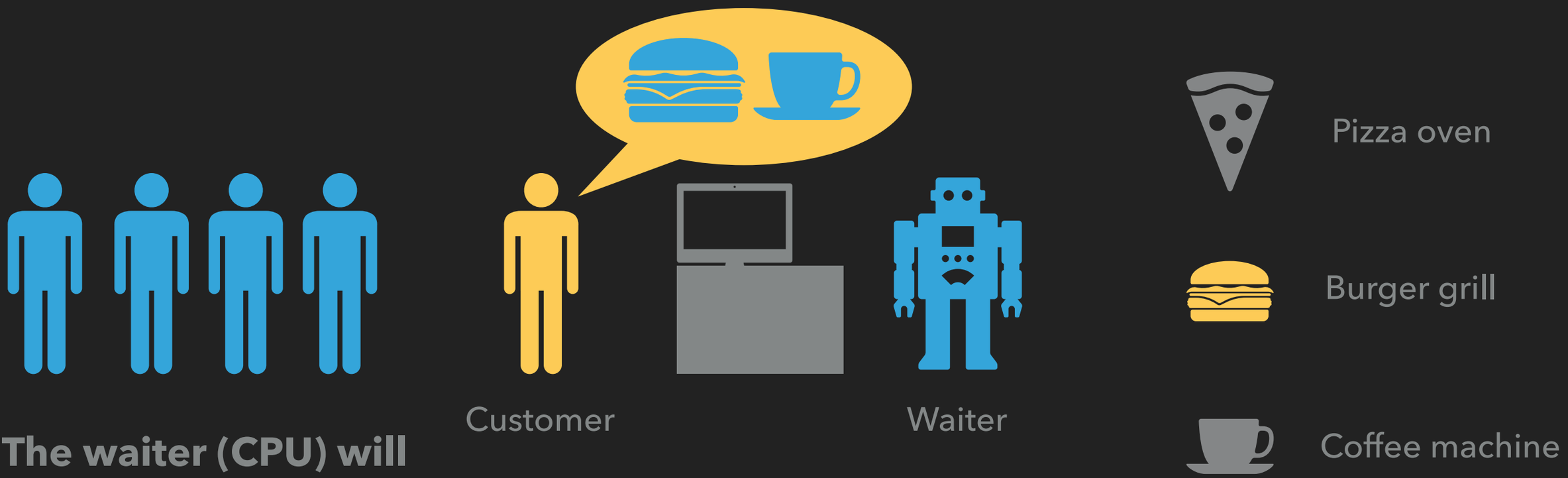
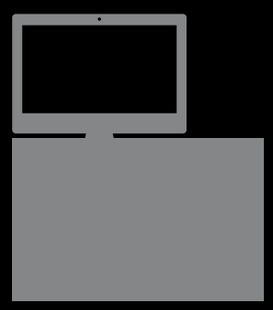


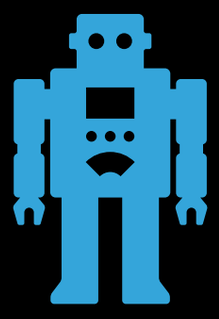
The waiter (CPU) will

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

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION

Customer





Waiter

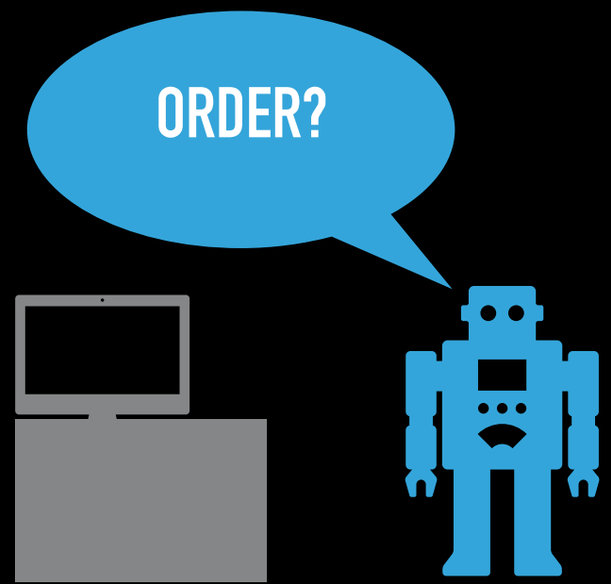
Pizza oven

Burger grill

Coffee machine

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION

Customer



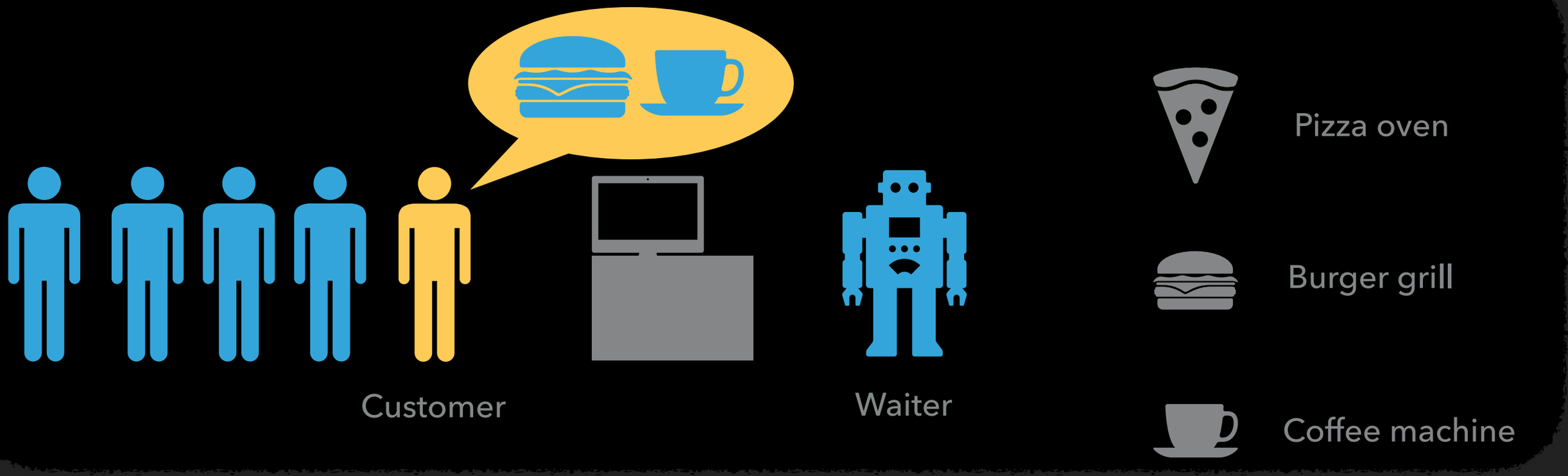
Waiter

Pizza oven

Burger grill

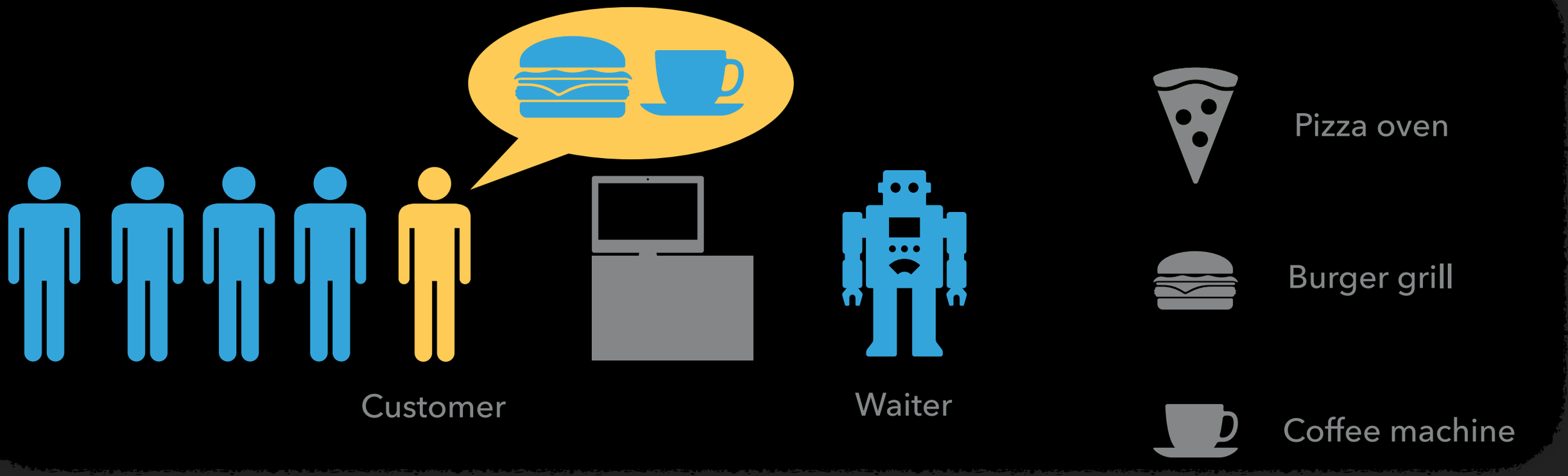
Coffee machine

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



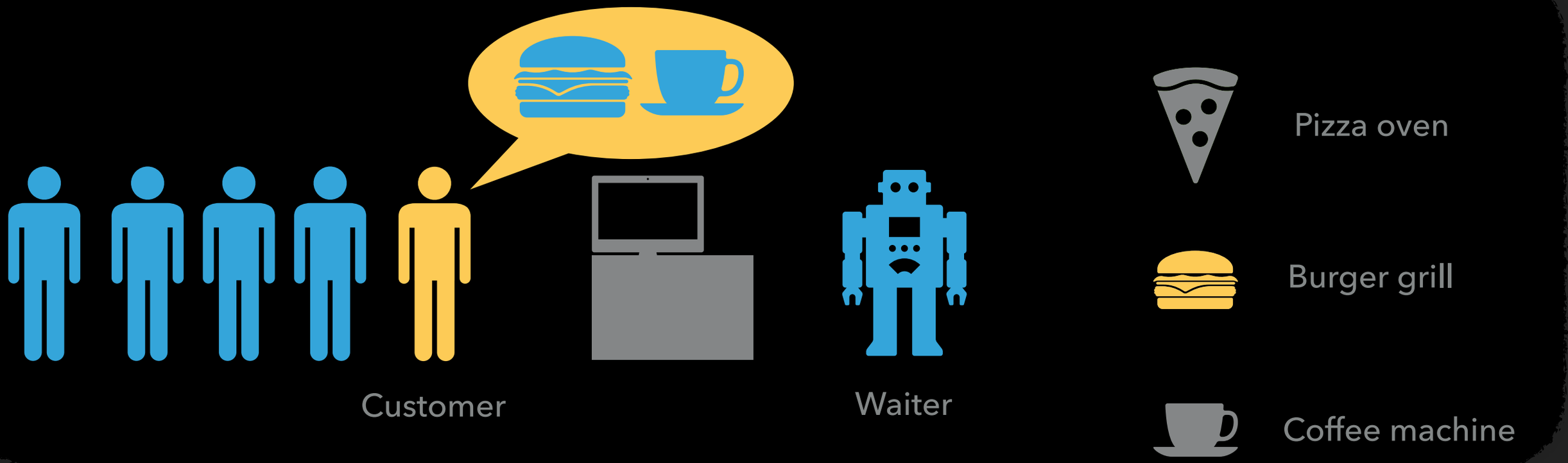
- Decode instruction into μOPs (“Burger”, “Coffee”)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



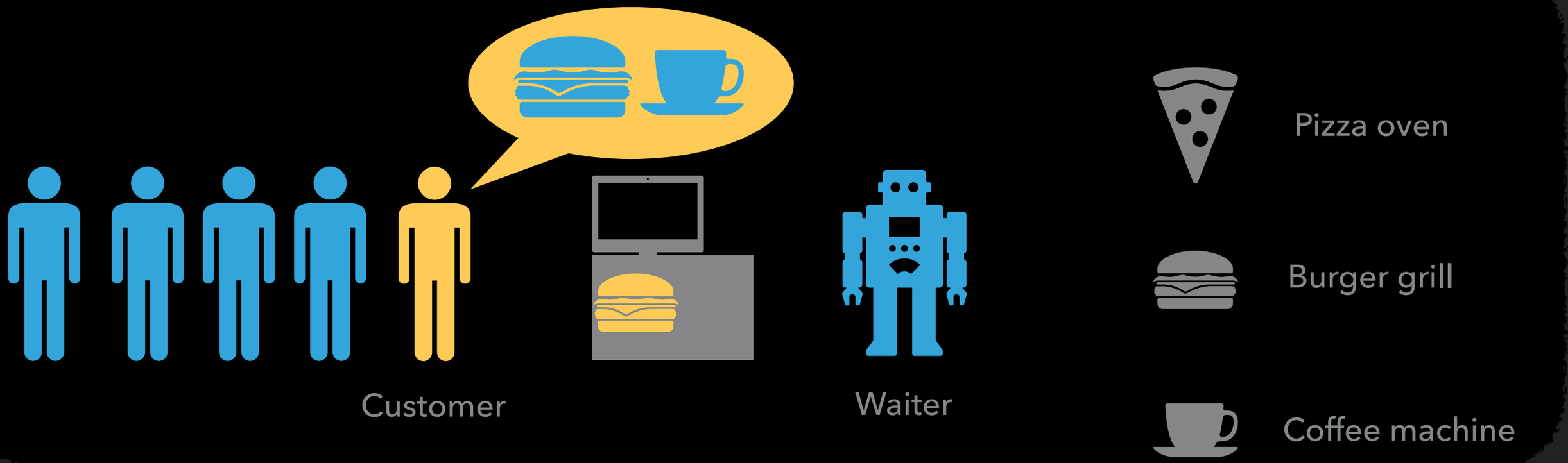
- Decode instruction into μOPs (“Burger”, “Coffee”)
- Schedule μOPs

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



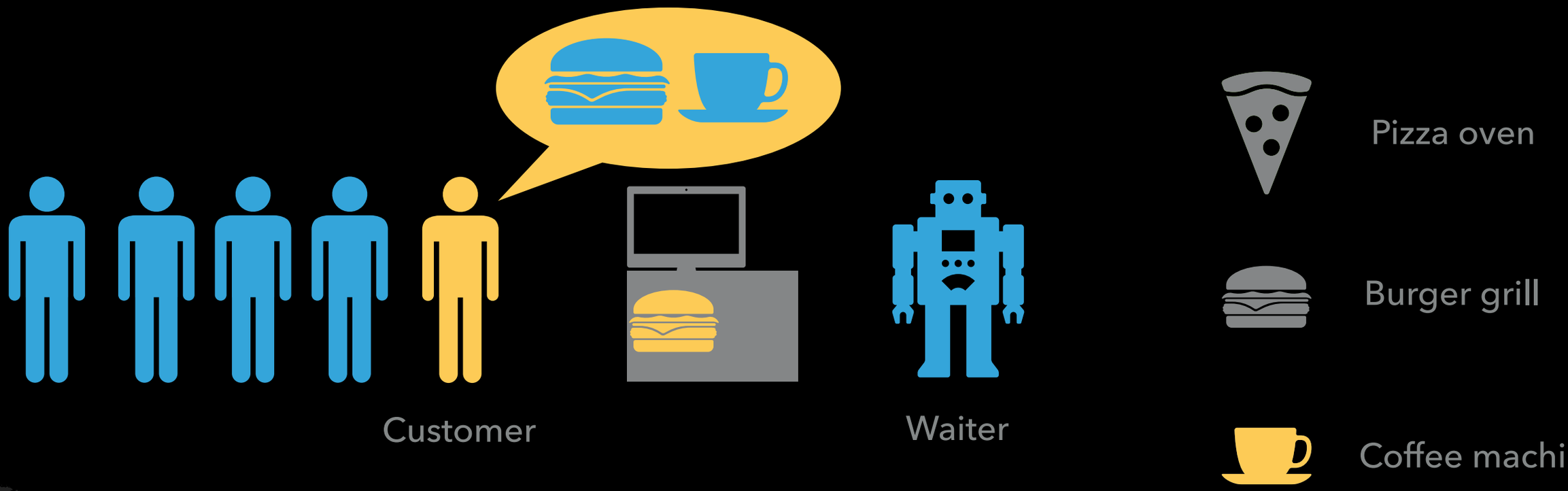
- Decode instruction into μOPs (“Burger”, “Coffee”)
- Schedule μOPs
  - run 1st μOP (grill the burger)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



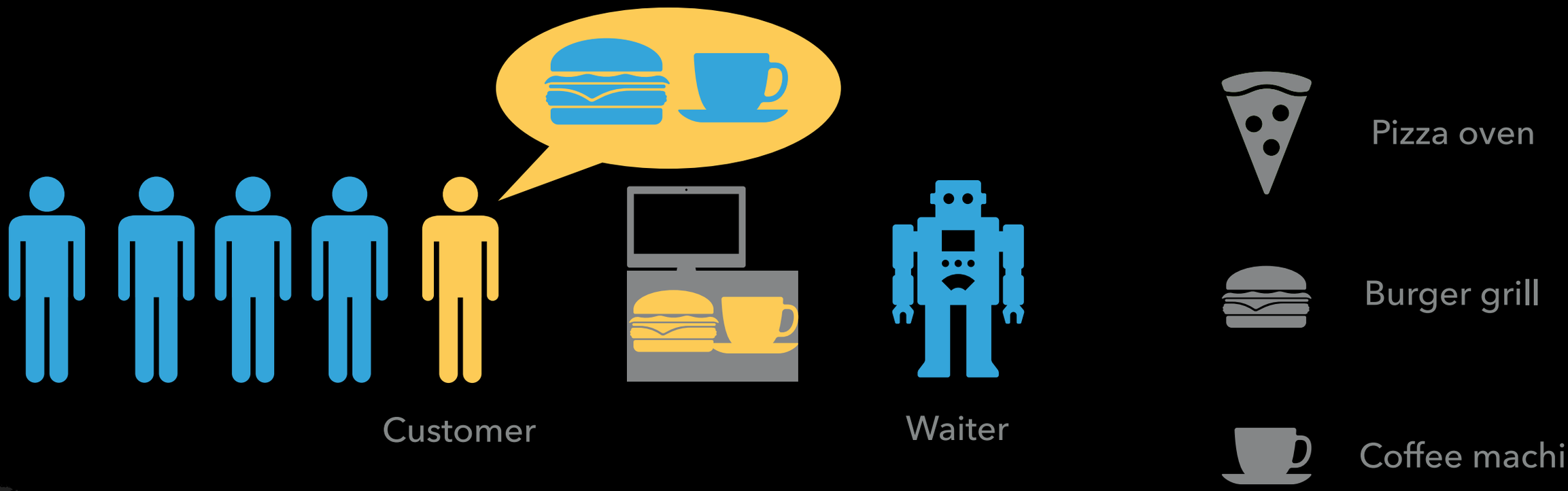
- Decode instruction into μOPs (“Burger”, “Coffee”)
- Schedule μOPs
  - run 1st μOP (grill the burger)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



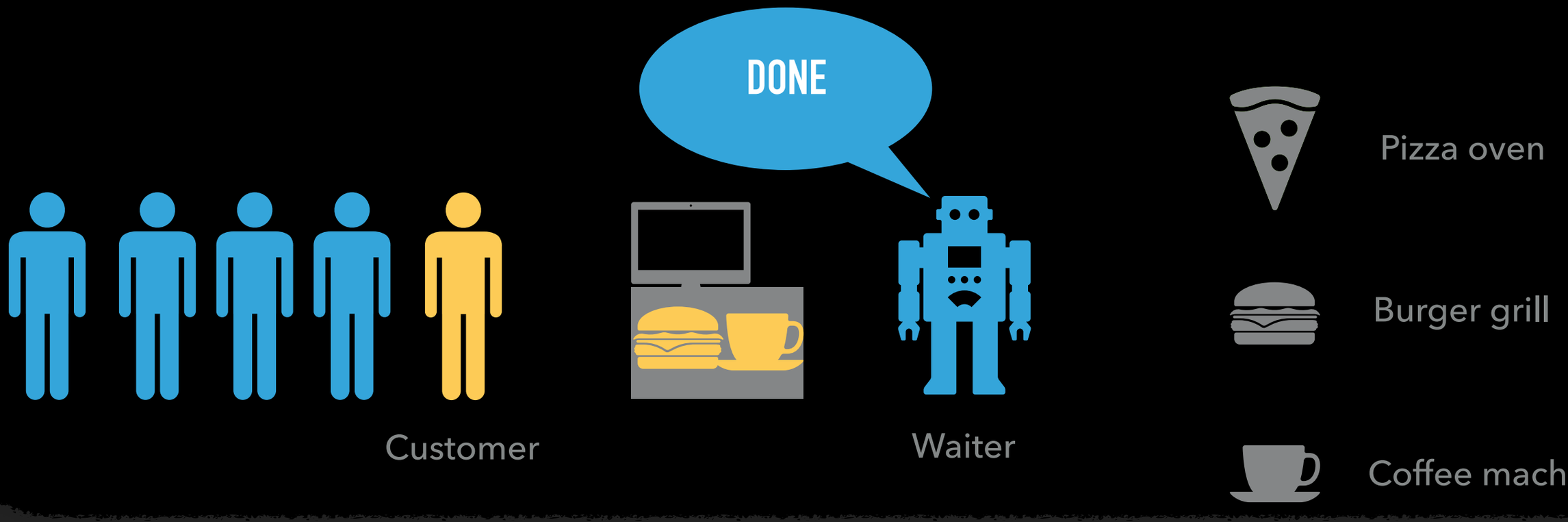
- Decode instruction into μOPs (“Burger”, “Coffee”)
- Schedule μOPs
  - run 1st μOP (grill the burger)
  - run 2nd μOP (brew coffee, serial execution)

CONFIDENTIAL BURGERS INC. : SERIAL, IN ORDER EXECUTION



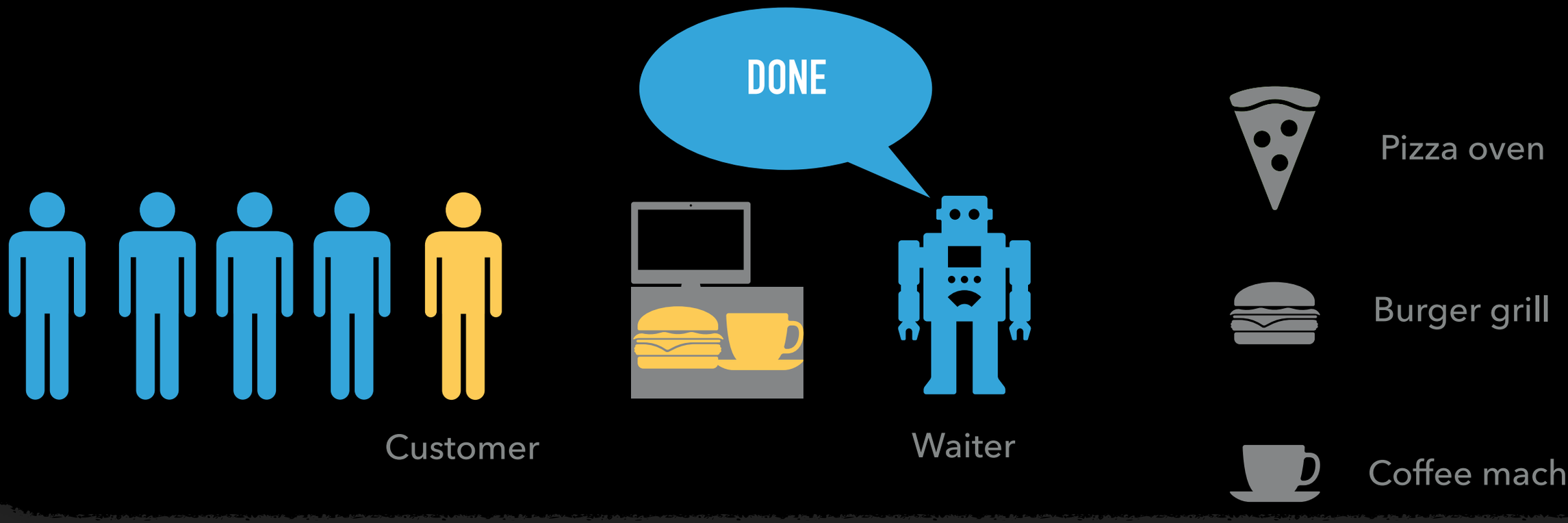
- Decode instruction into μOPs (“Burger”, “Coffee”)
- Schedule μOPs
  - run 1st μOP (grill the burger)
  - run 2nd μOP (brew coffee, serial execution)

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 customer[1] after another (**in order**)
- Each part of the order [2] executed **serially**

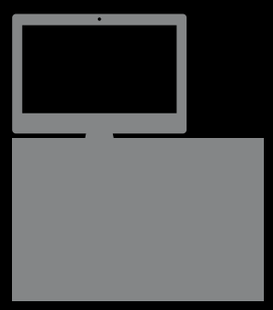
I.e. first the burger, then the coffee

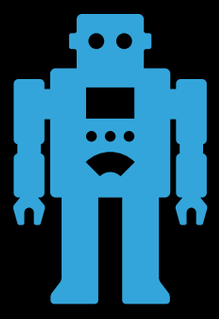
- PRO: Easy to implement and understand
- CON: Slow because resources[3] not utilised fully

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

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION

Customer





Waiter

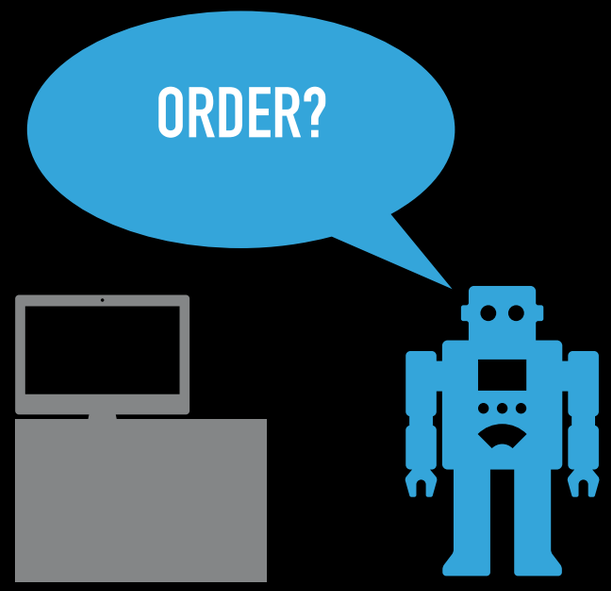
Pizza oven

Burger grill

Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION

Customer



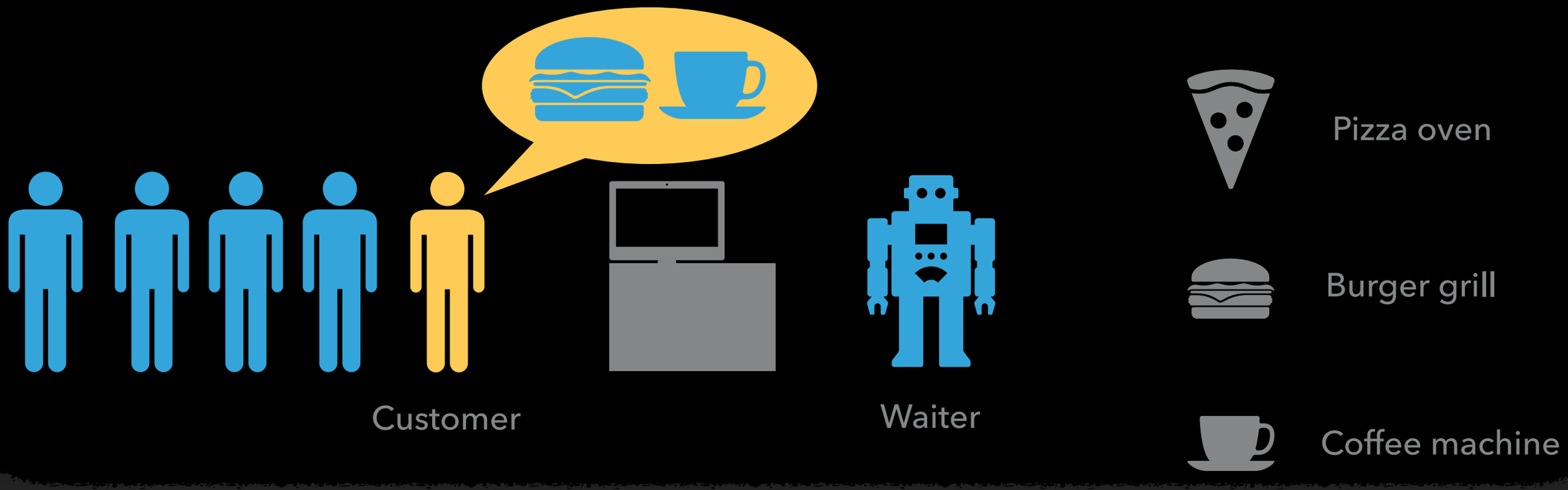
Waiter

Pizza oven

Burger grill

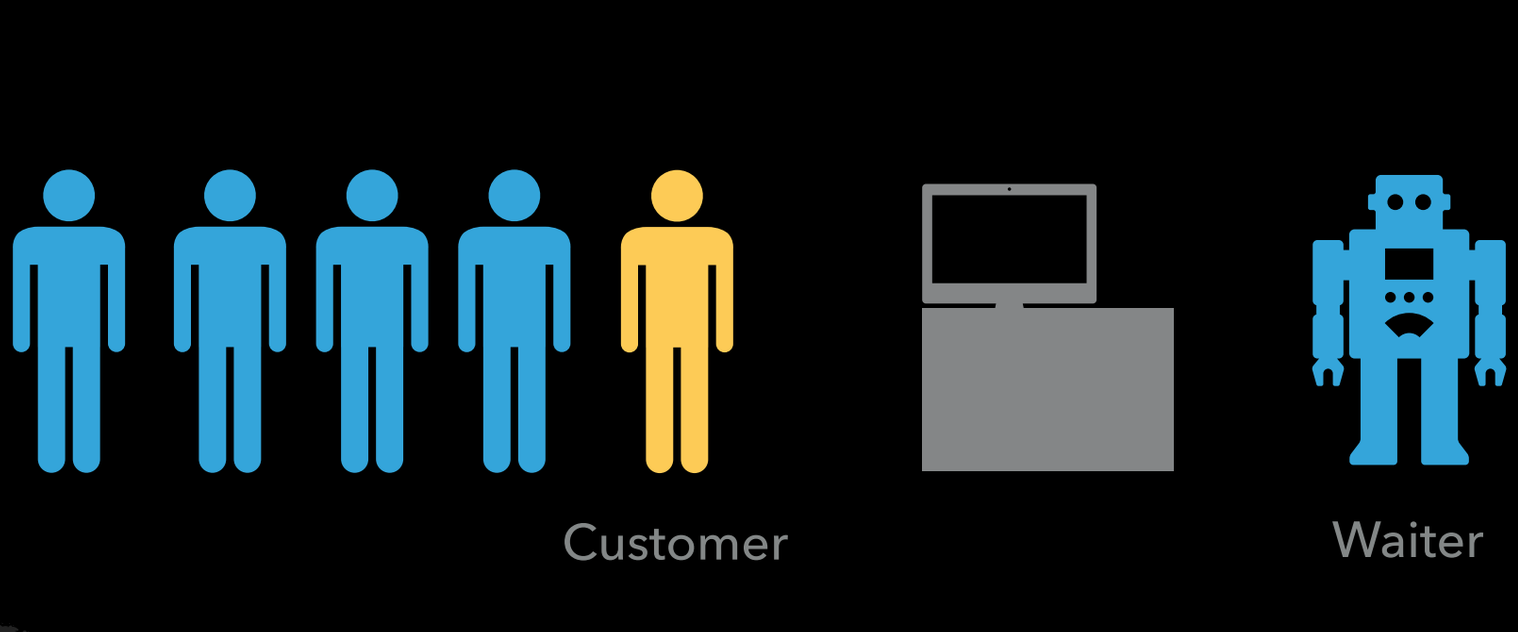
Coffee machine

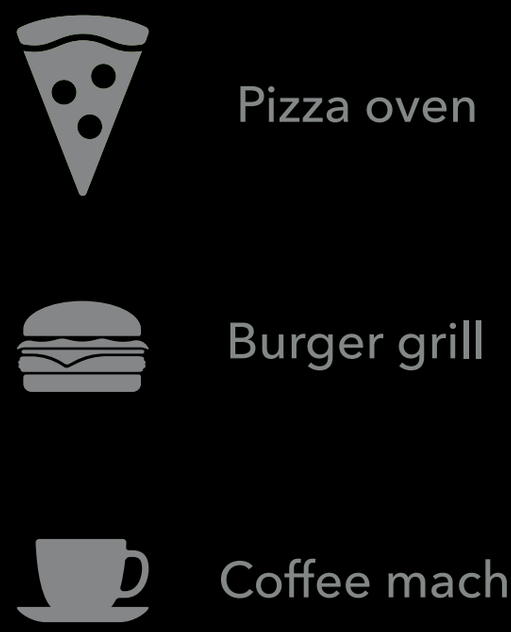
CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION



- Decode instruction into μOPs

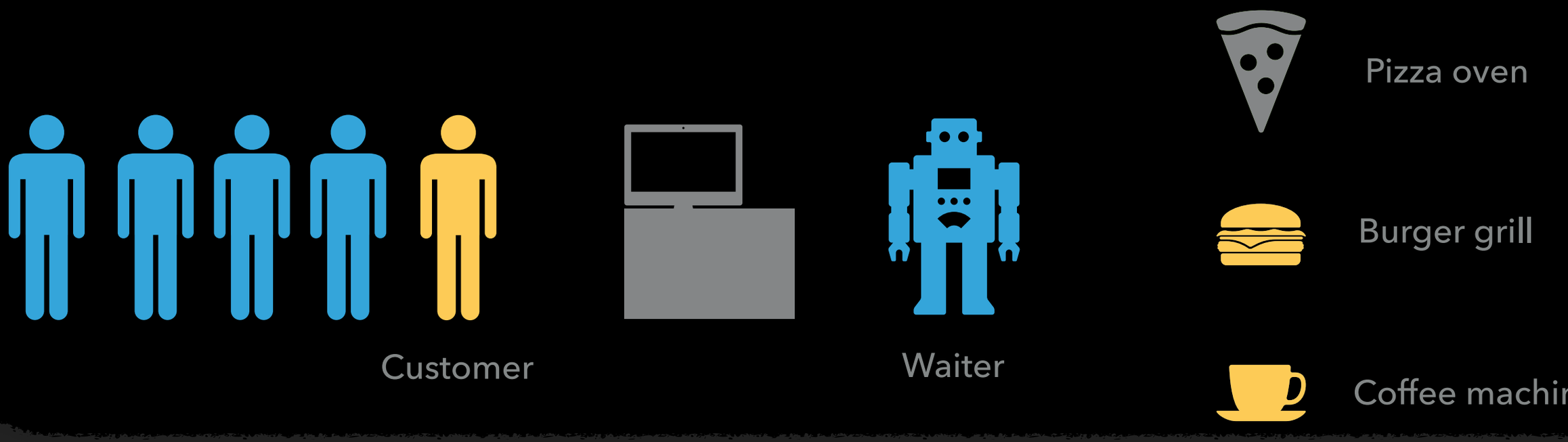
CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION





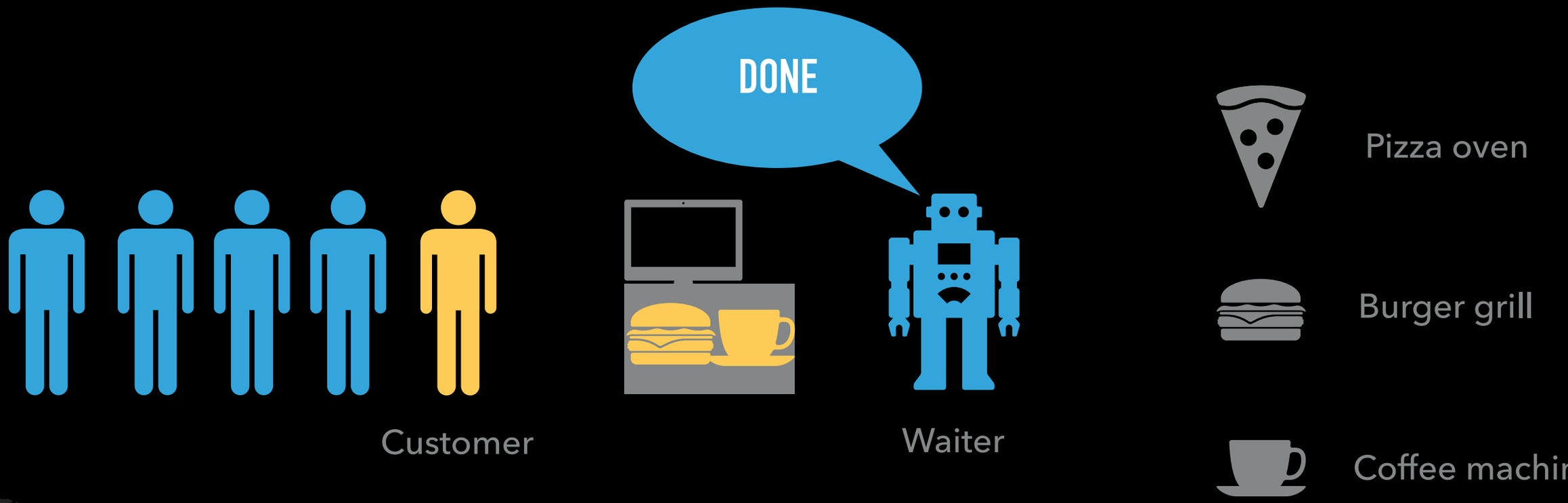
- Decode instruction into µOPs
- Schedule µOPs

CONFIDENTIAL BURGERS INC. : PARALLEL, IN ORDER EXECUTION



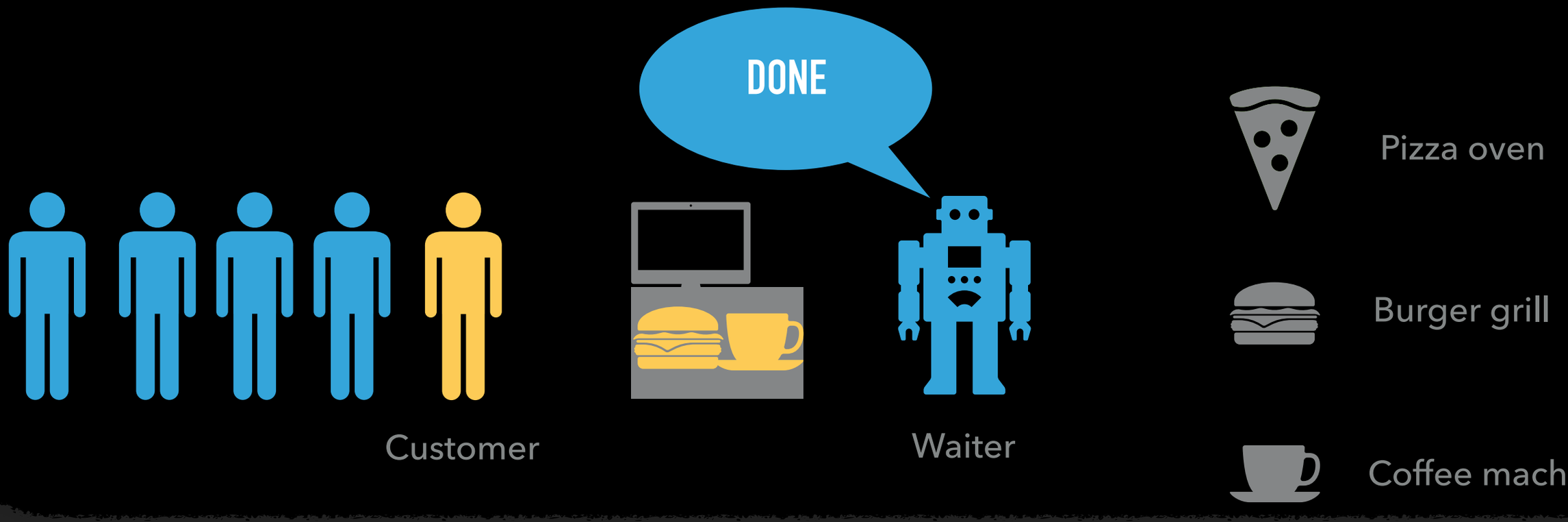
- Decode instruction into μOPs
- Schedule μOPs
  - run 1st μOP and 2nd μOP (parallel execution of μOPs)

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

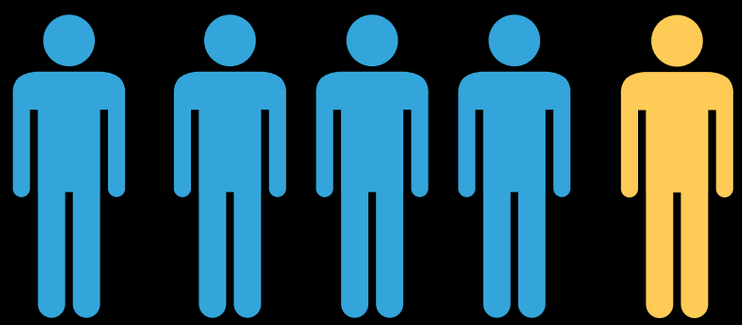


- One customer[1] after another (**in order**)
- Each part of the order [2] executed **in parallel**

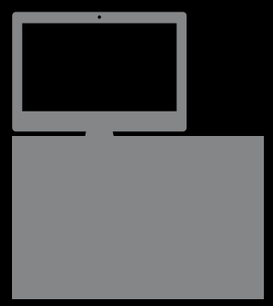
I.e. burger and coffee prepared at the same time

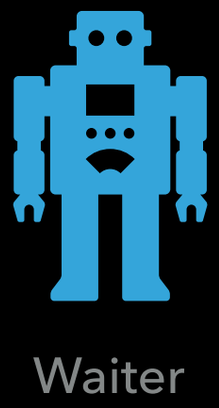
- PRO: **Faster bc. of better resource utilisation.**
- CON: Still not perfect, more complex

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



Customer





Waiter

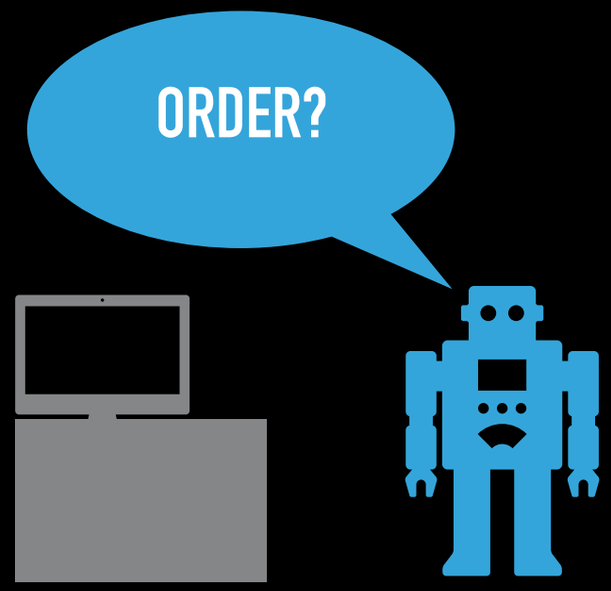
Pizza oven

Burger grill

Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION

Customer



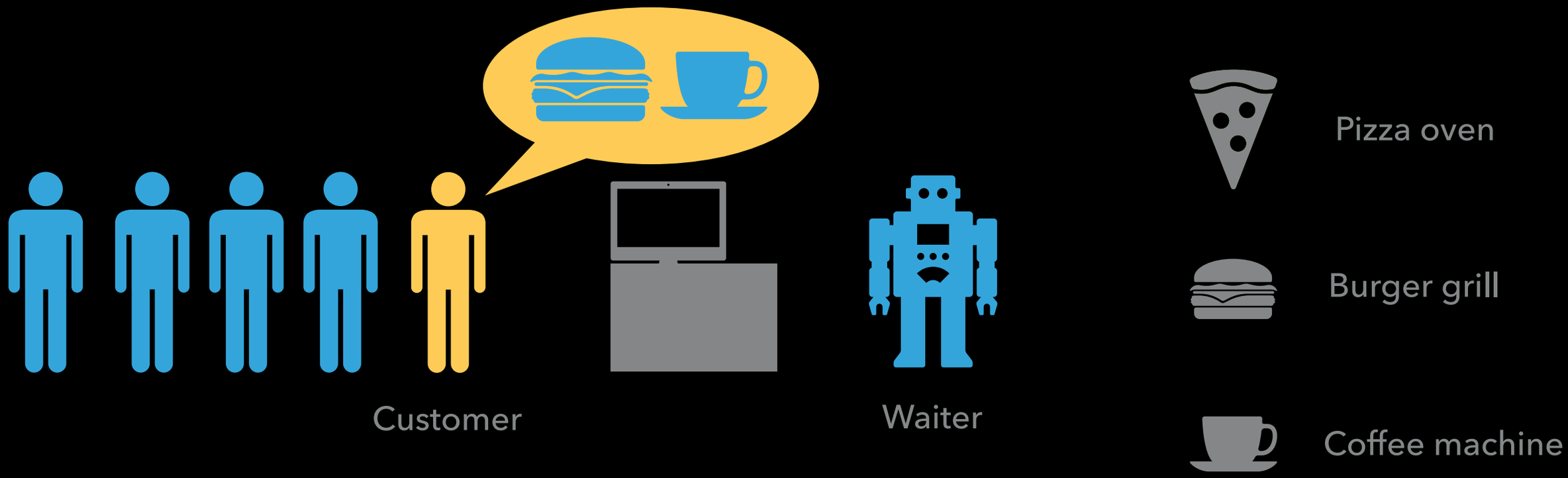
Waiter

Pizza oven

Burger grill

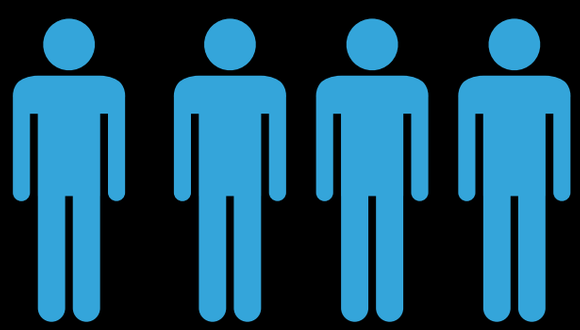
Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION

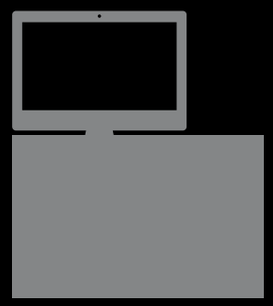


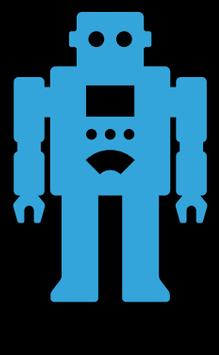
CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



Customer





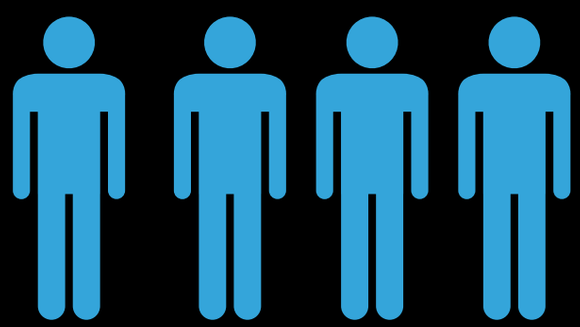
Waiter

Pizza oven

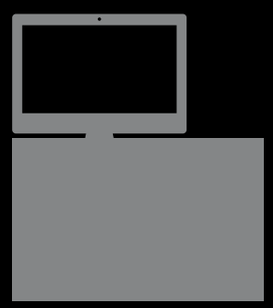
Burger grill

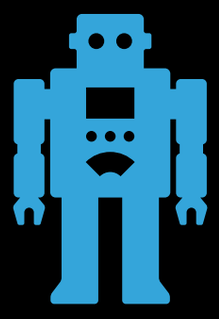
Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



Customer





Waiter

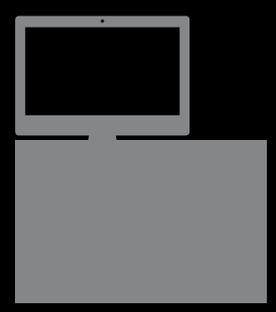
Pizza oven

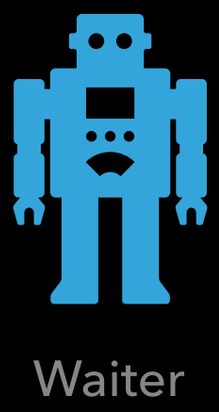
Burger grill

Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION

Customer





Waiter

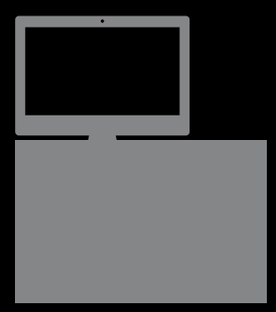
Pizza oven

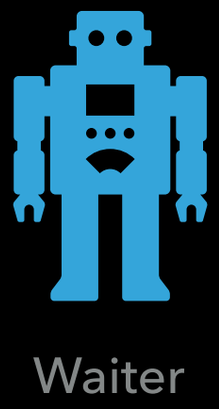
Burger grill

Coffee machine

CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION

Customer





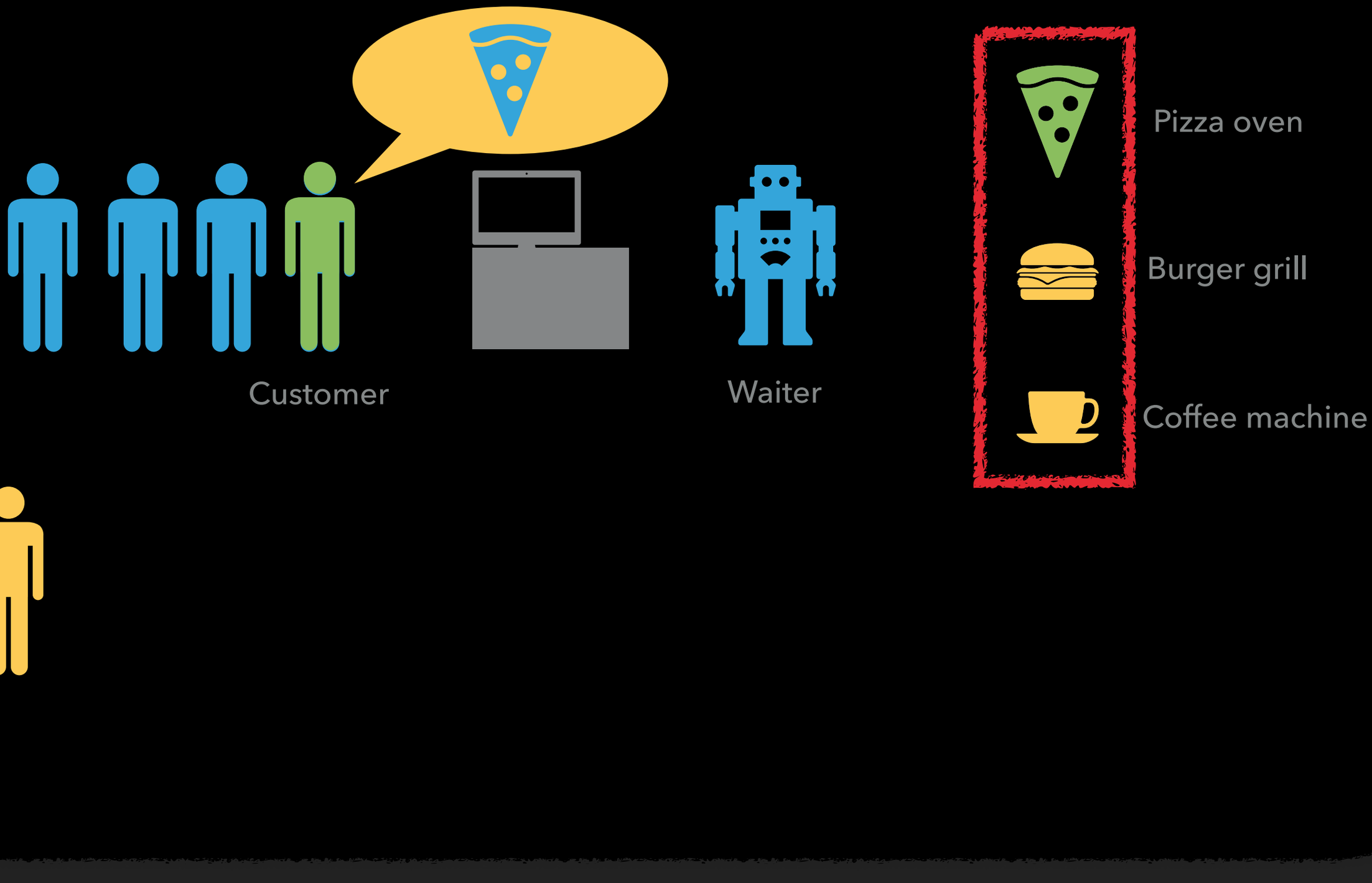
Waiter

Pizza oven

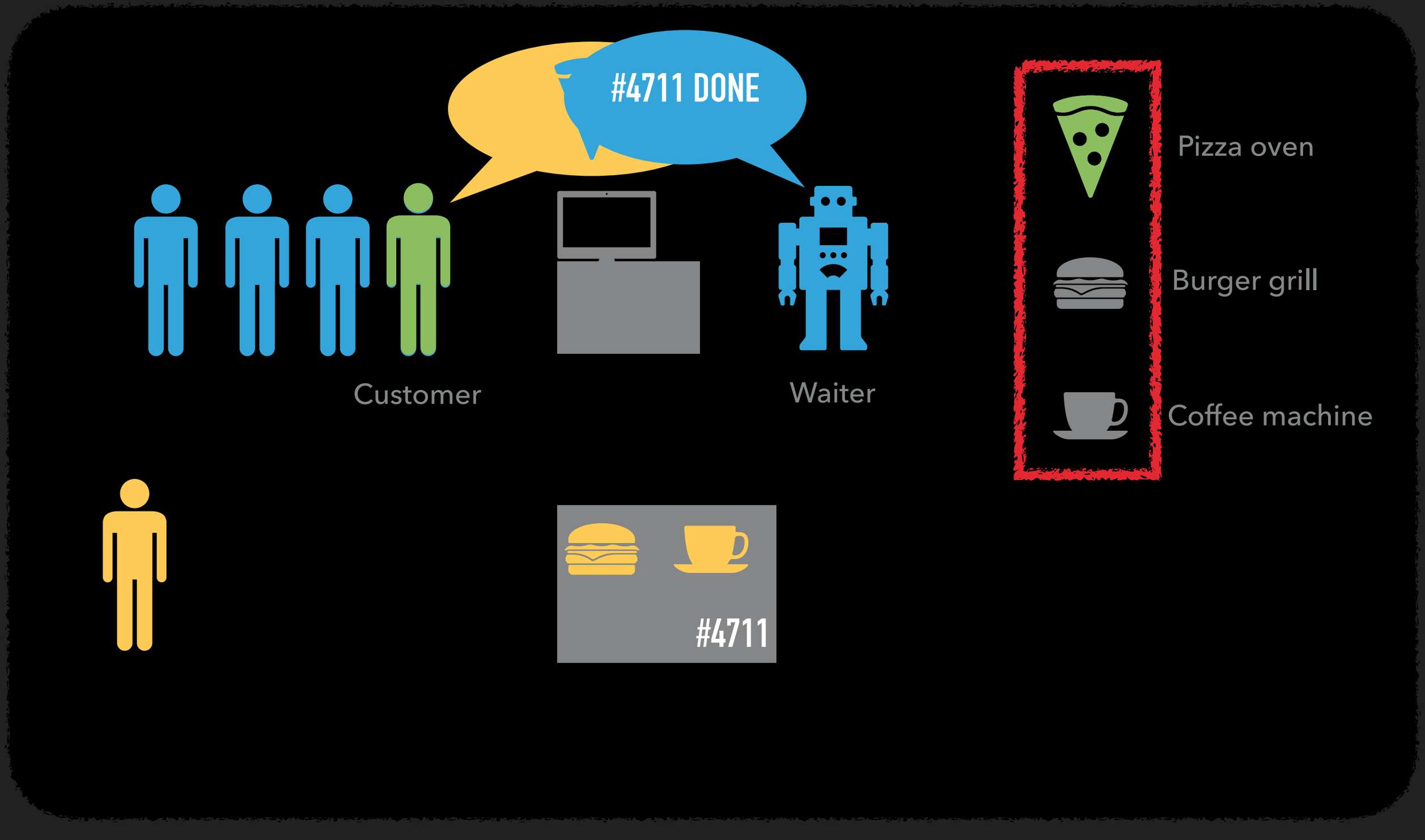
Burger grill

Coffee machine

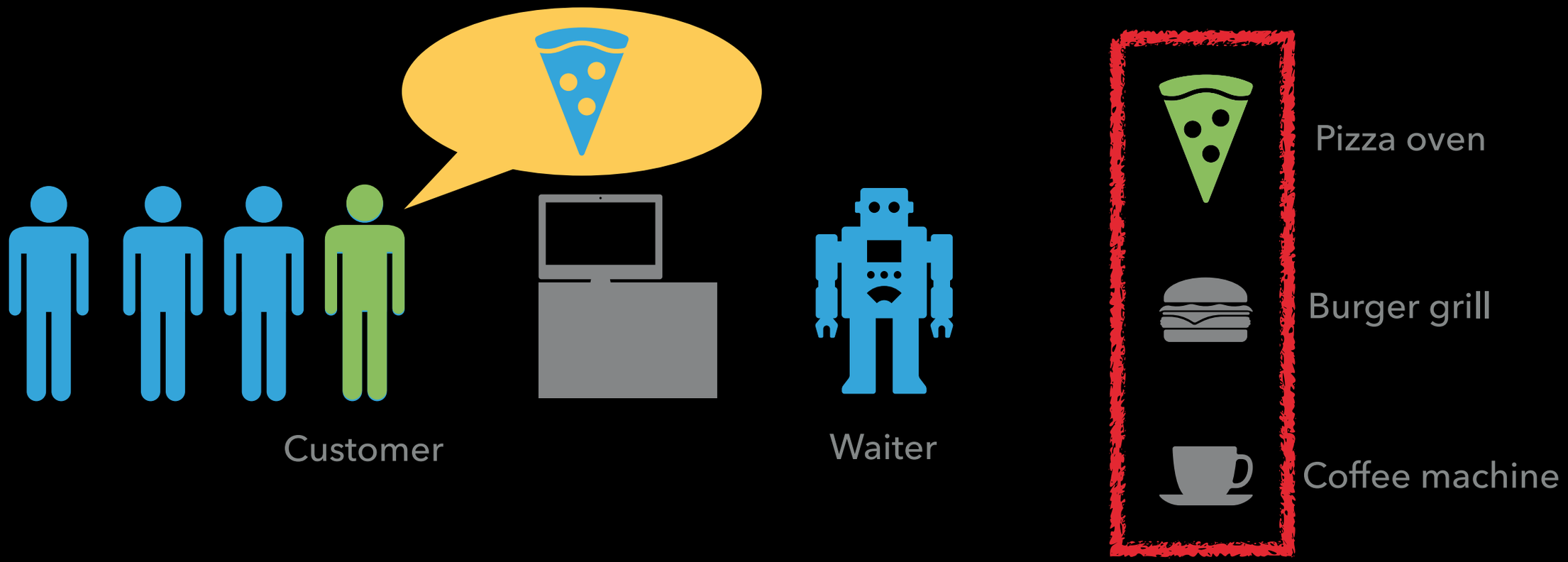
CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



CONFIDENTIAL BURGERS INC. : PARALLEL, OUT OF ORDER EXECUTION



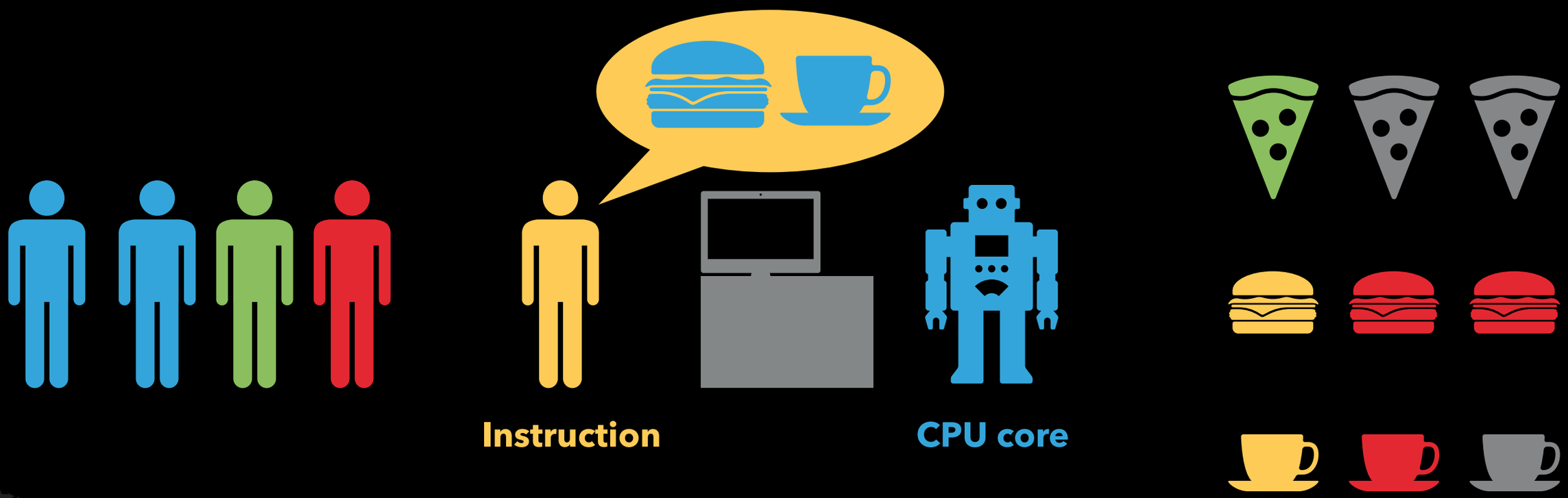
- Multiple customers' orders **executed in parallel**[1] and **delivered** (retired) **in order**

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*

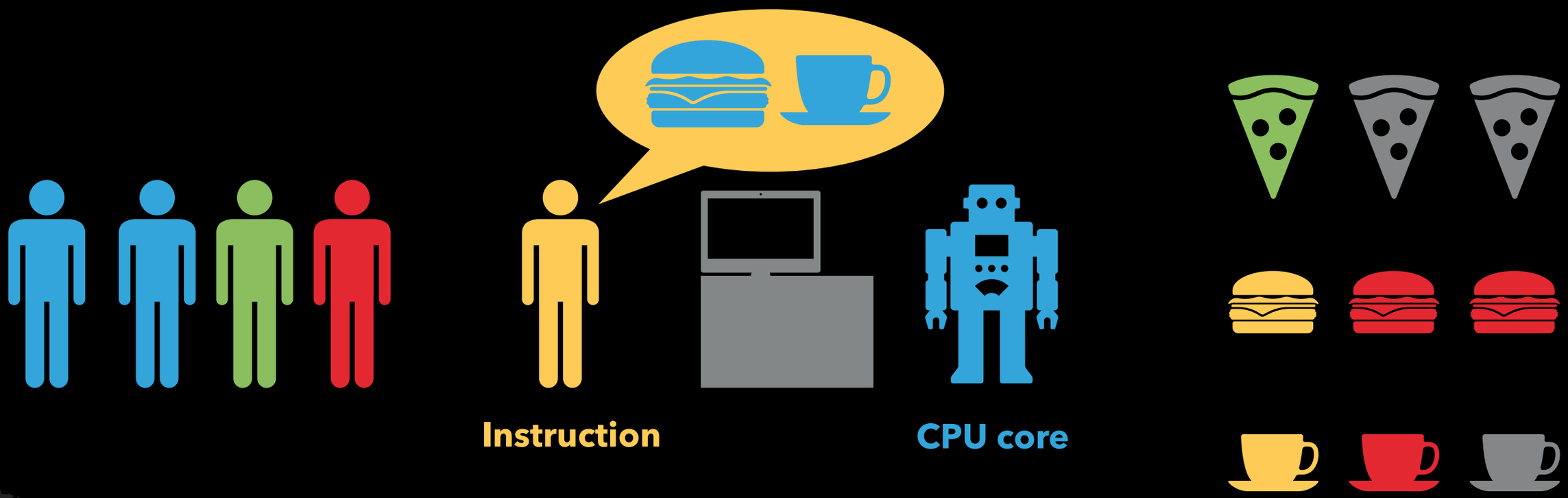
CONFIDENTIAL BURGERS INC.



Adding more resources increase parallelism & throughput.

This is all on one CPU core.

CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT

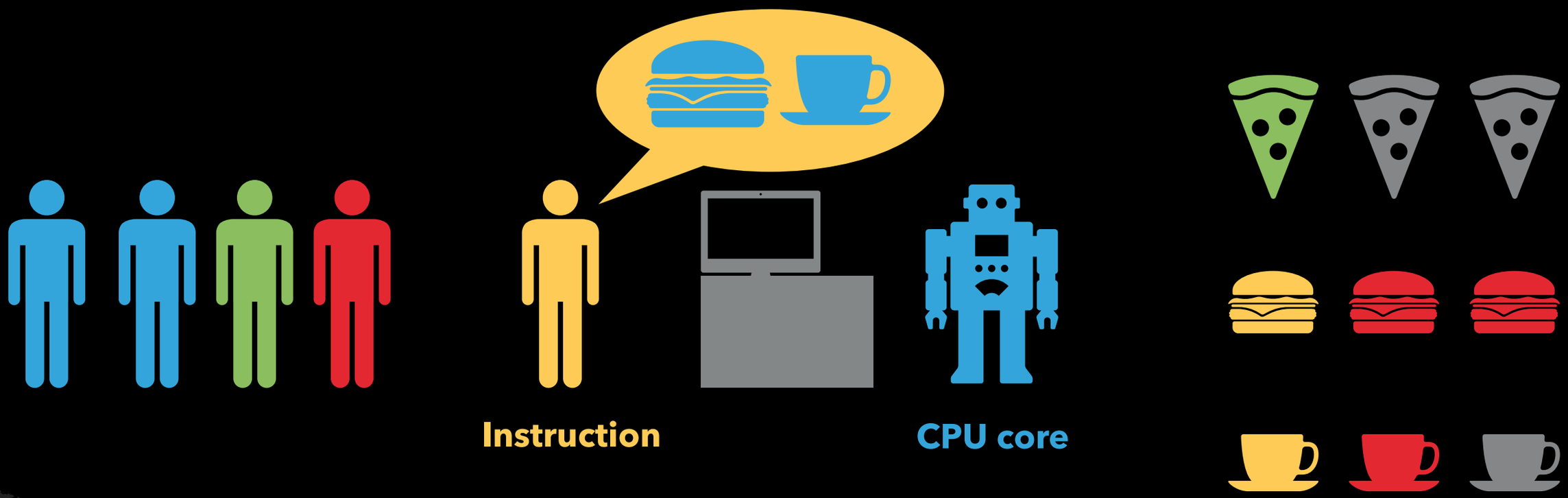


The green instruction will finish before the red instruction.

The CPU ensures that red is seen before green.

Actual µOP execution order

CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT



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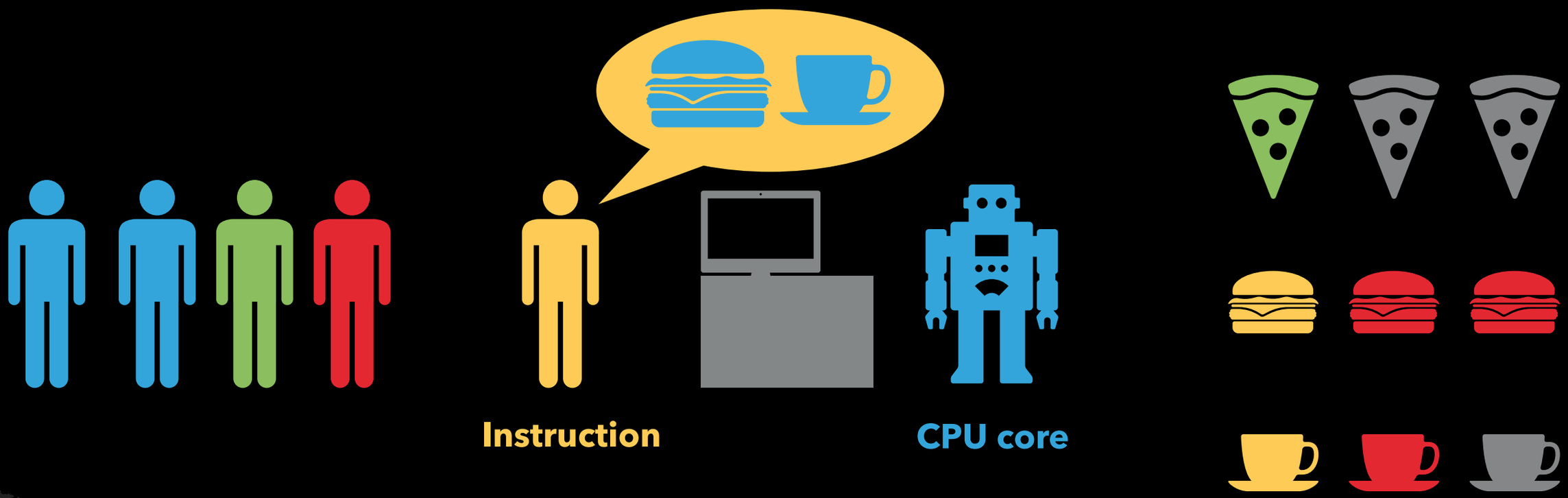

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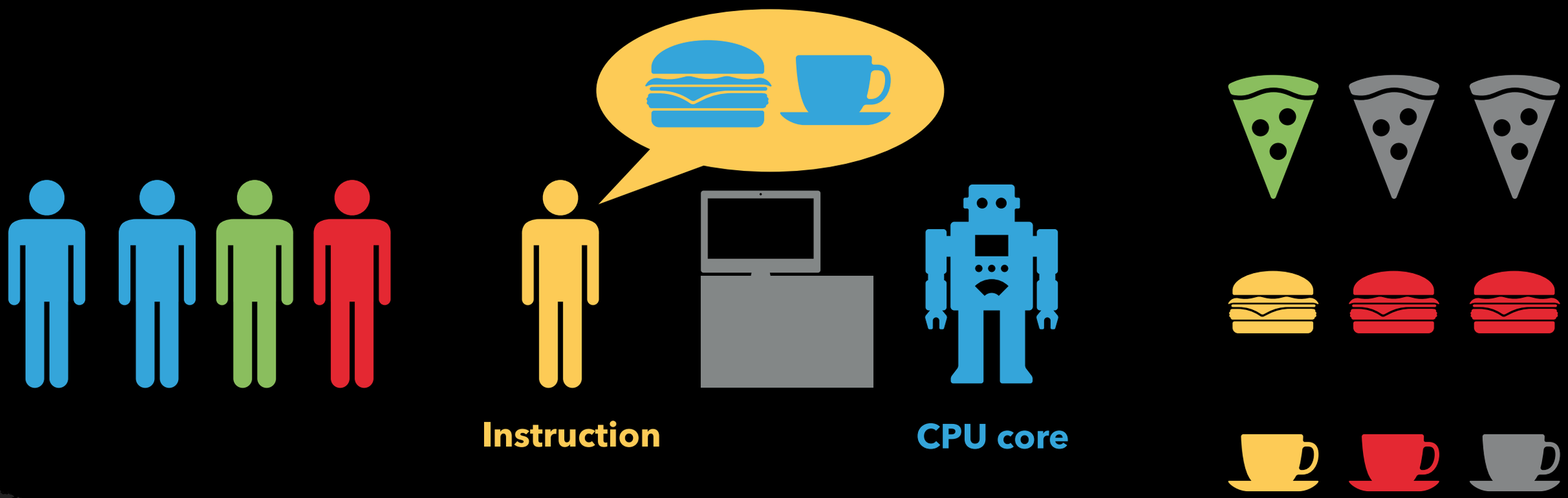

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Actual µOP execution order

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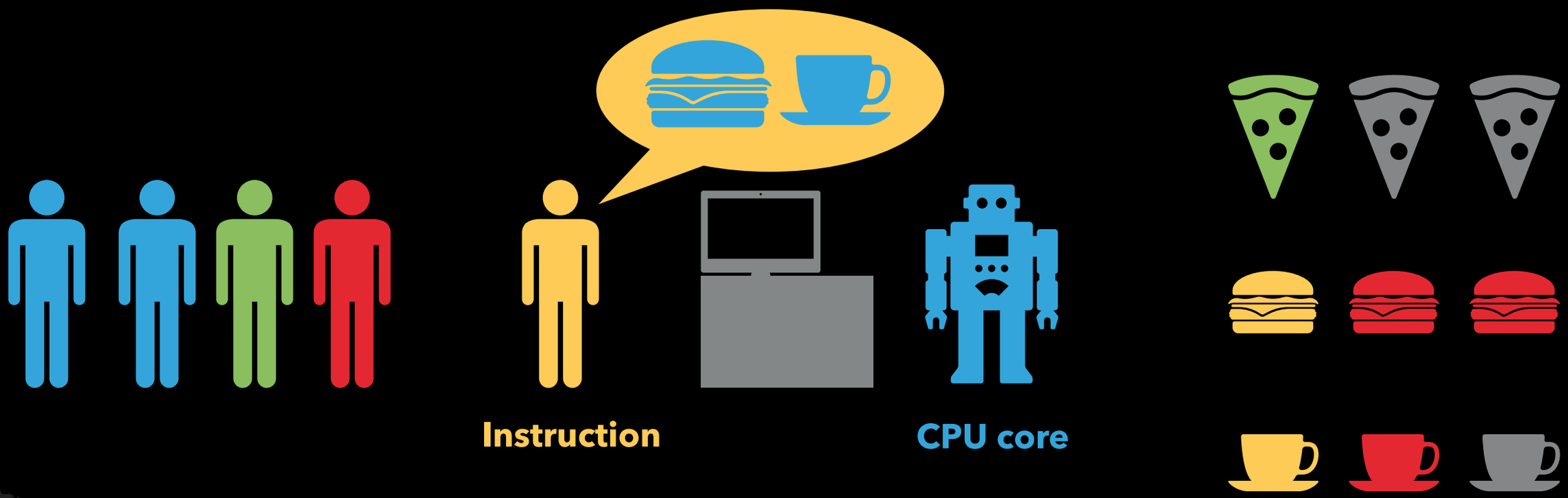

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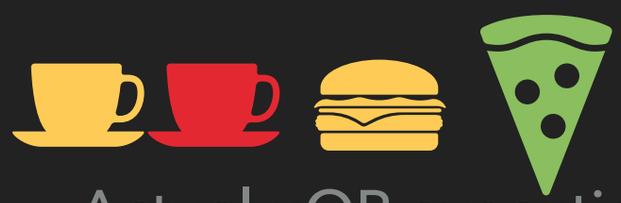
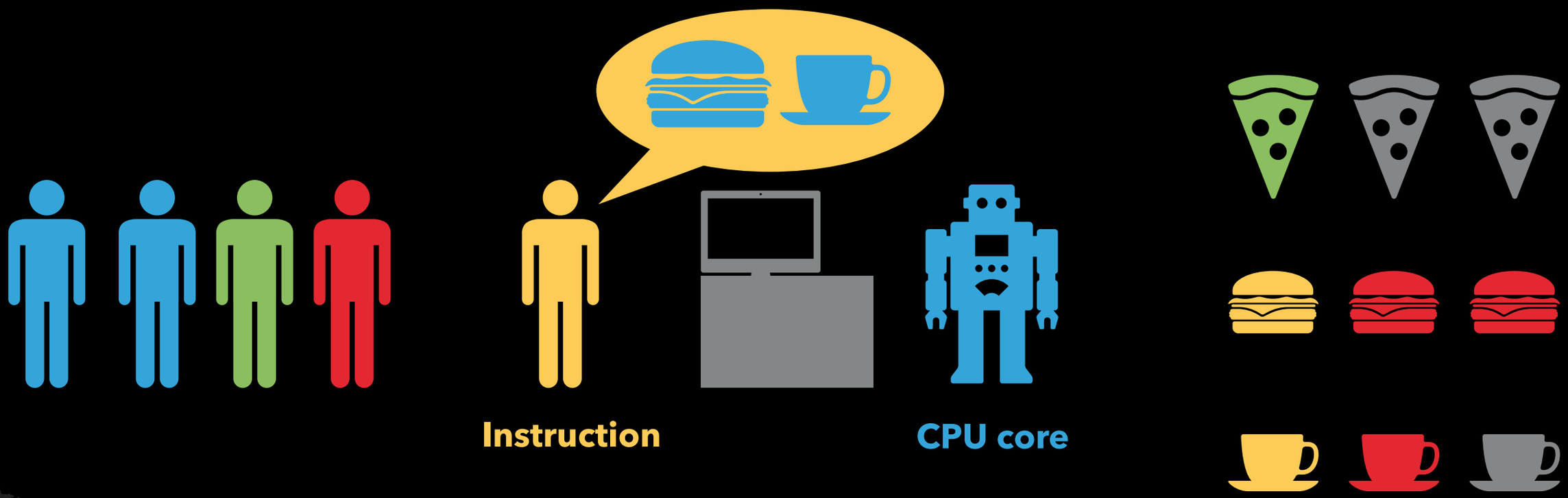


Actual µOP execution order

CONFIDENTIAL BURGERS INC. : ORDER IS IMPORTANT



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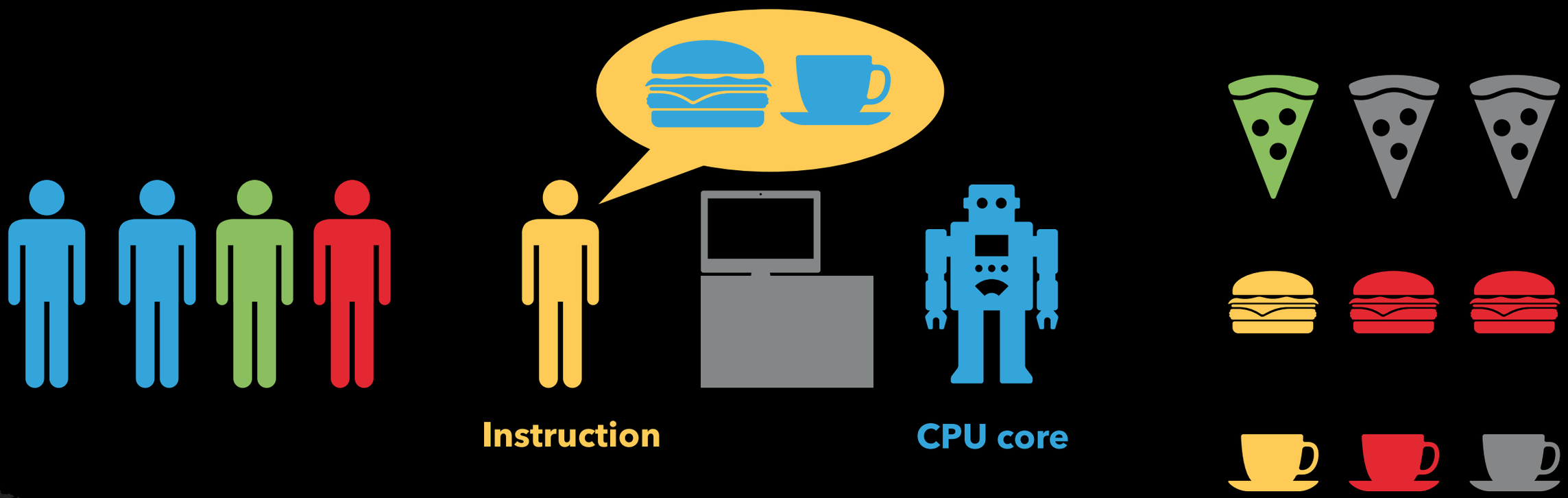

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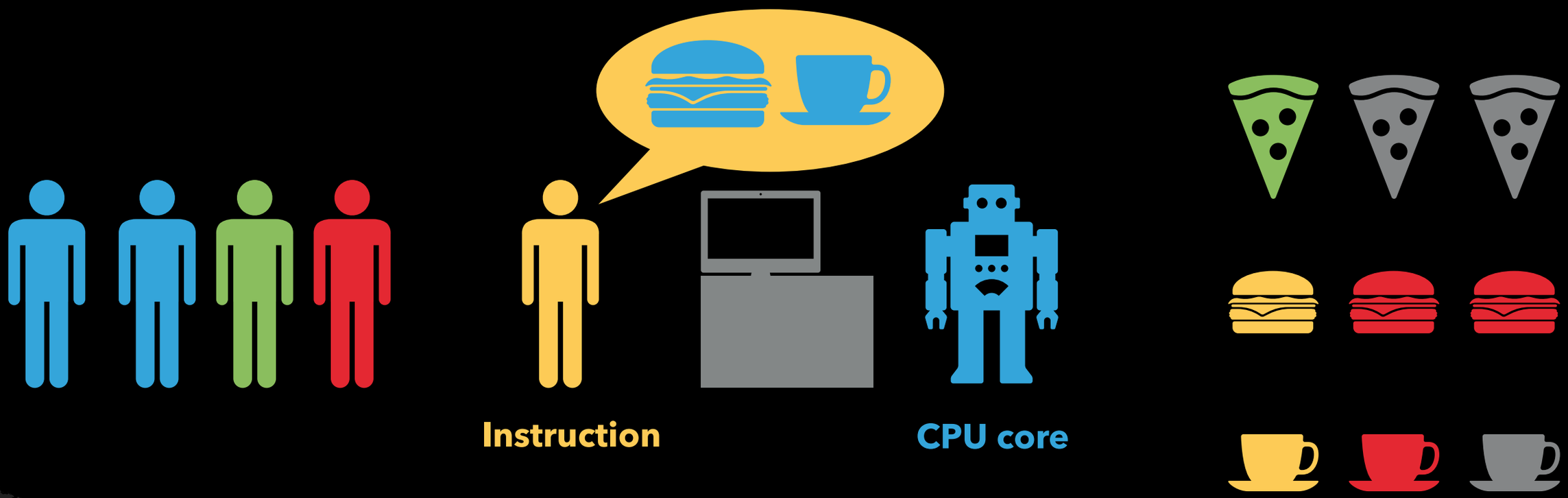

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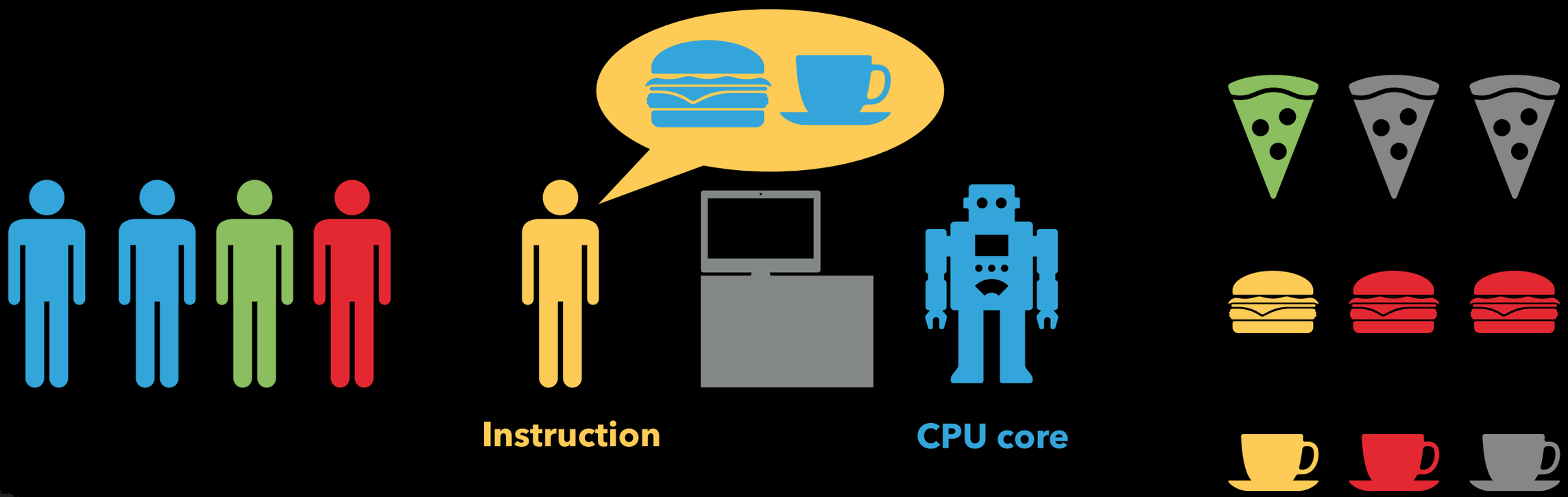

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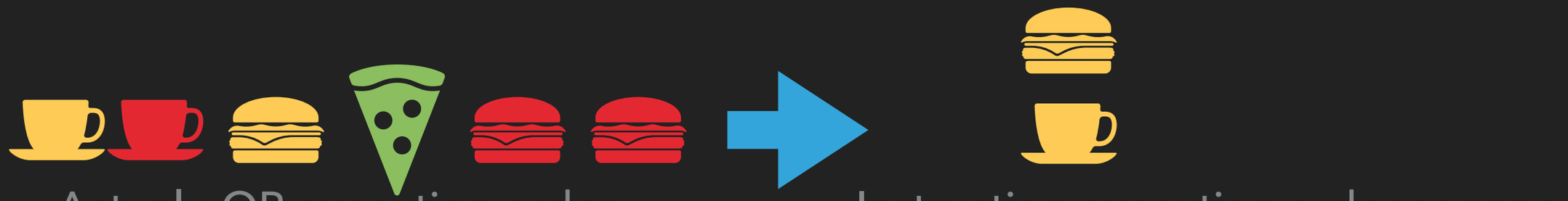

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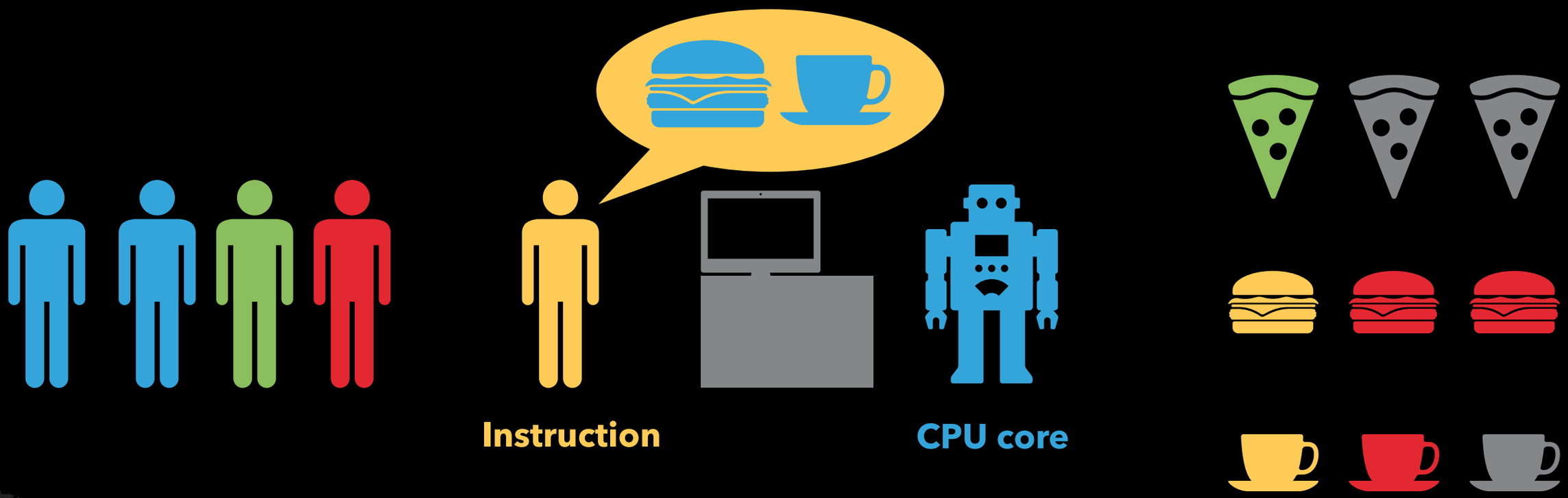

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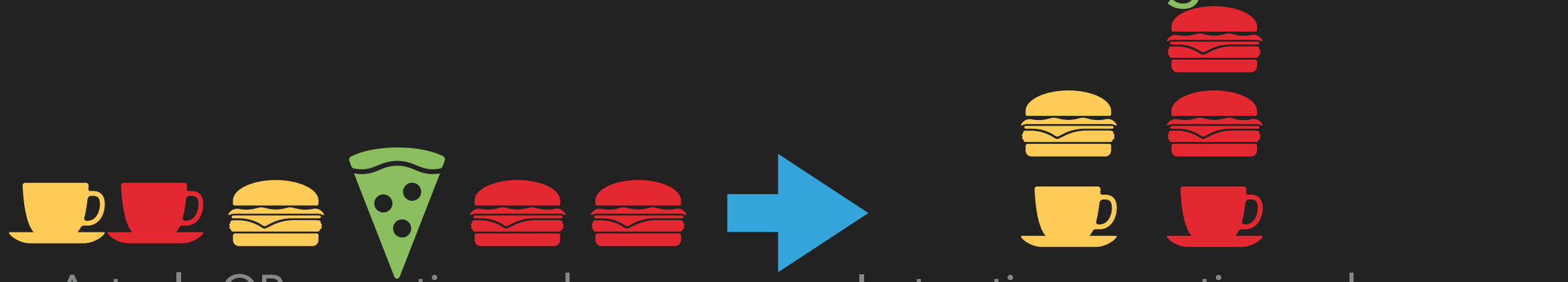

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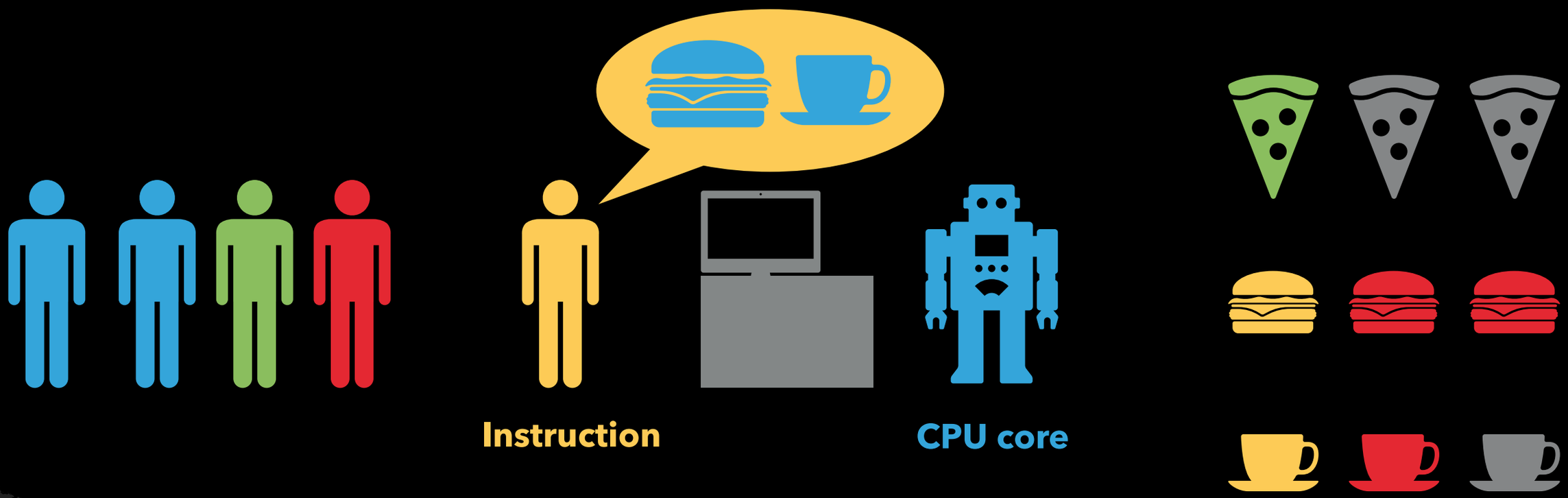

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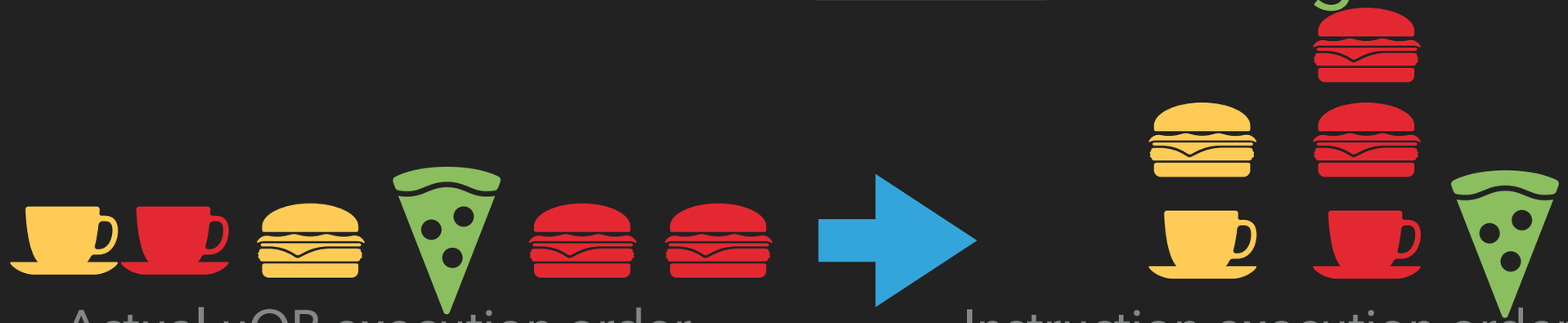

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...

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

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

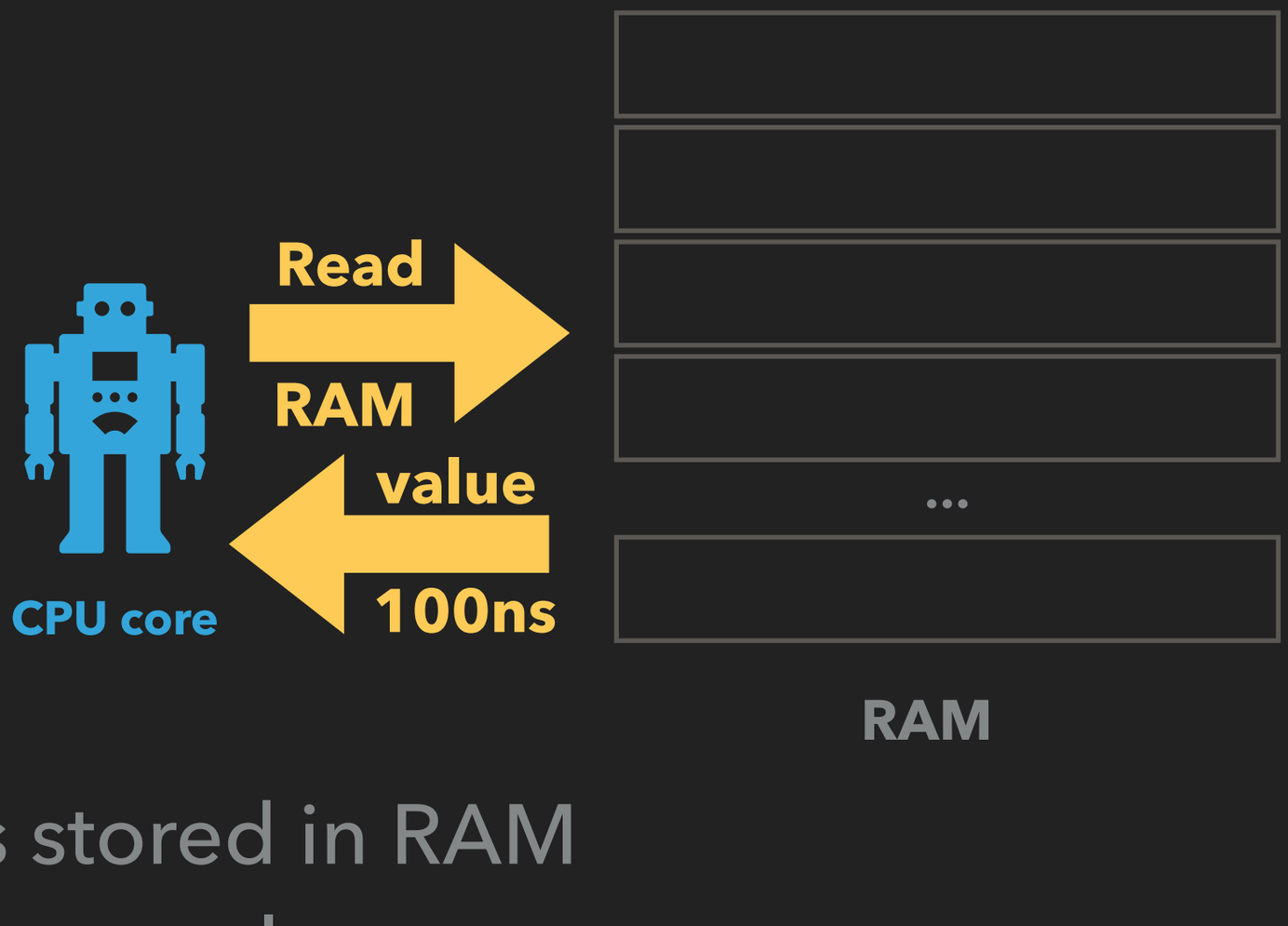
MELTDOWN

"Stashing" and "retrieving" the secret works via *side channels*.

Side channels are *observable side effects* of actions.

- READ secret from forbidden address
- Stash away secret by caching a memory location that depends on the secret
- Retrieve secret by finding which memory location is cached

MELTDOWN: STASHING AWAY – SIDECHANNEL



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- RAM is very slow
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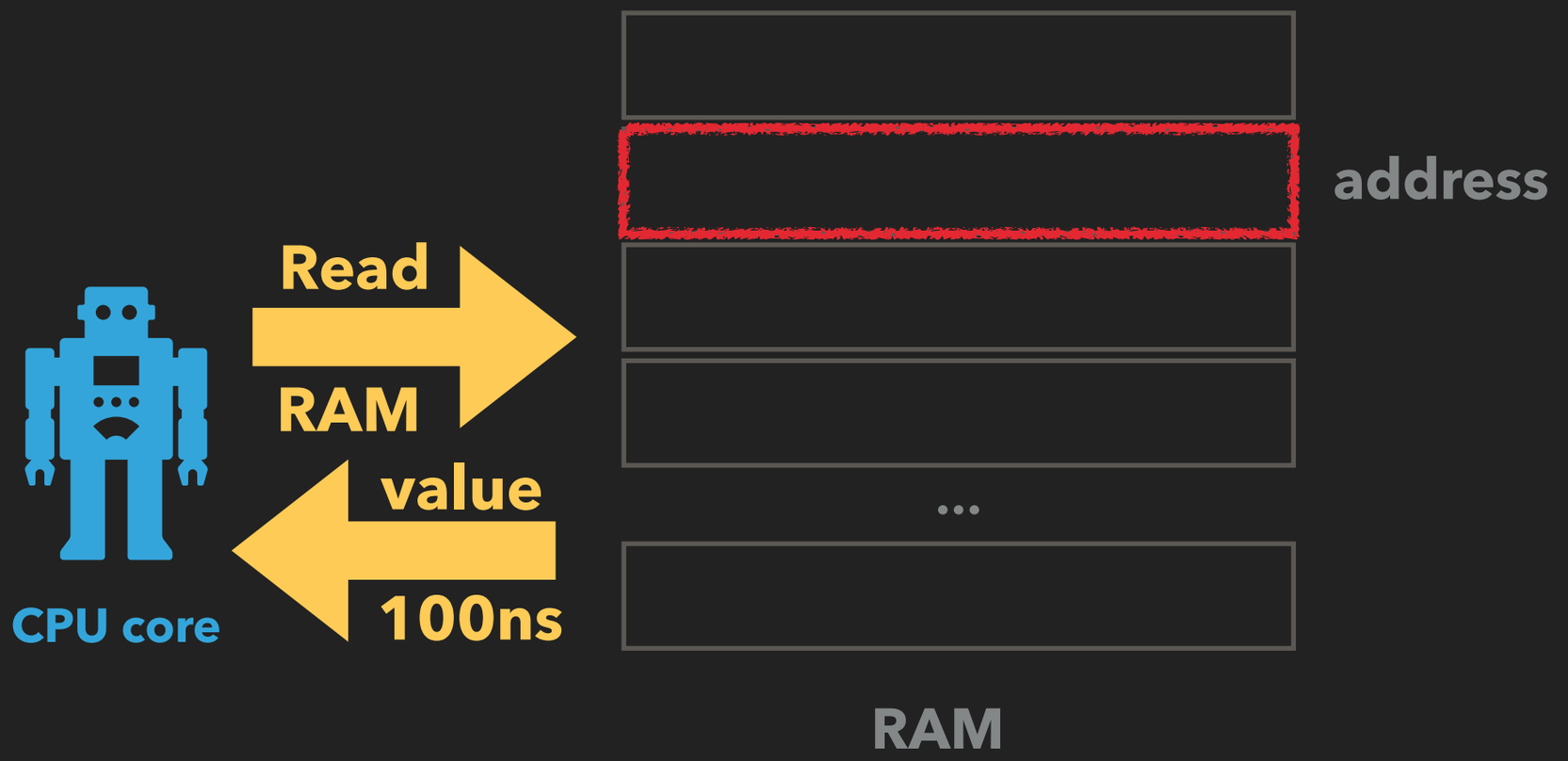

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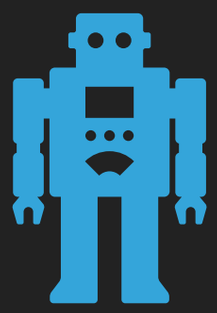
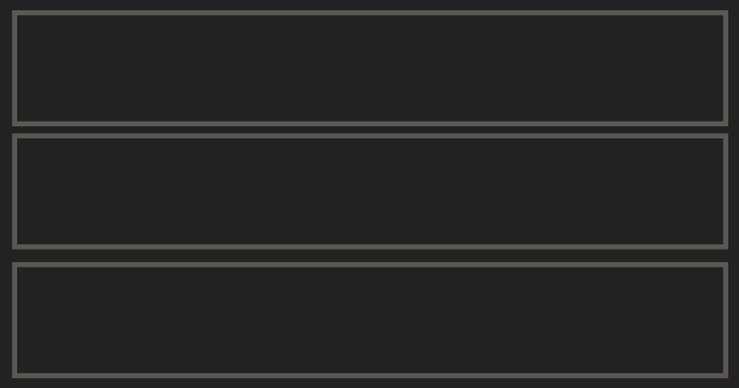
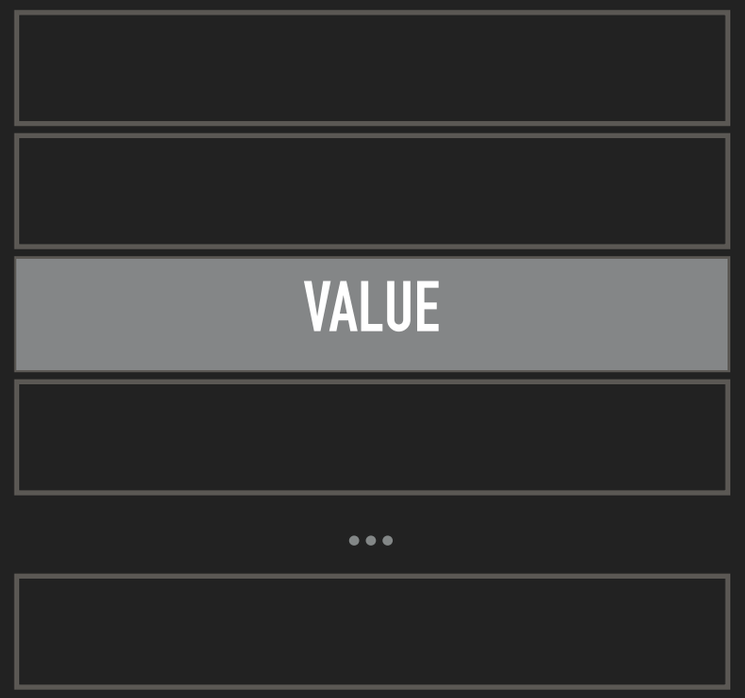


CPU core



Cache



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- 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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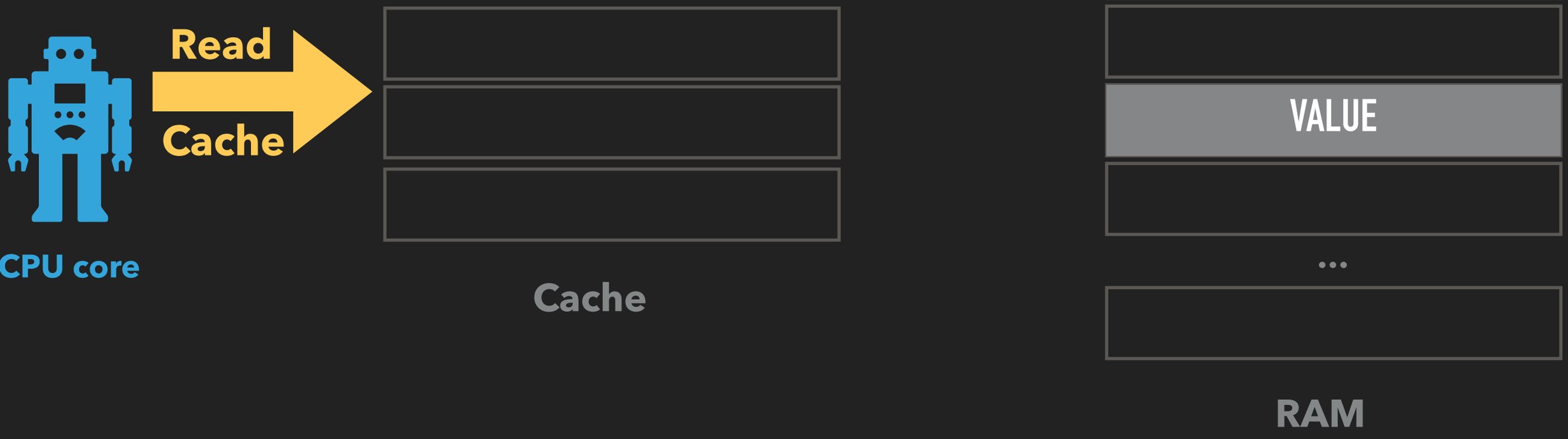

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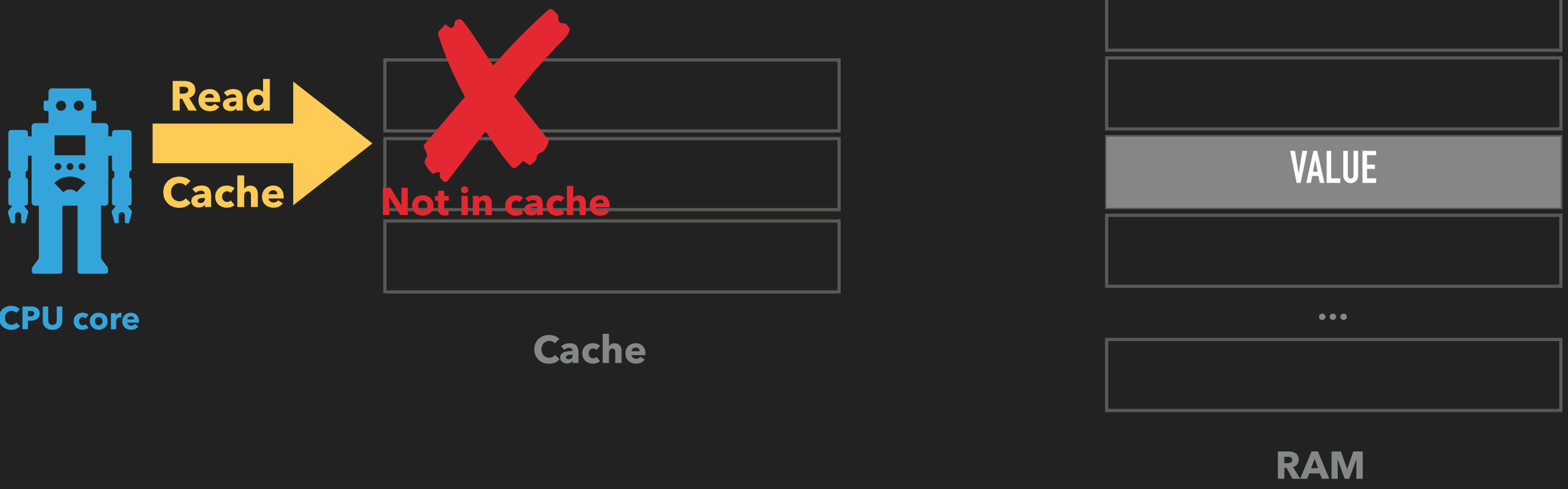

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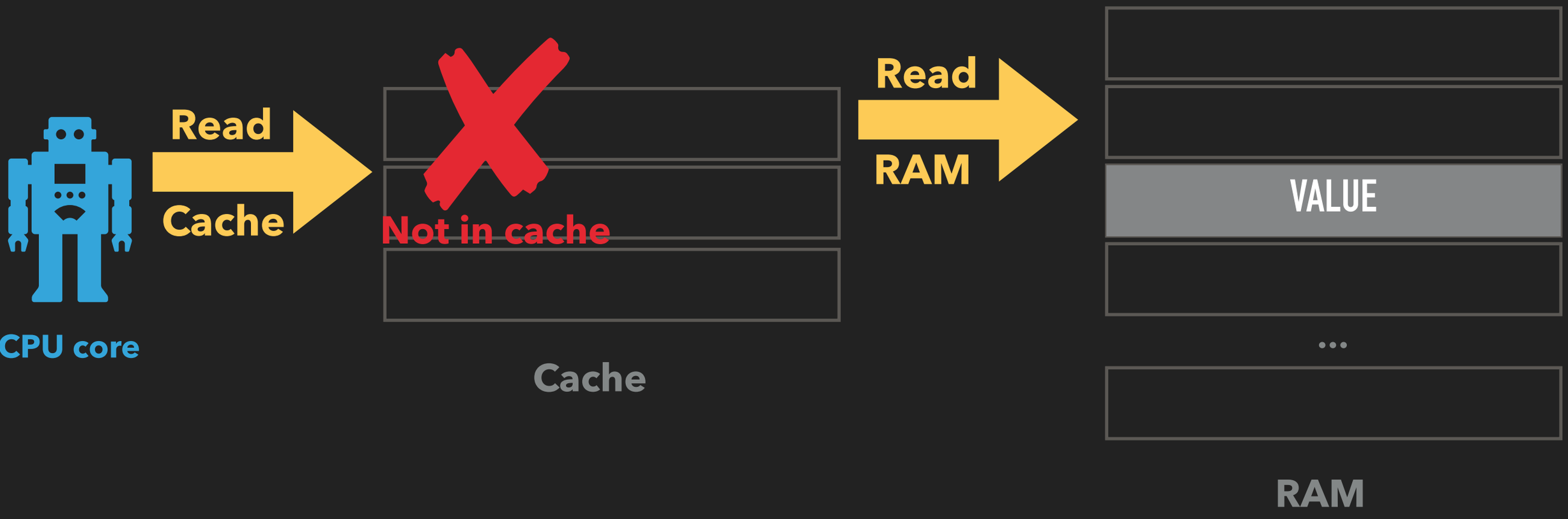

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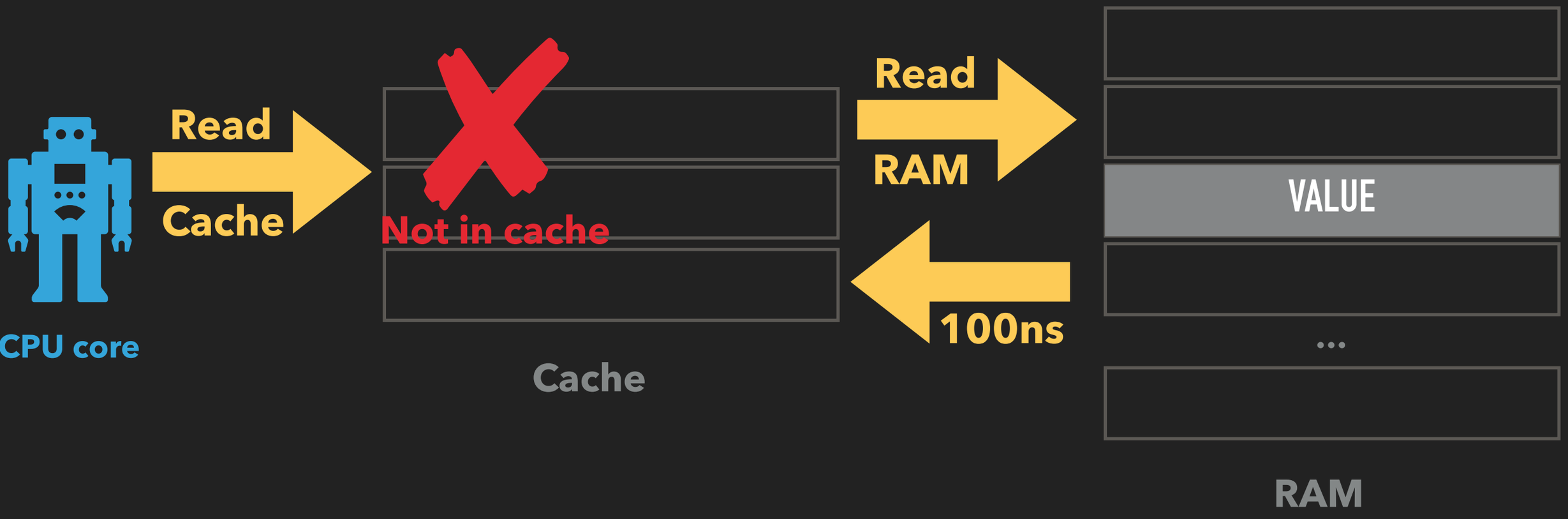

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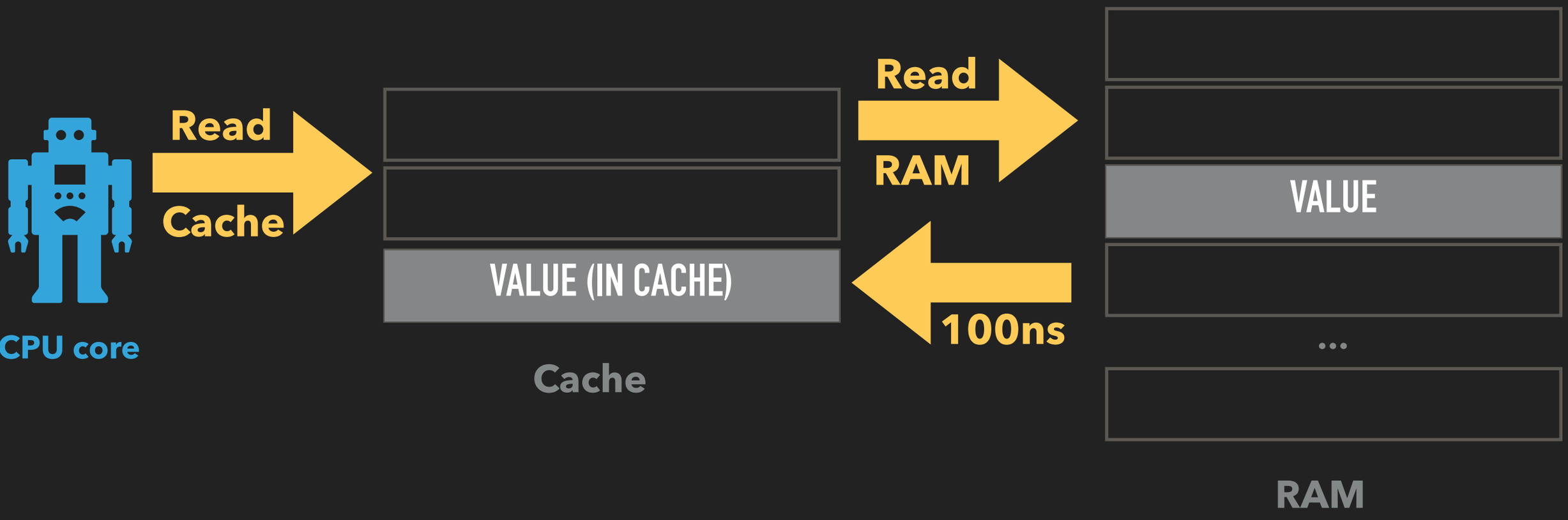

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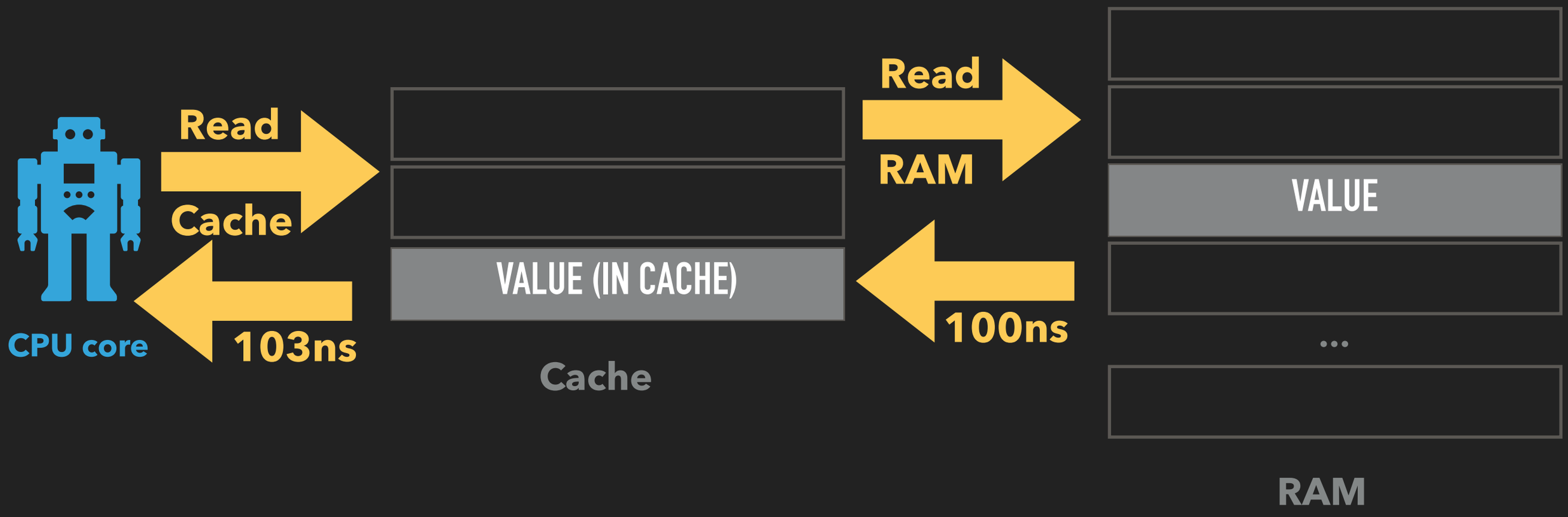

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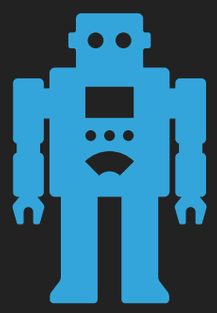

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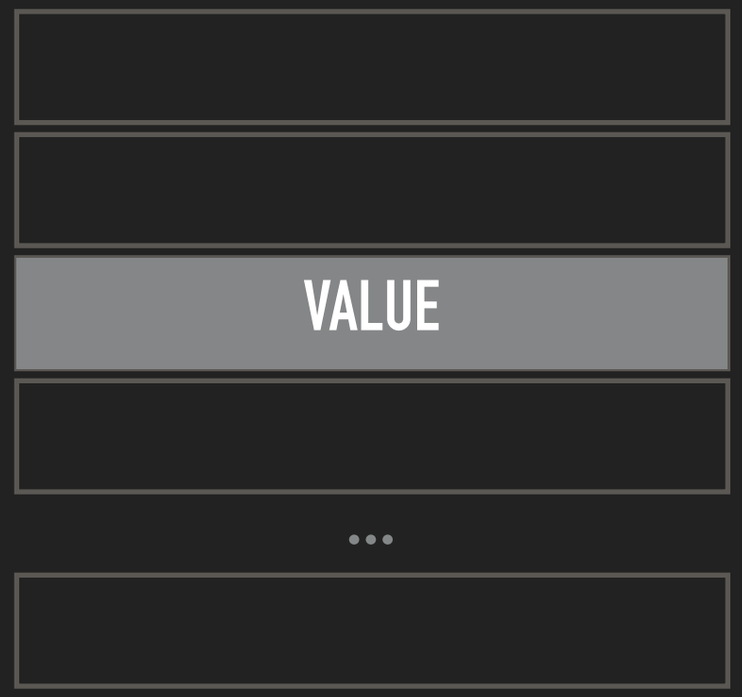

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For a CPU the “READ value from memory at 4711” instruction looks like this (μOPs):

1. Check that program may read from address 1
2. Store the value at address in register[1] 2

If 1 fails the program is aborted.

This can be handled by the program.

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In our burger example:

1. Customer orders a burger
2. Customer has not enough money
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*	μOPs ordered by *execution*
1 Check access	2 Read into register
2 Read into register	1 *Magic*
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The re-ordering on the right happens, when the “forbidden data” is already cached (because cache access is so fast).

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In our burger example:

1. **Customer orders a burger**
2. **Customer gets his burger**
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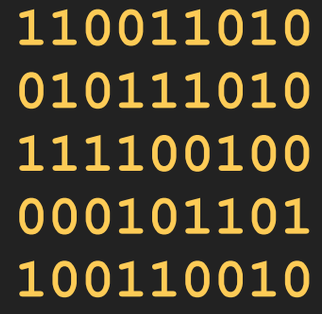
4. **Customer runs away with burger**

MELTDOWN

For Meltdown two actors are needed

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

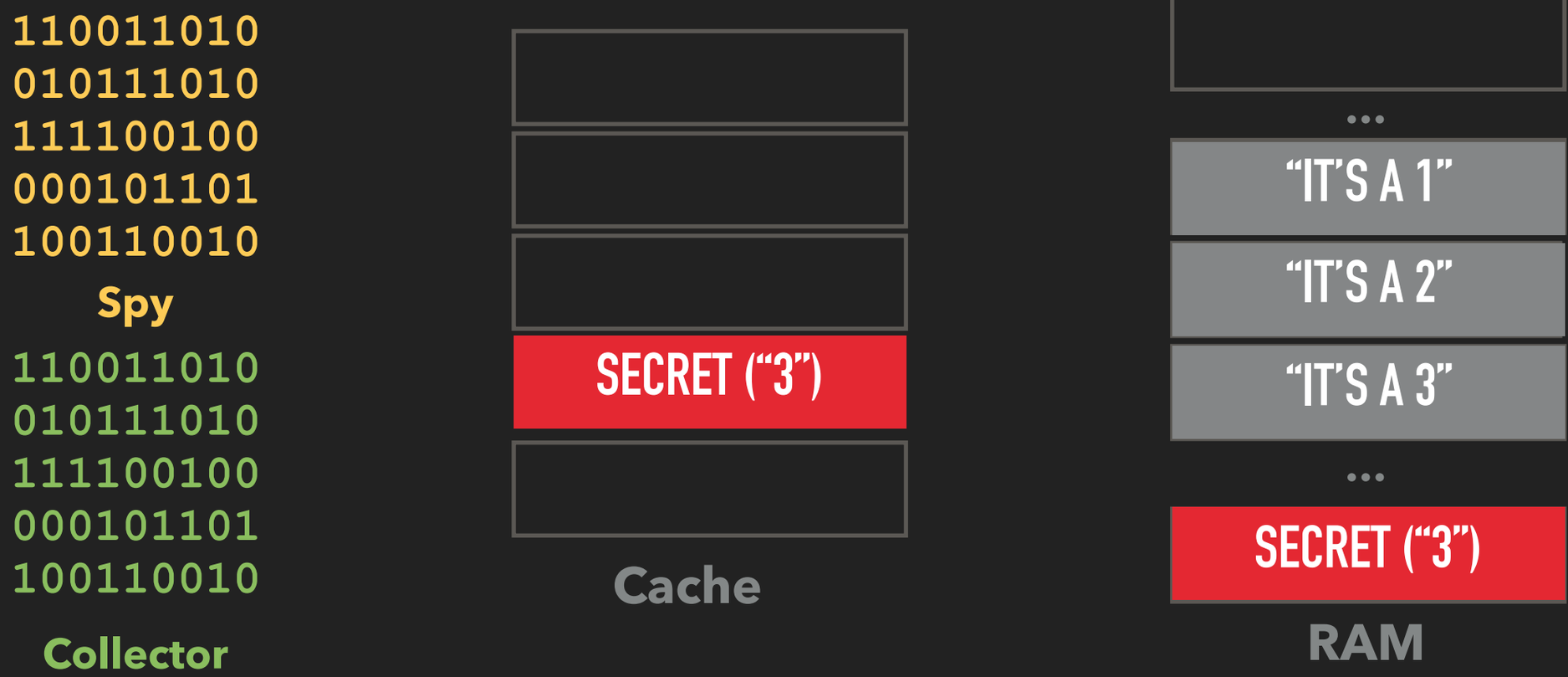


The **spy** will “steal” the secret and stash it away.

The CPU will kill him for accessing the secret information.

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

MELTDOWN: THE ATTACK



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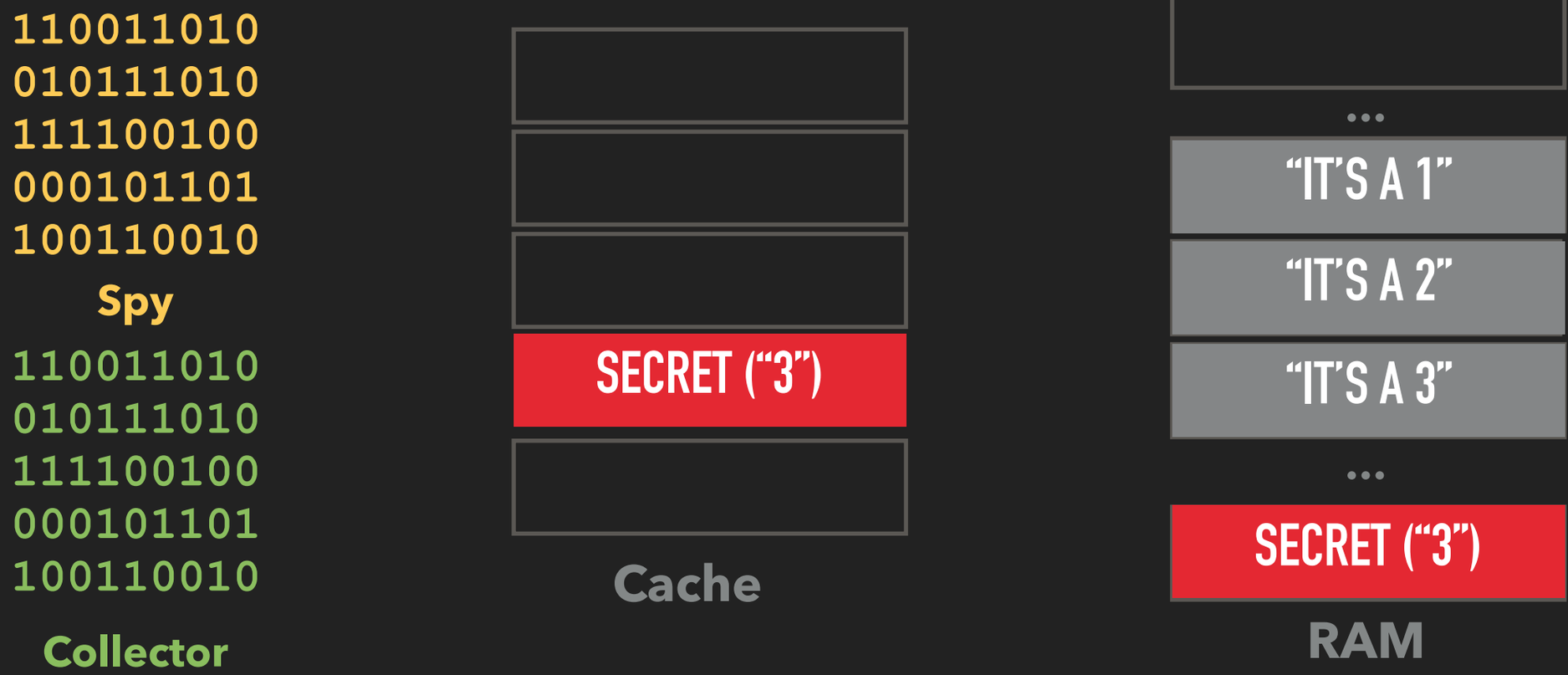

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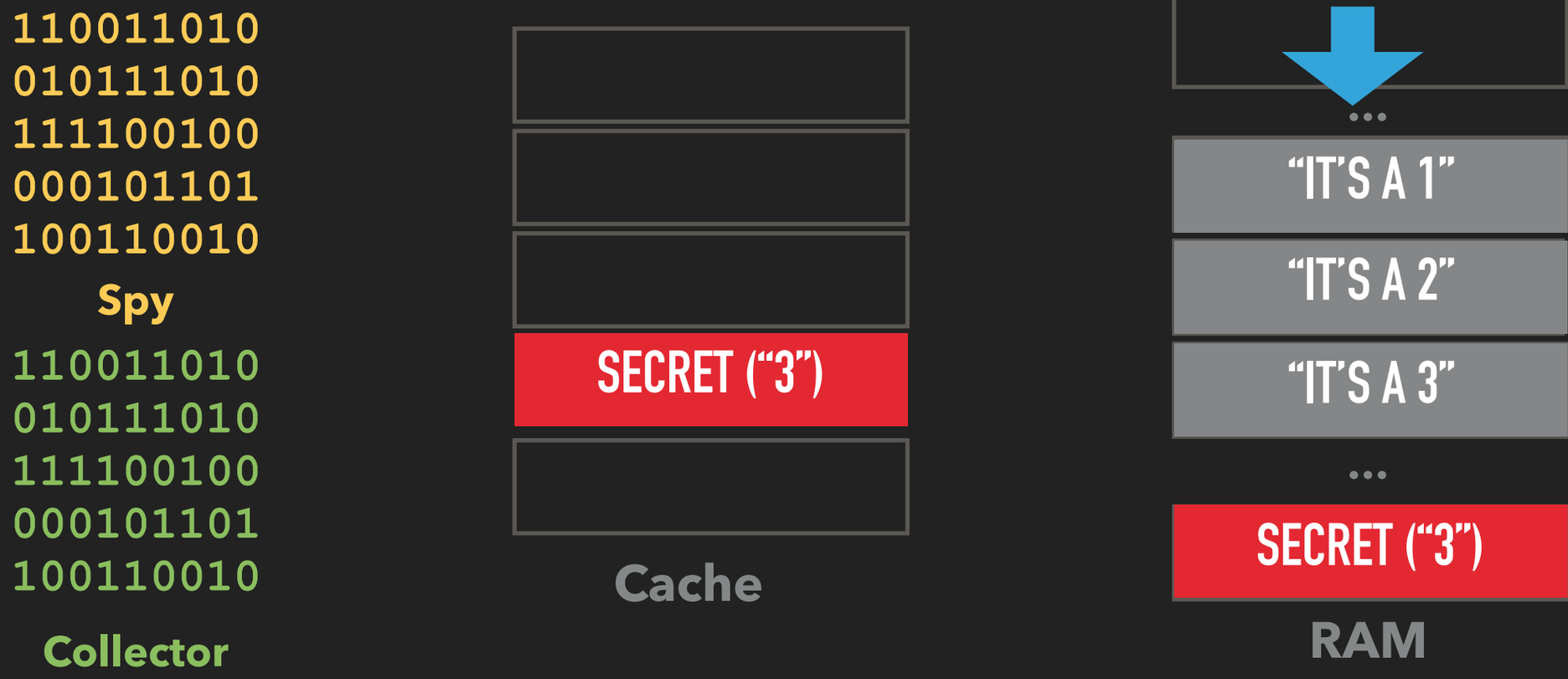

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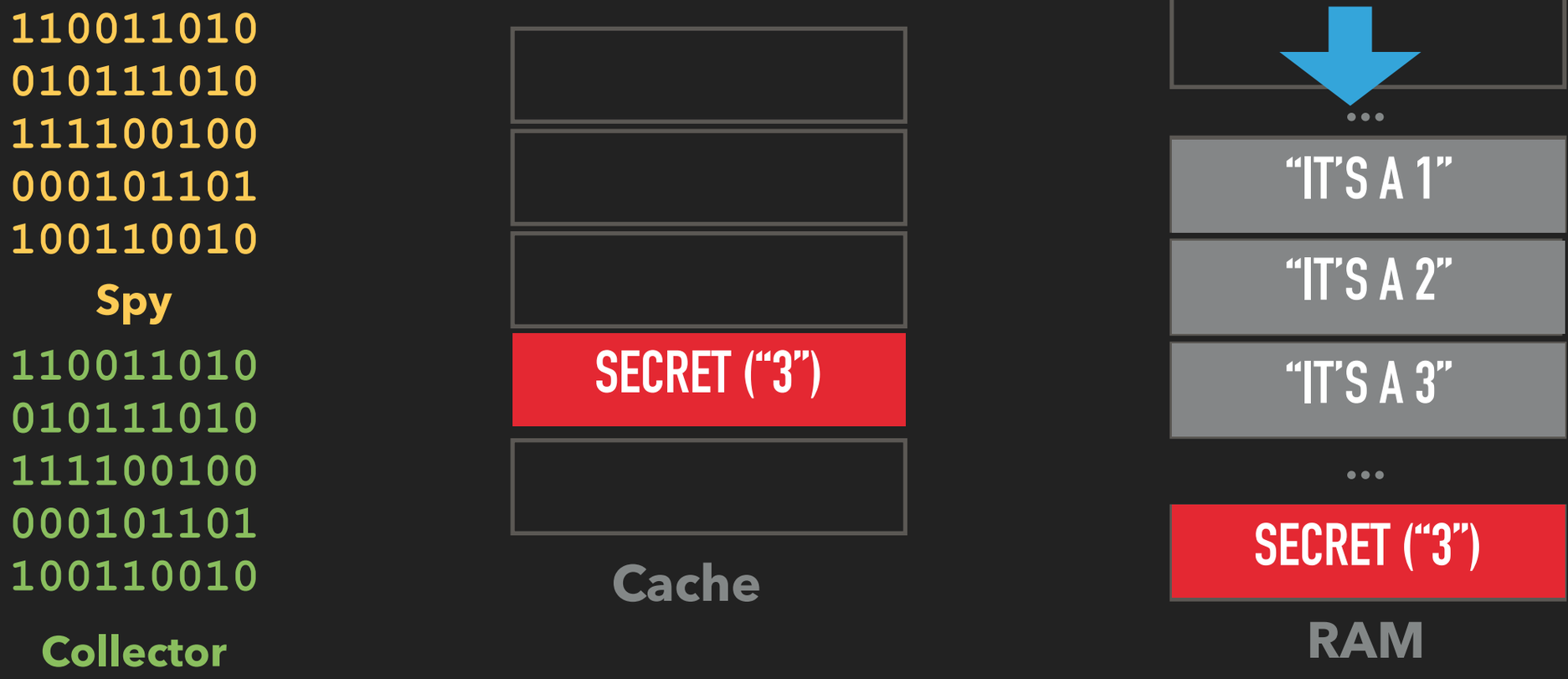

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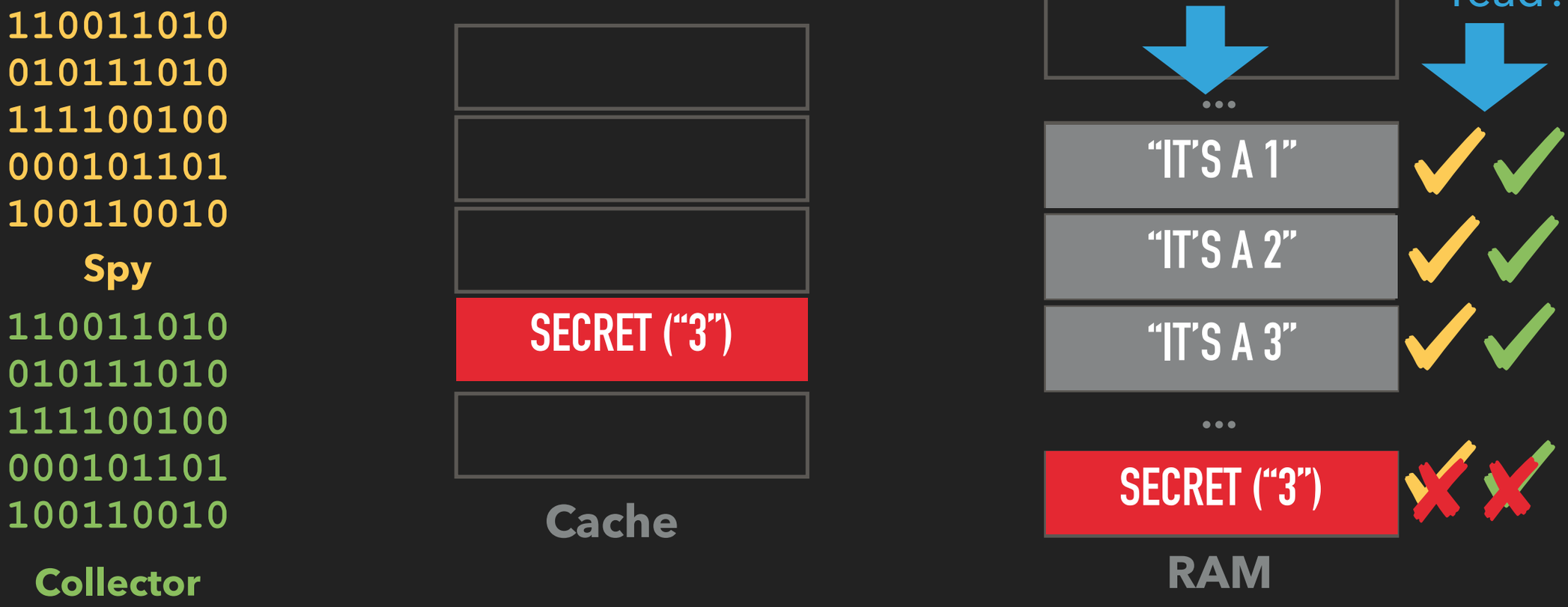

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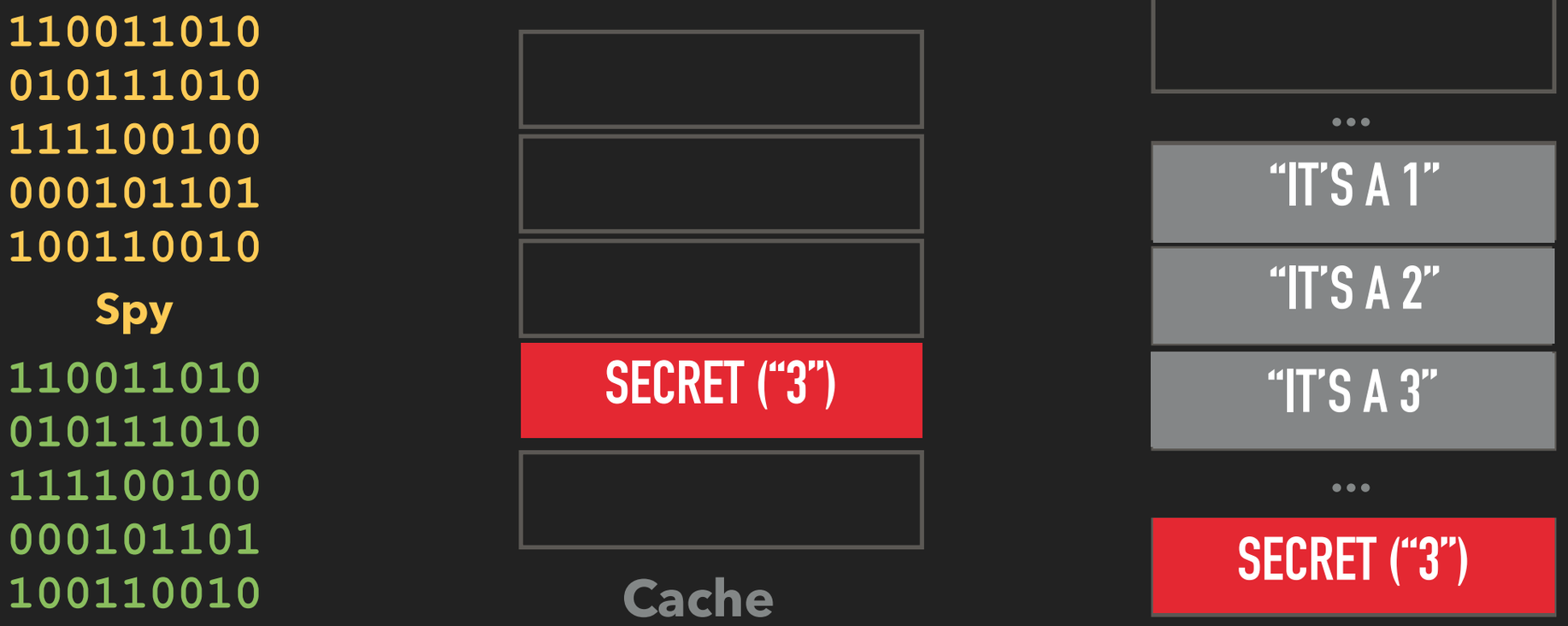
MELTDOWN: THE ATTACK



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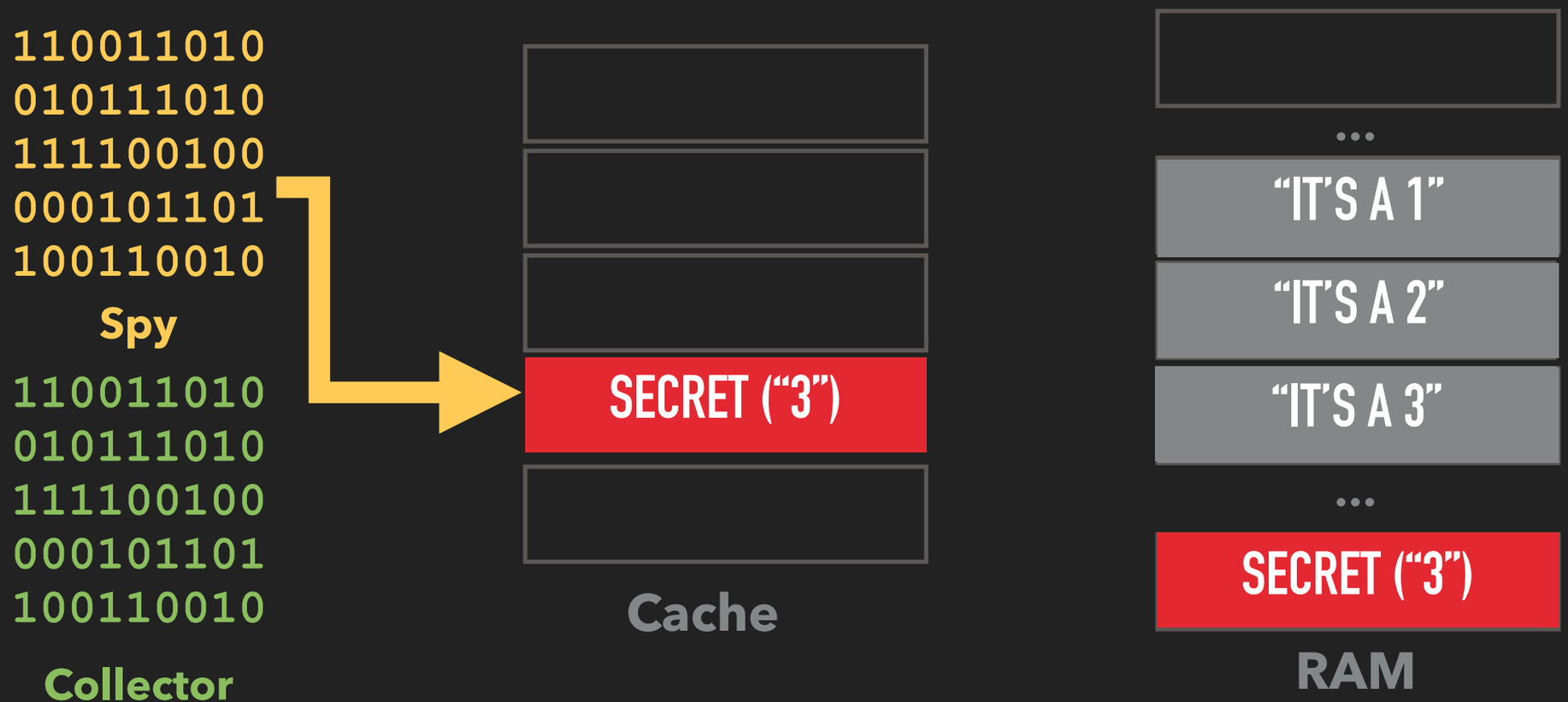

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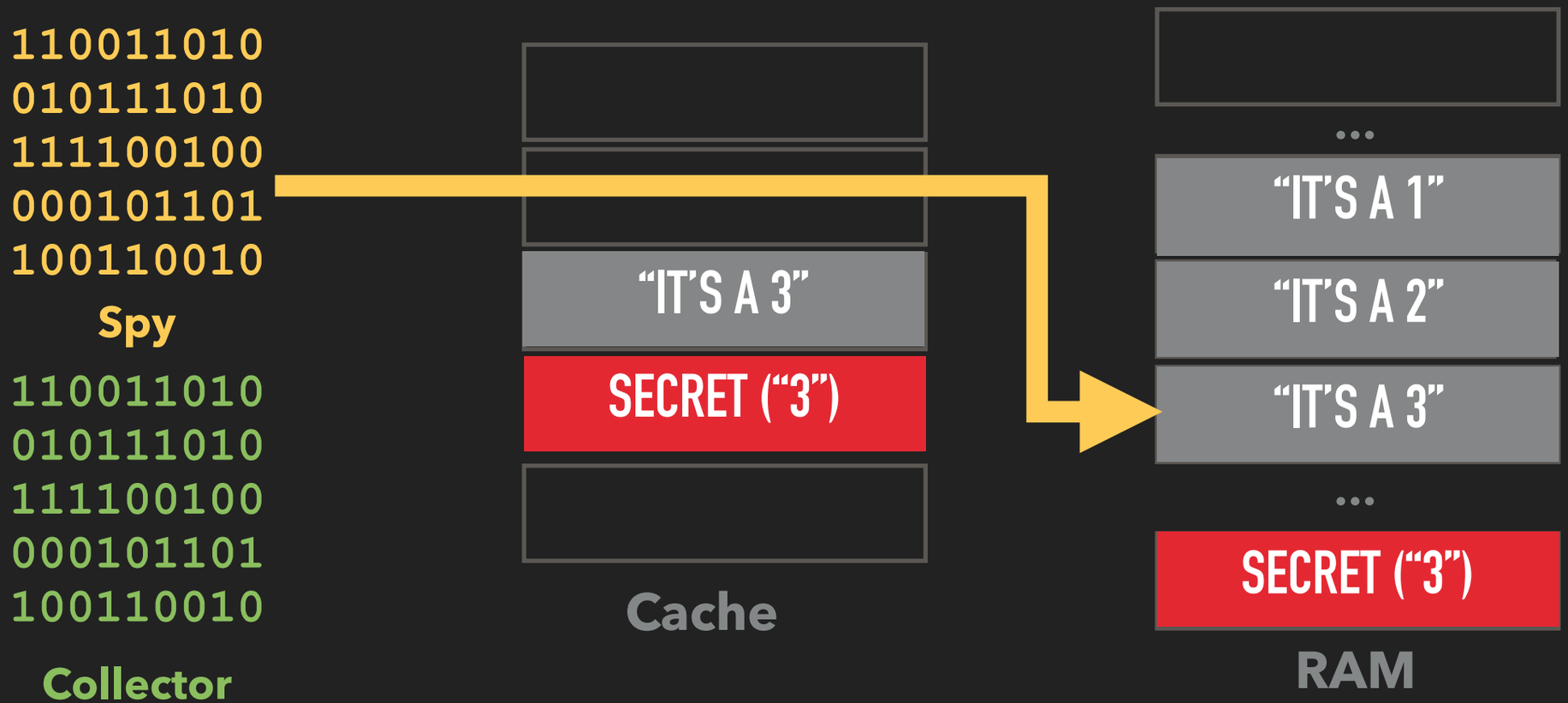

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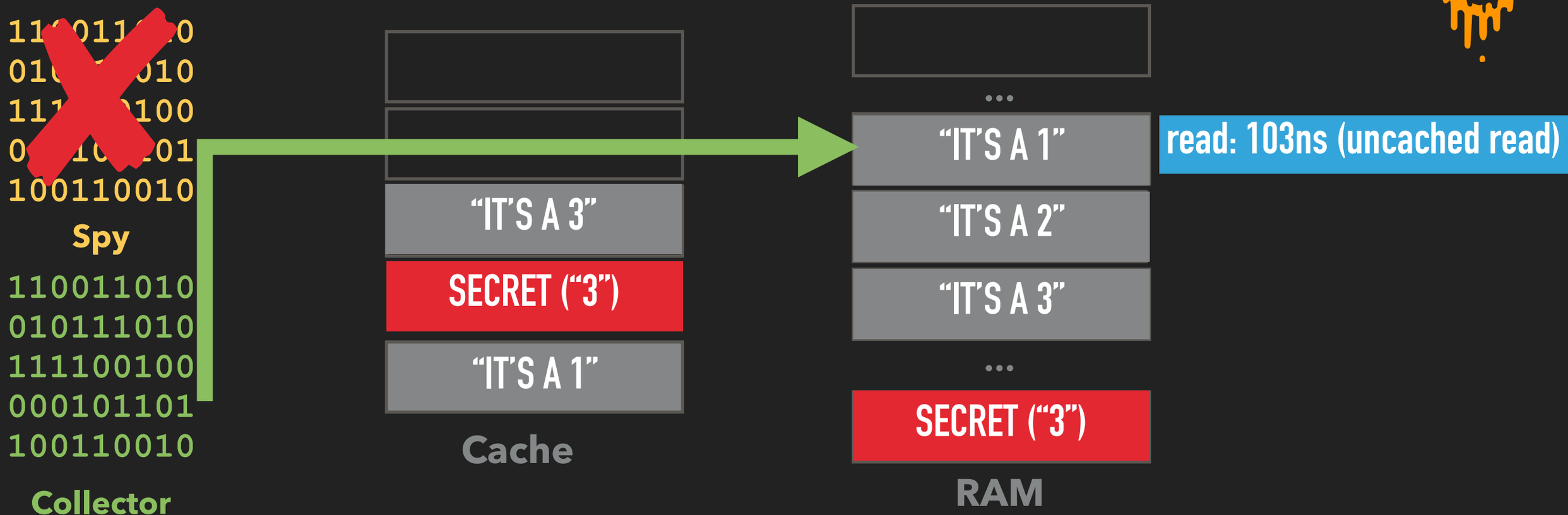

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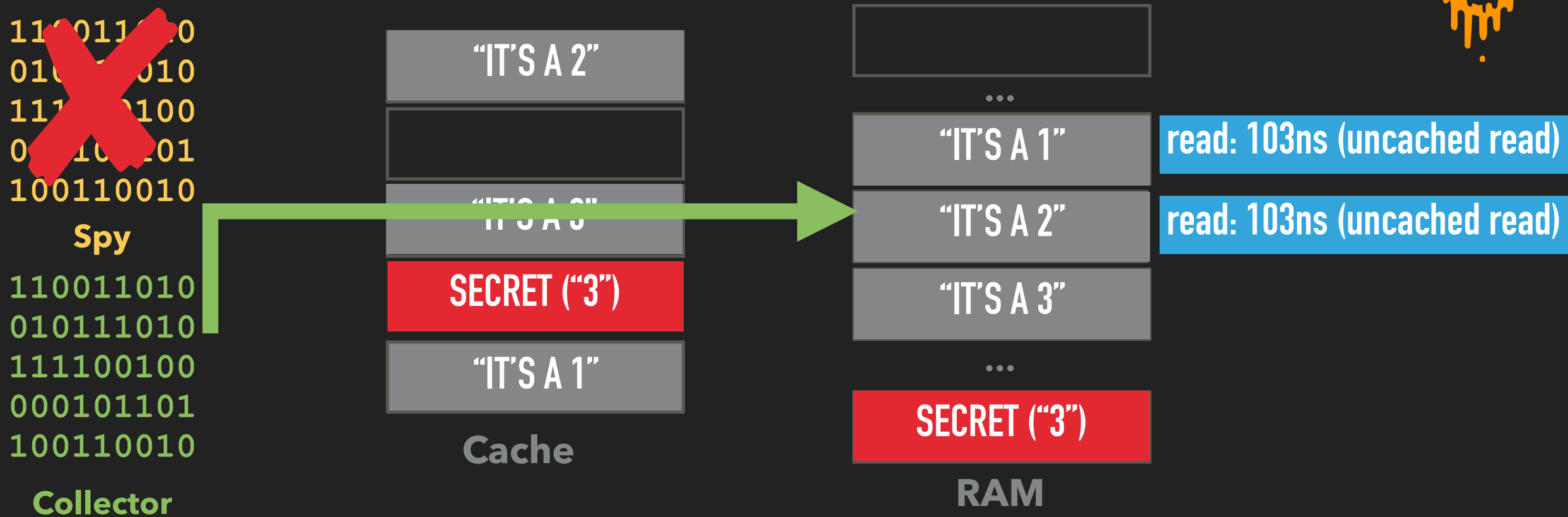

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2. Depending on the **value**, **Spy** will cache a grey block[1]

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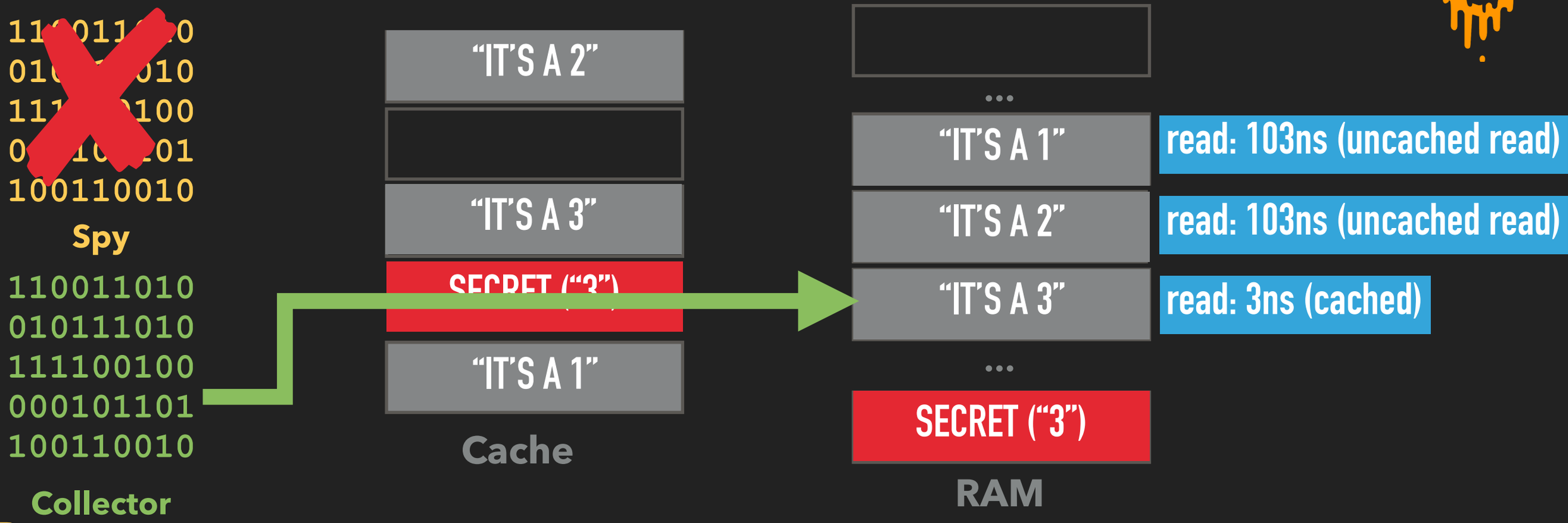

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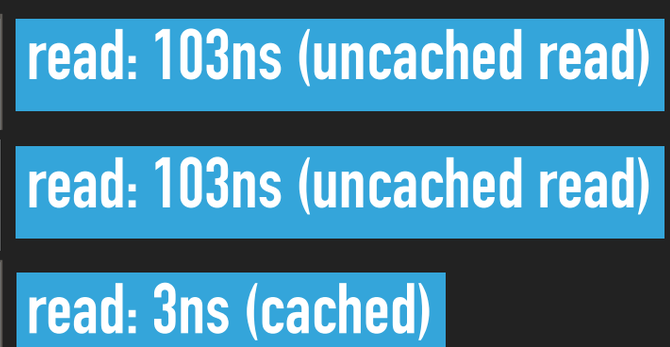

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MELTDOWN: THE ATTACK

read: 103ns (uncached read)

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read: 3ns (cached)

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MELTDOWN

Meltdown exploits two properties of modern CPUs

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

This allows an attacker to

- Read all memory mapped[1] in a process
- This often includes all other processes memory
- This does NOT allow reading “outside of a VM[2]”

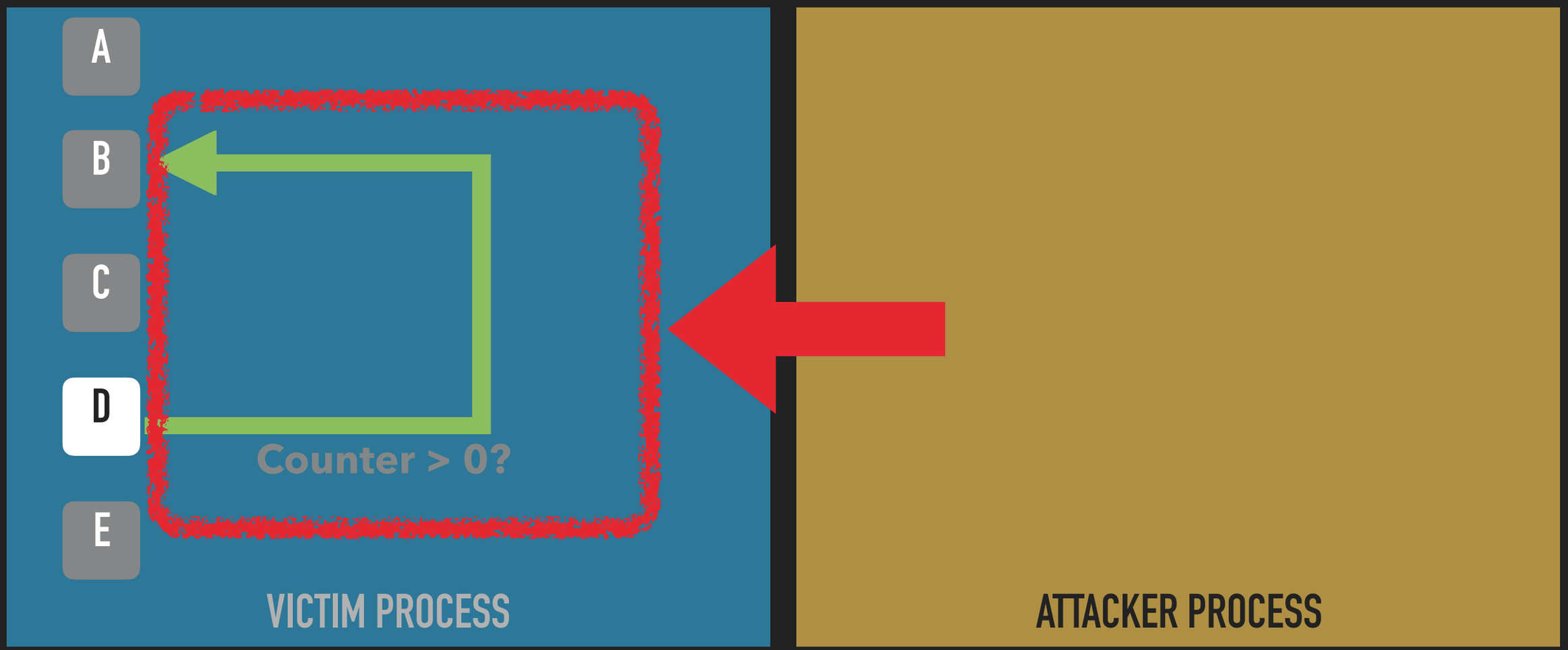
[1] Virtual vs. physical memory is a subject for another time [2] For fully virtualised VMs

SPECULATIVE
EXECUTION

SPECTRE

SPECTRE

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



SPECTRE

Spectre basically works like this:

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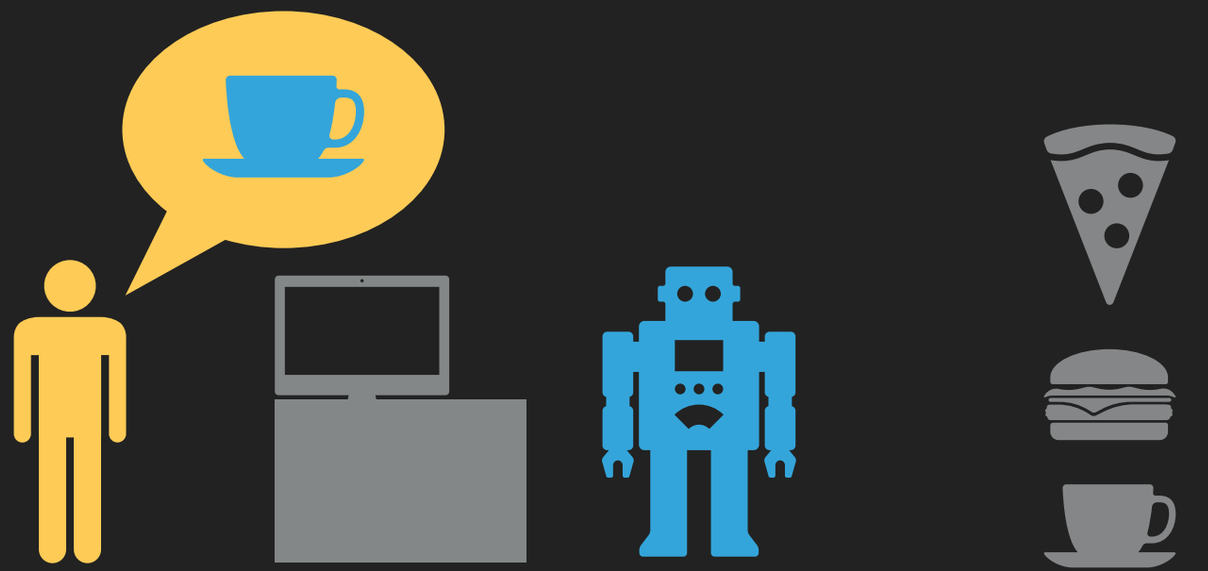
- and *basically* work like in Meltdown
- works by manipulating the *branch prediction* of the CPU

SPECTRE: BRANCH PREDICTION



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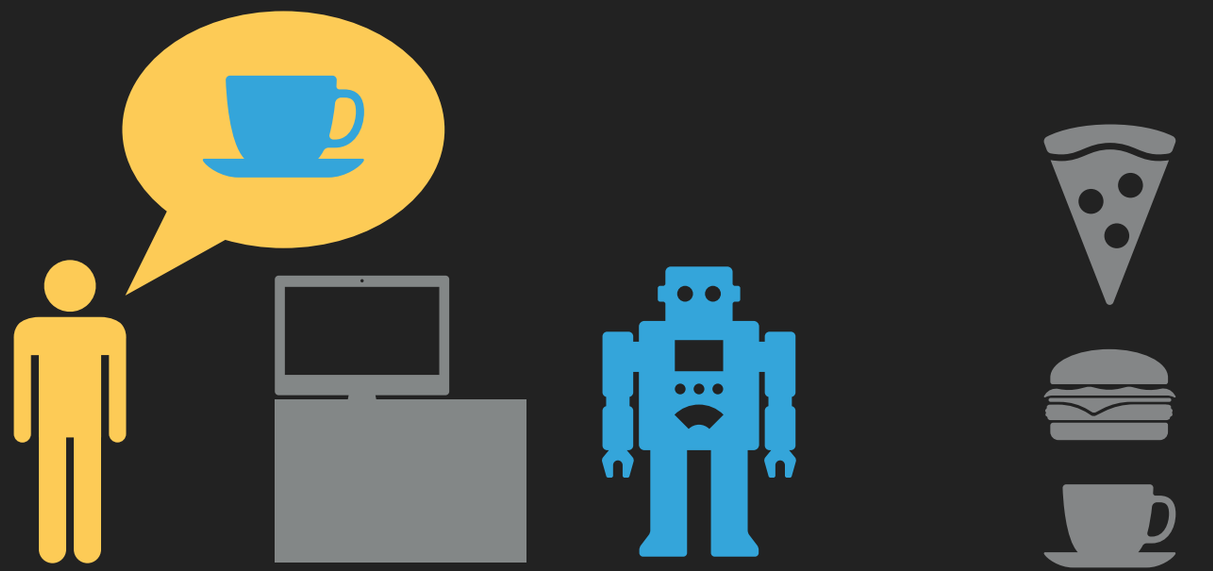

Monday

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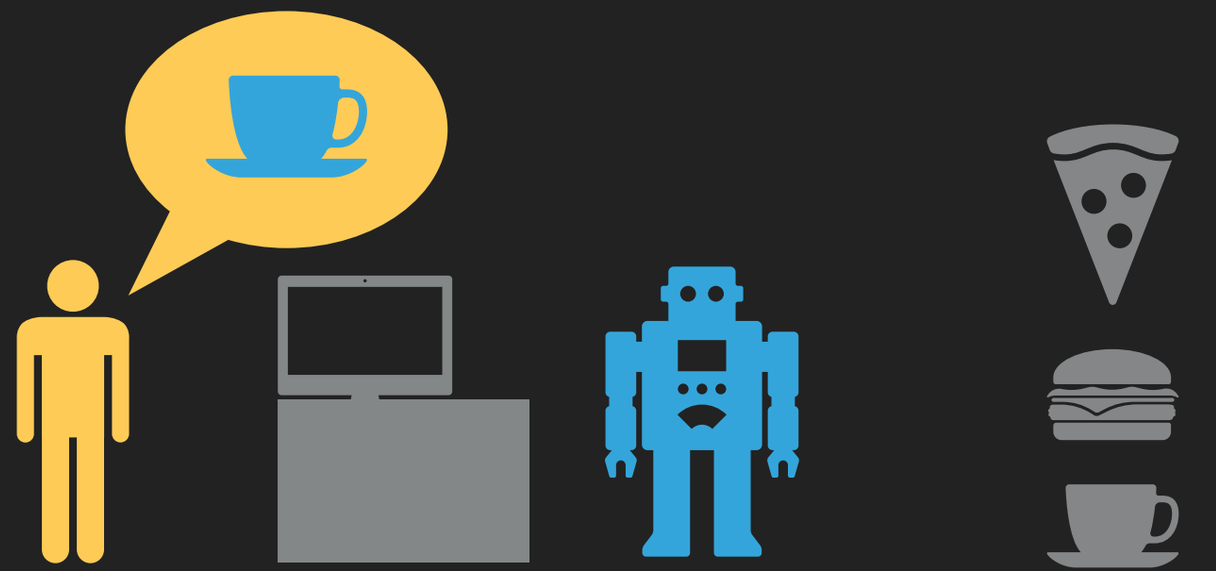
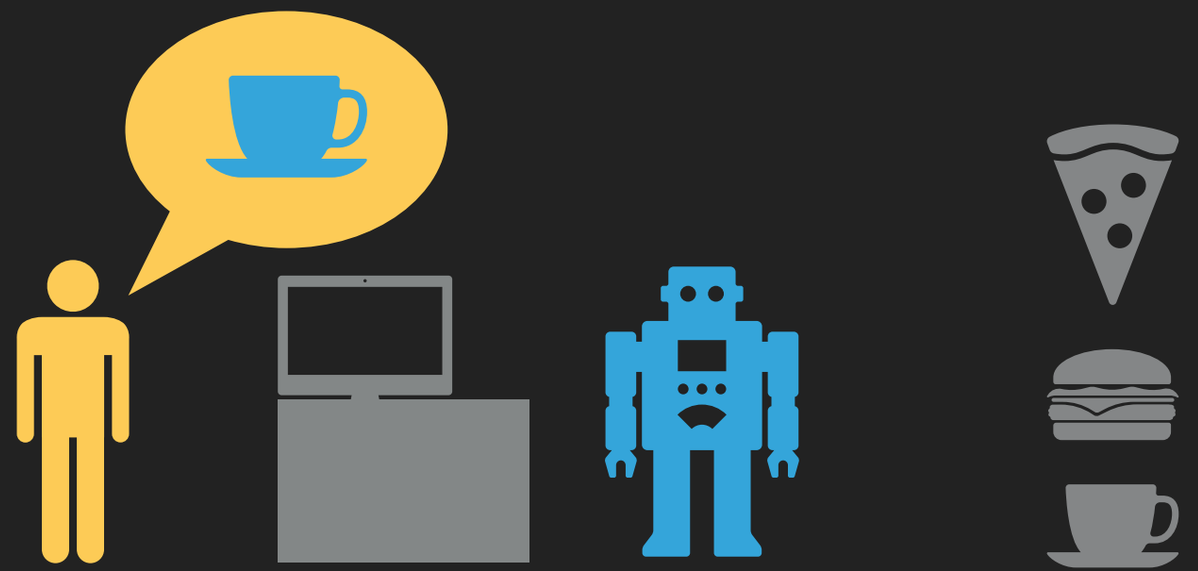


Monday

Tuesday

SPECTRE: BRANCH PREDICTION



Monday

Wednesday

Tuesday

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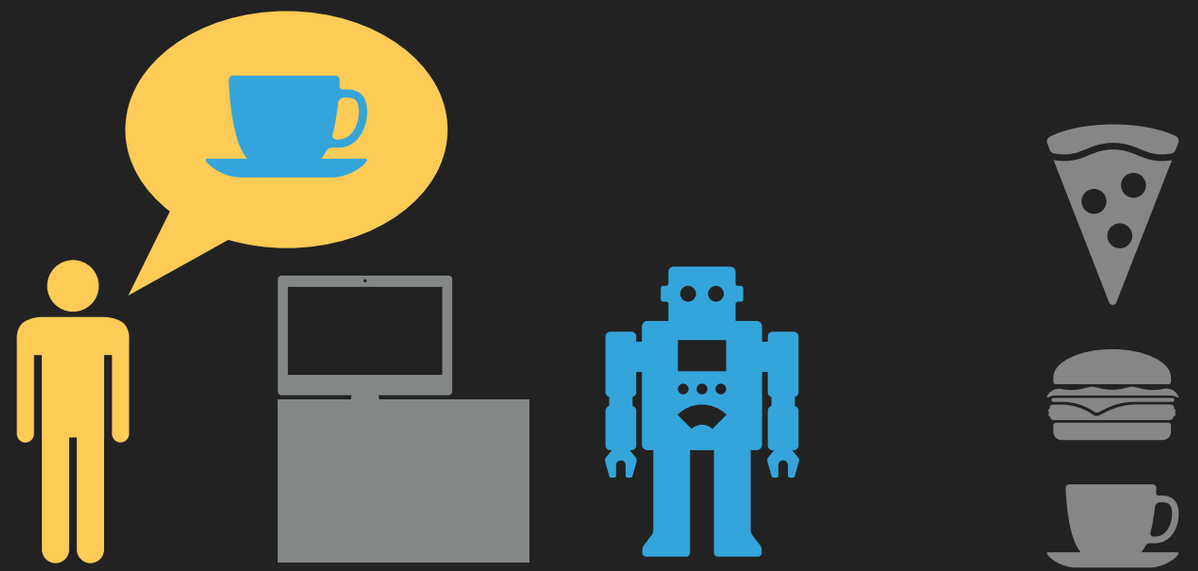

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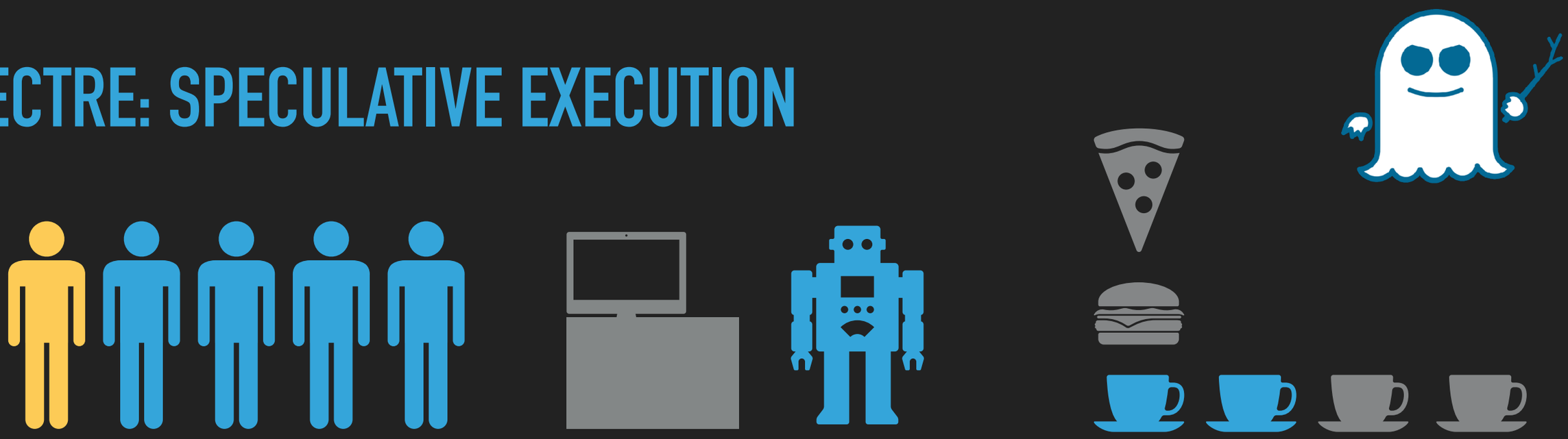
...

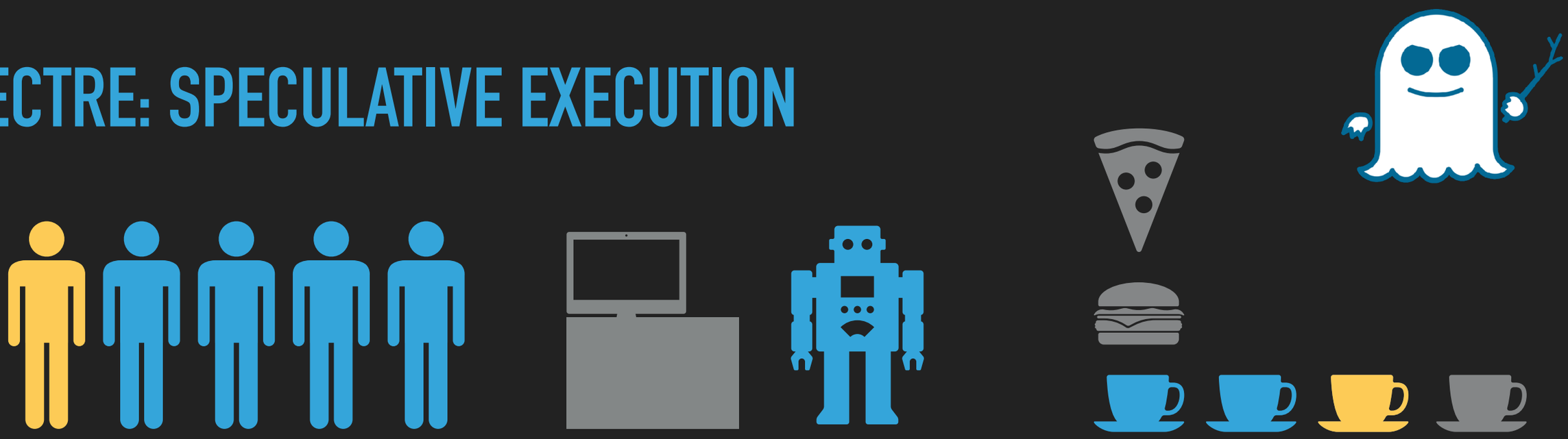
SPECTRE: SPECULATIVE EXECUTION



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



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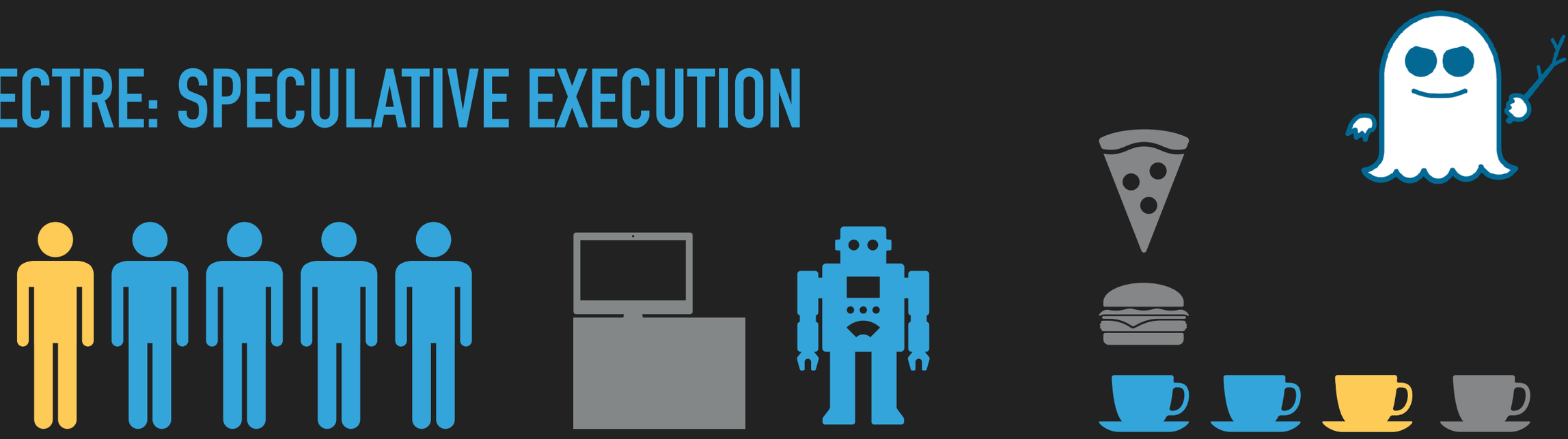

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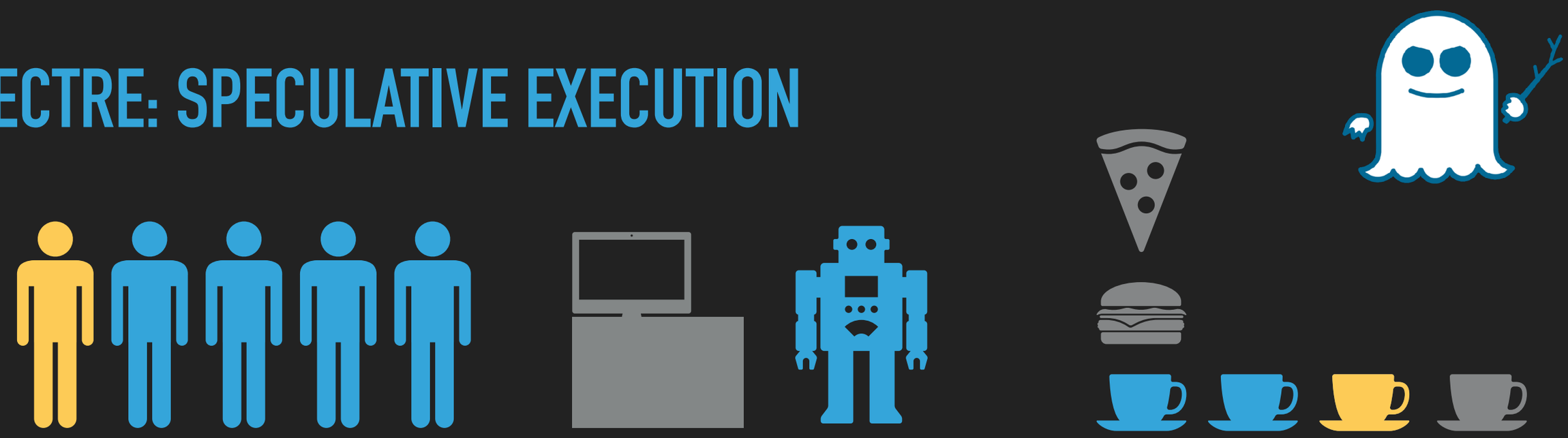

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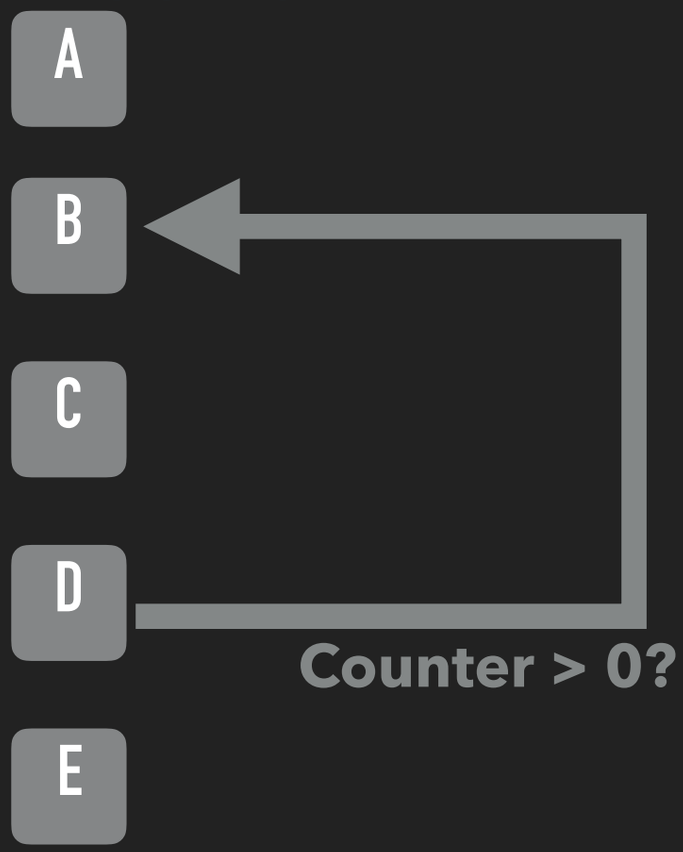
This is very similar to the effect seen in Meltdown.

- 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

SPECTRE: SPECULATIVE EXECUTION



3

Counter

COUNTER

Some variable used in branch

A B … E

Instructions

A

Currently active instruction

Conditional branch

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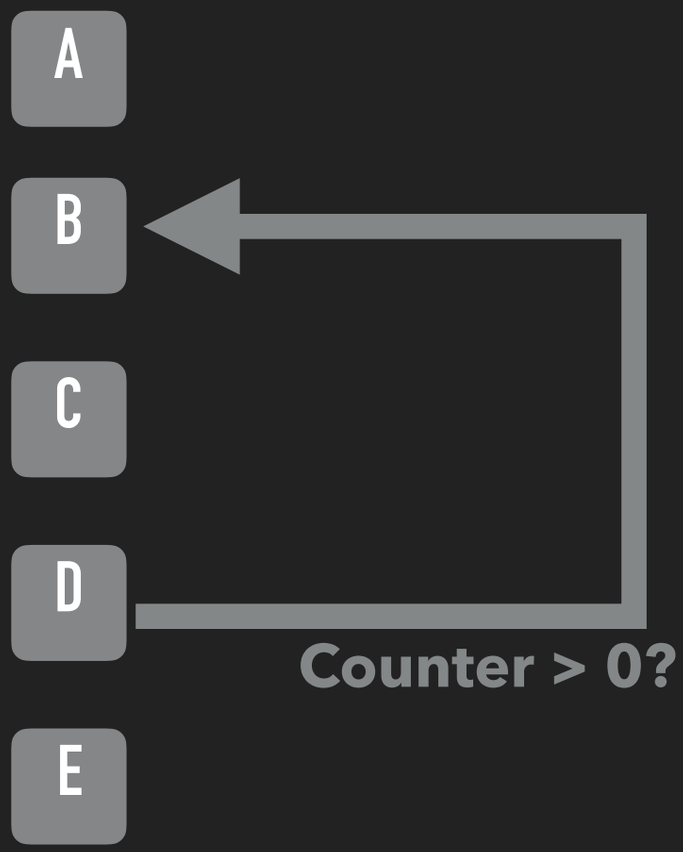

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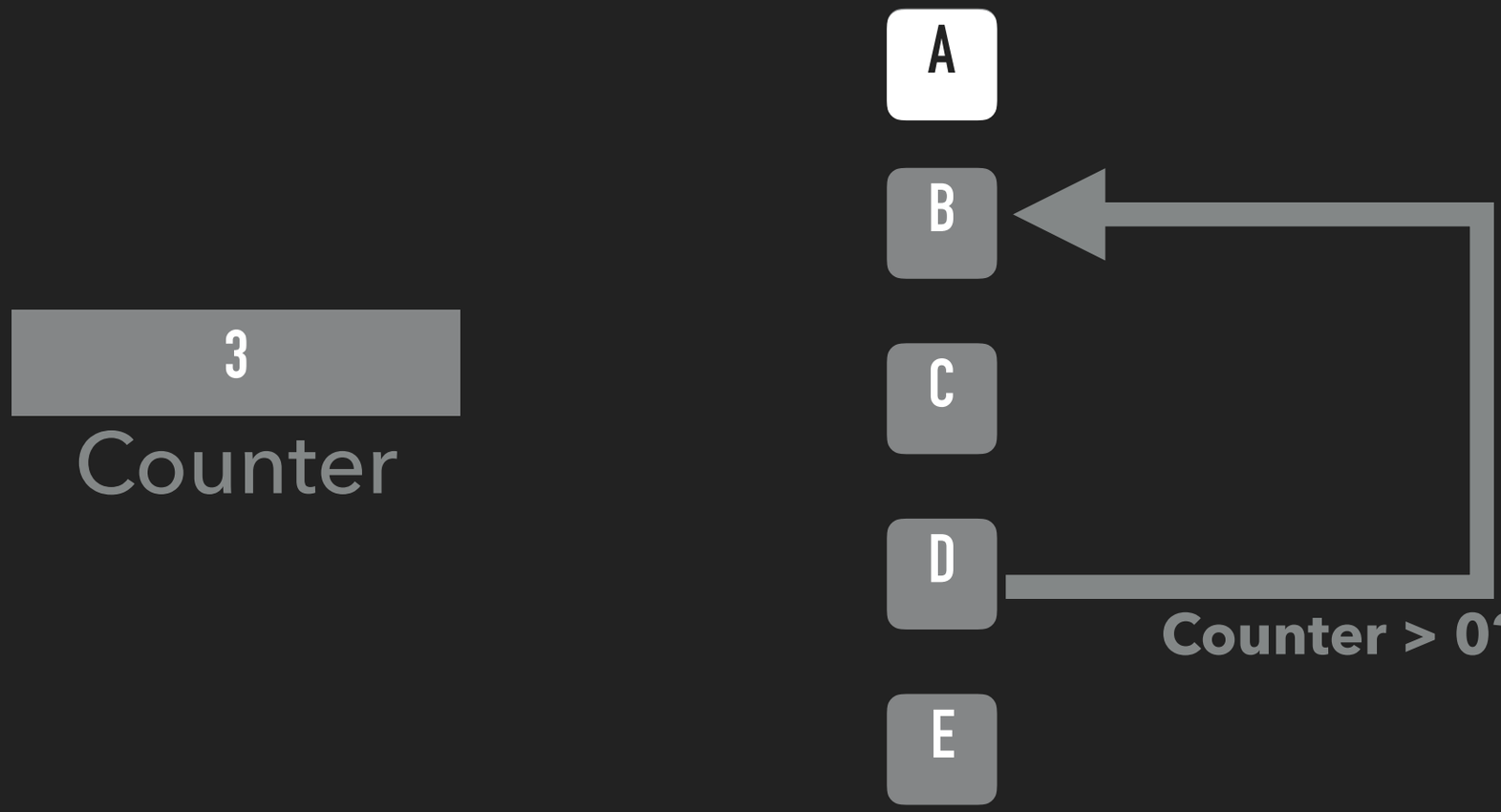

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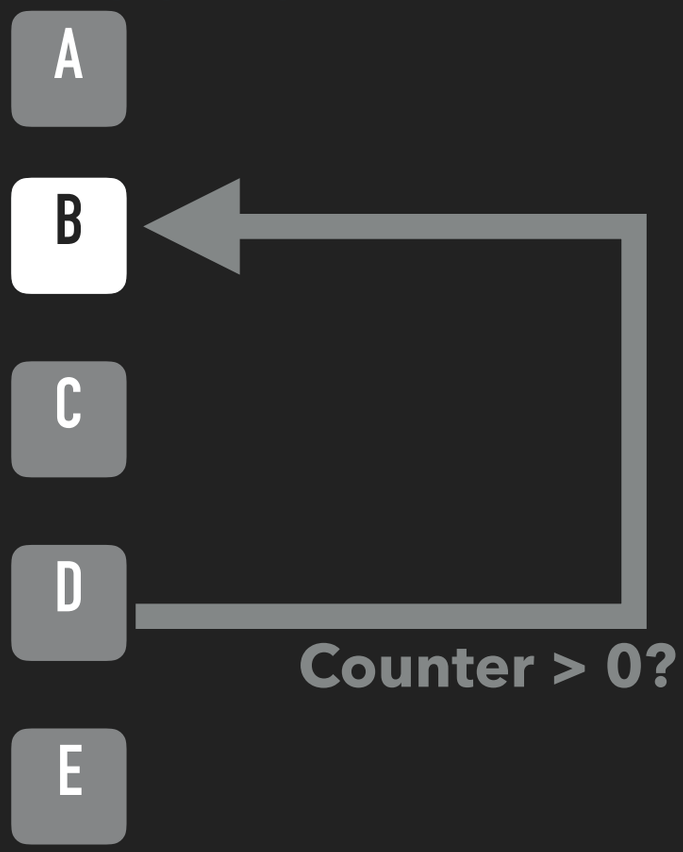

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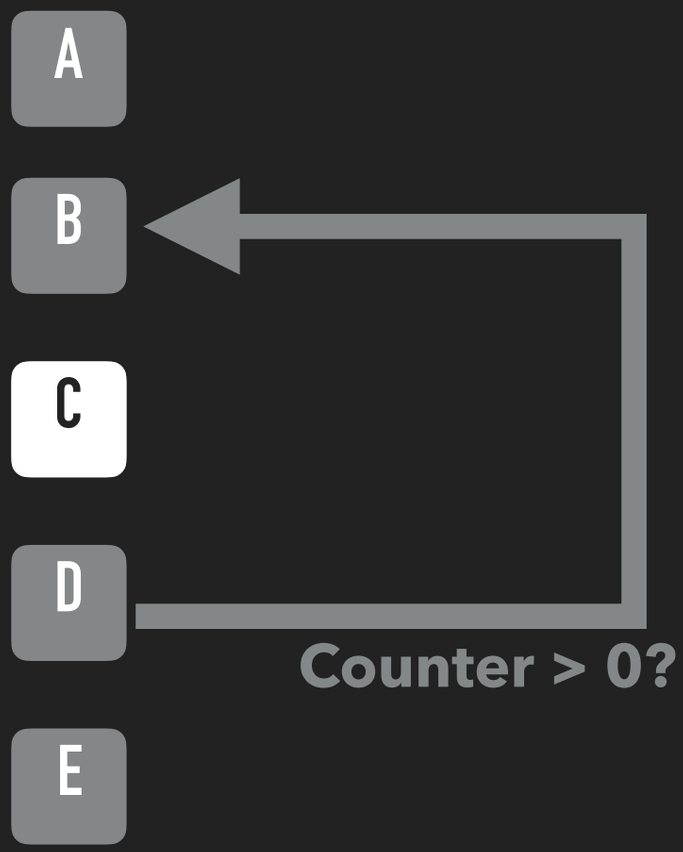

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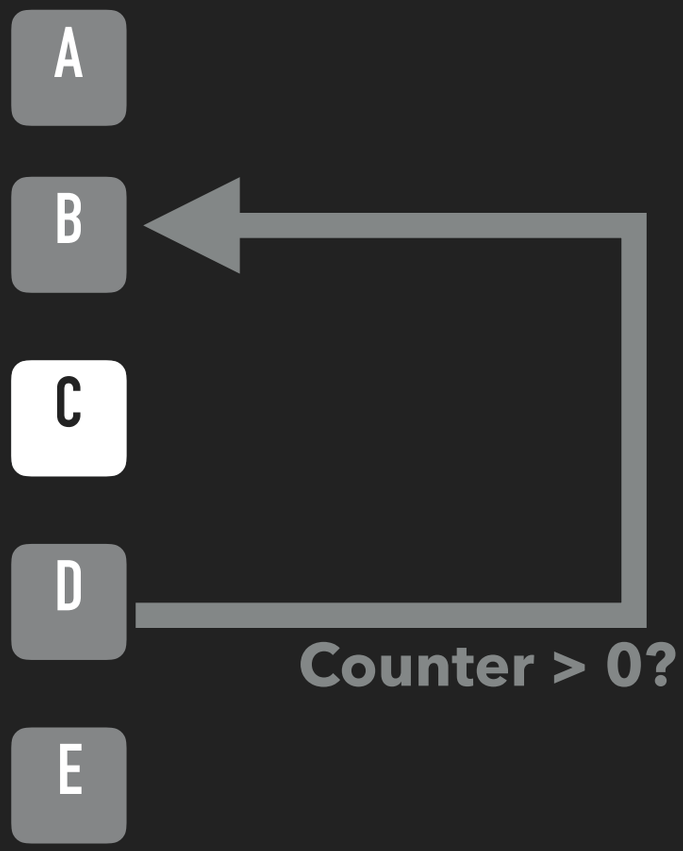

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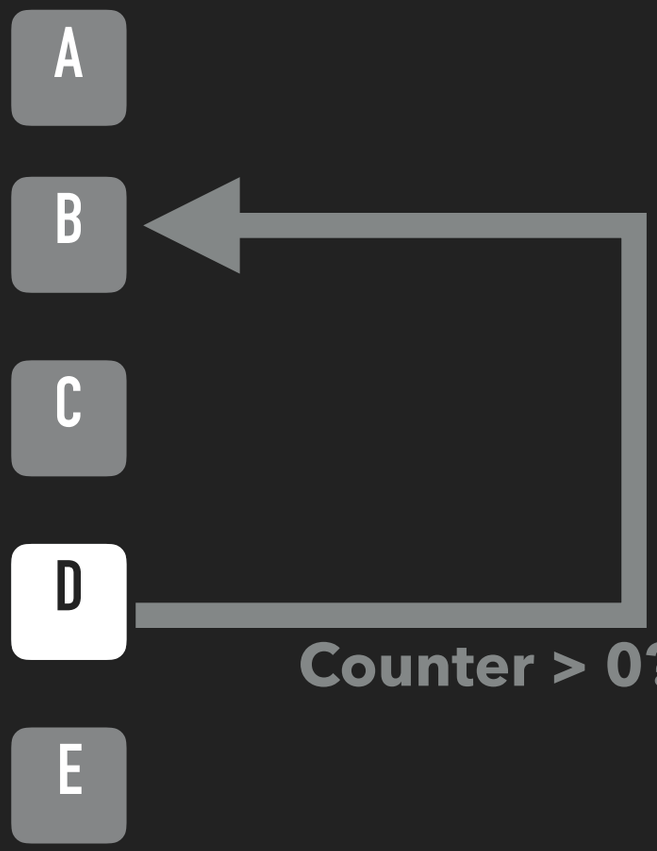

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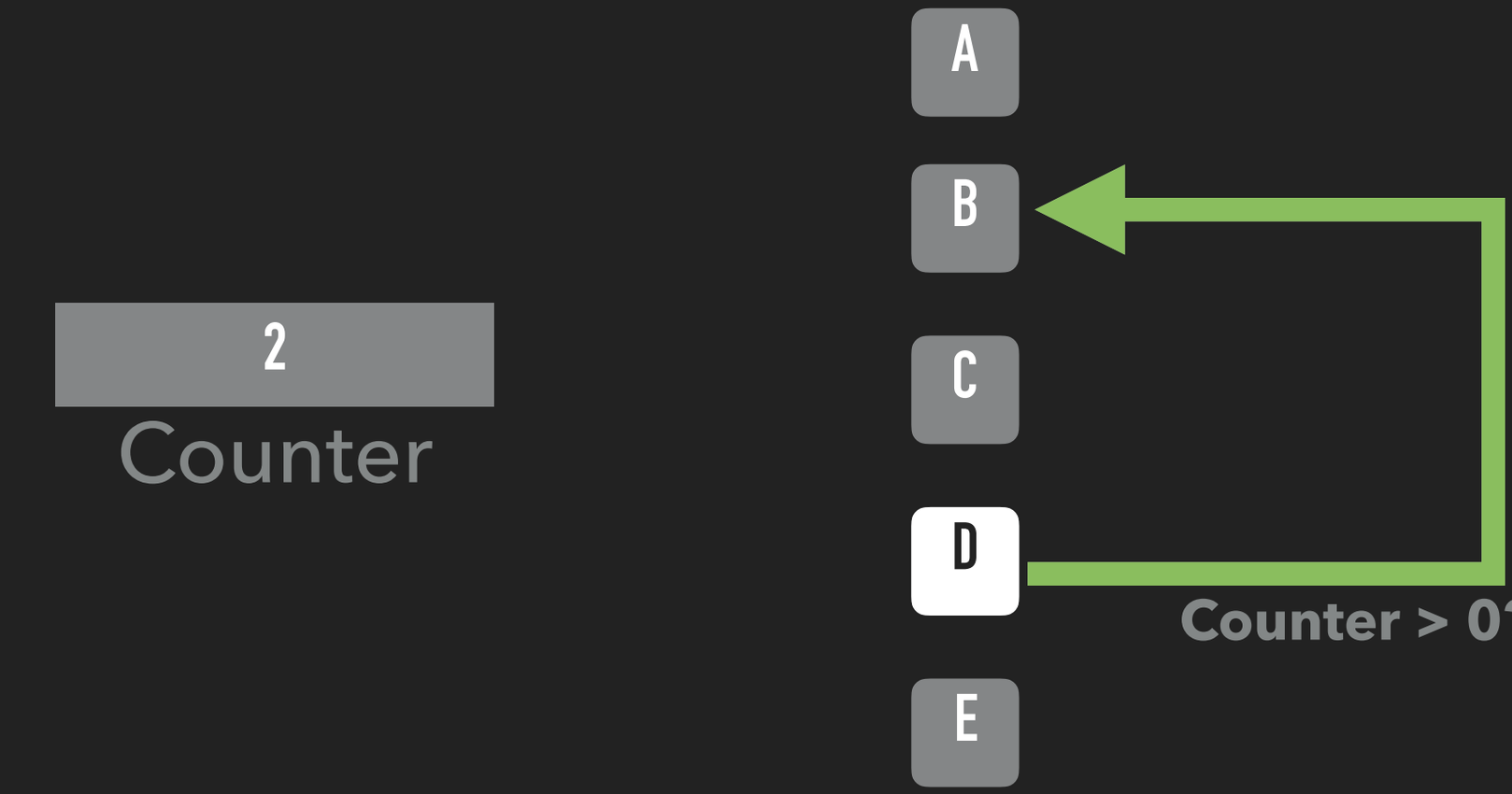

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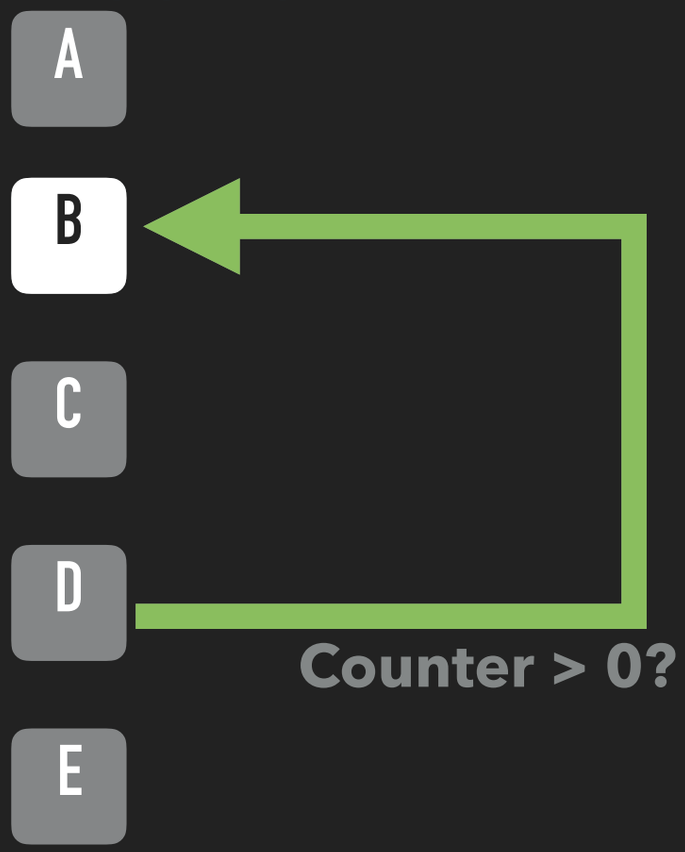

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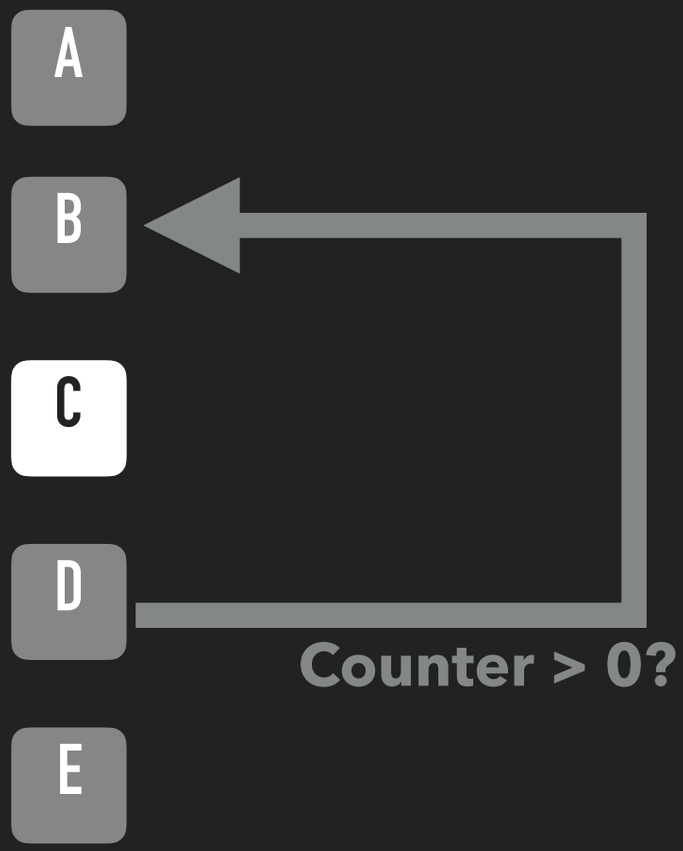

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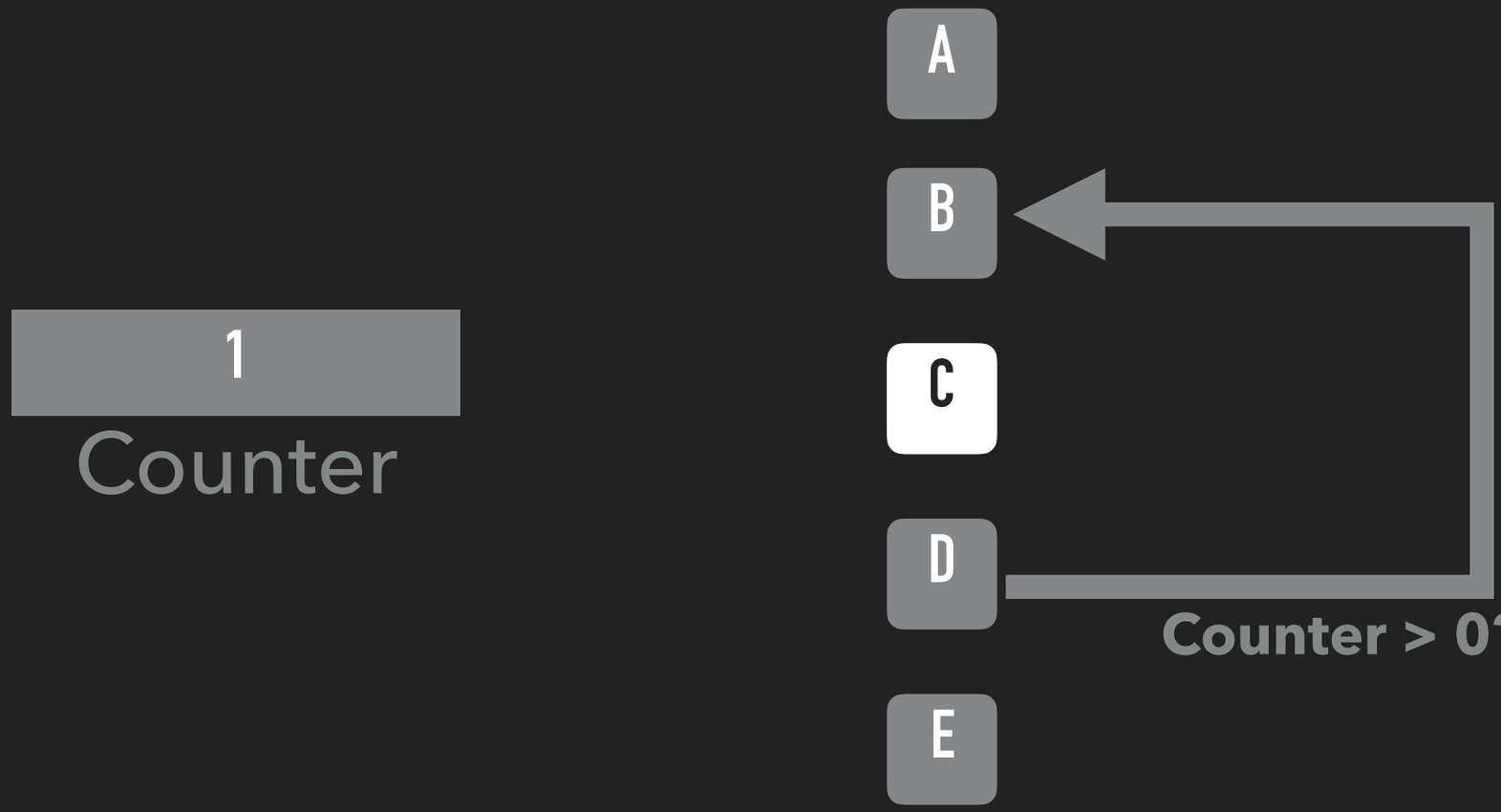

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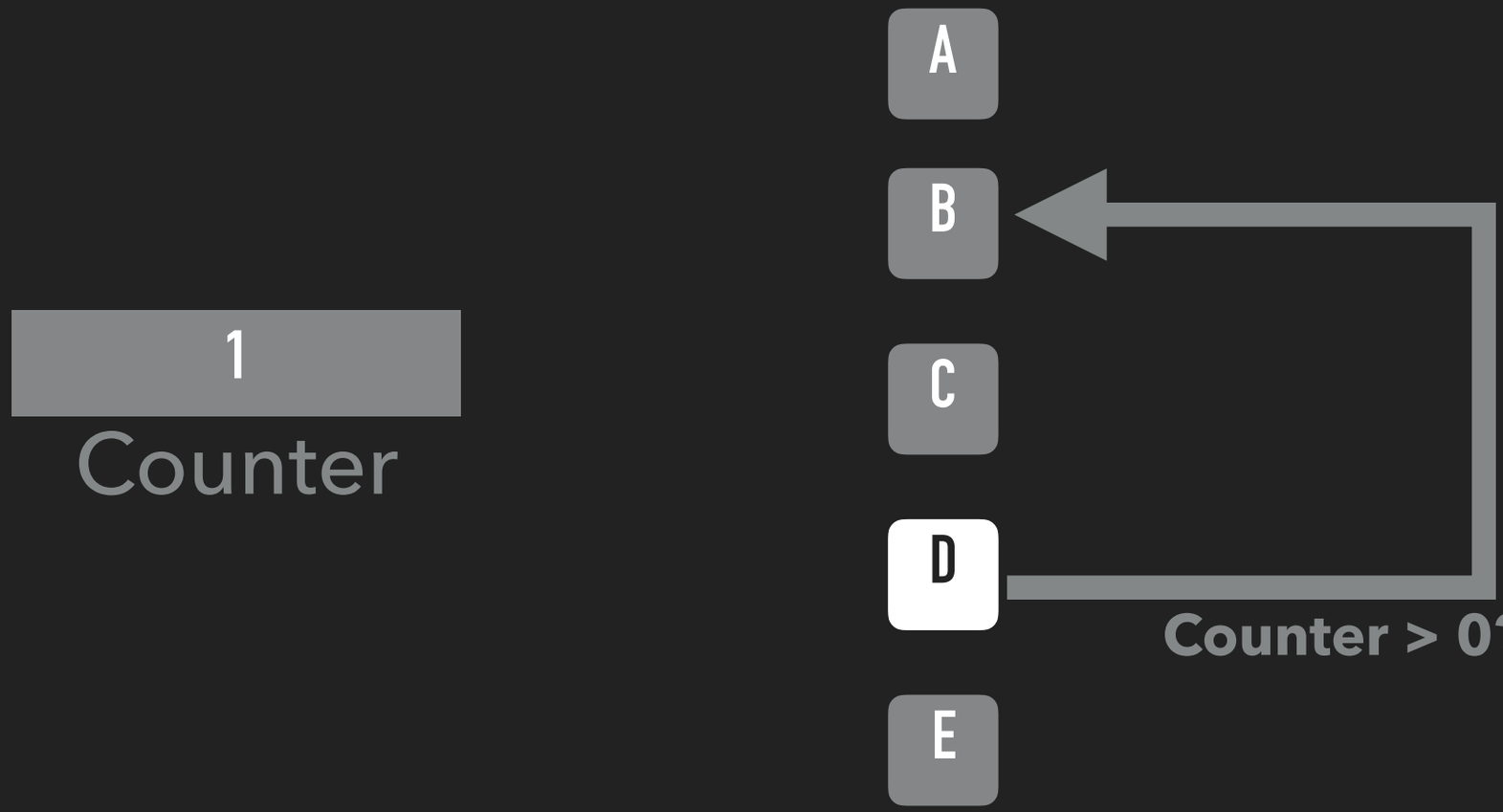

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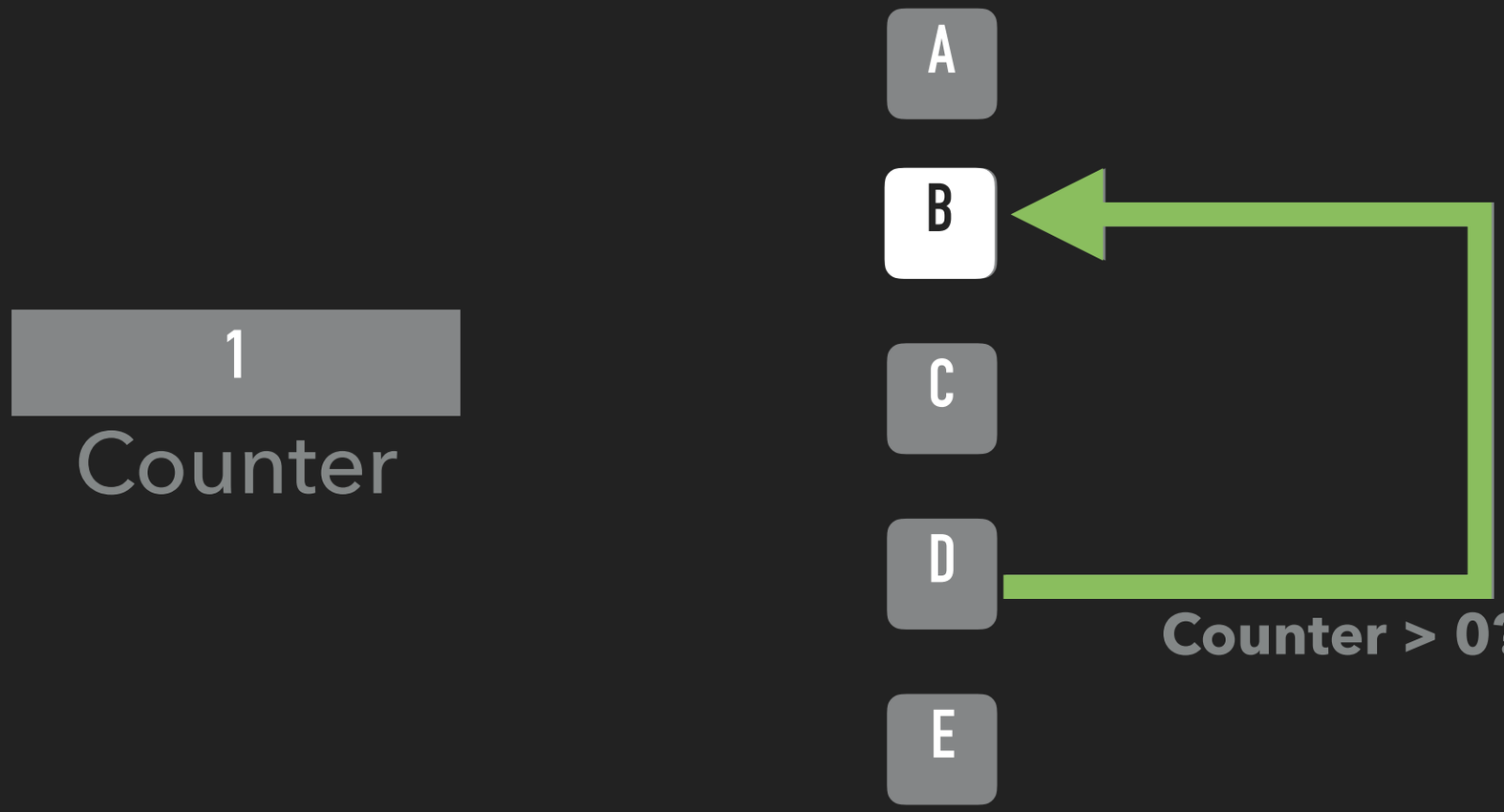

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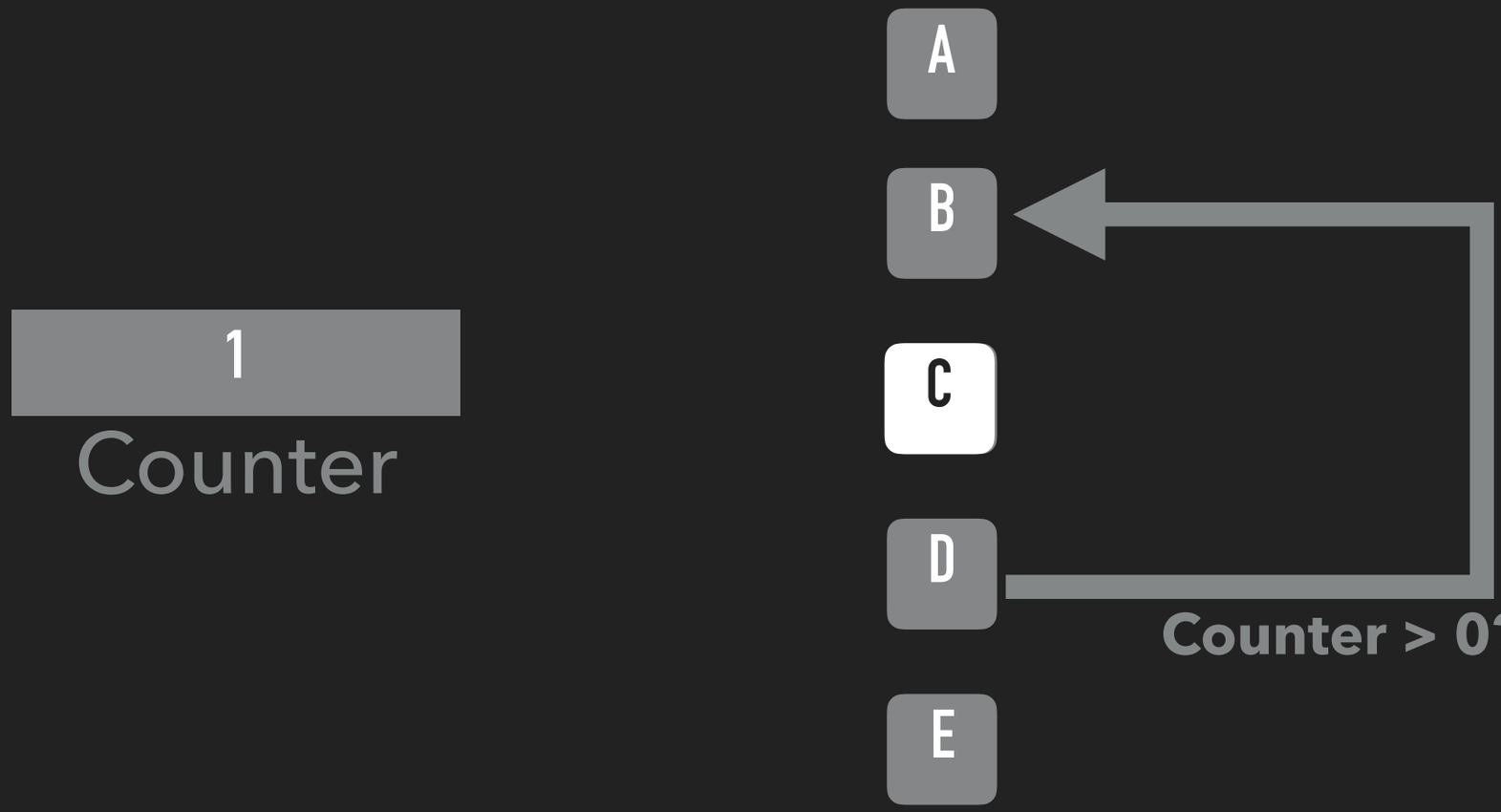

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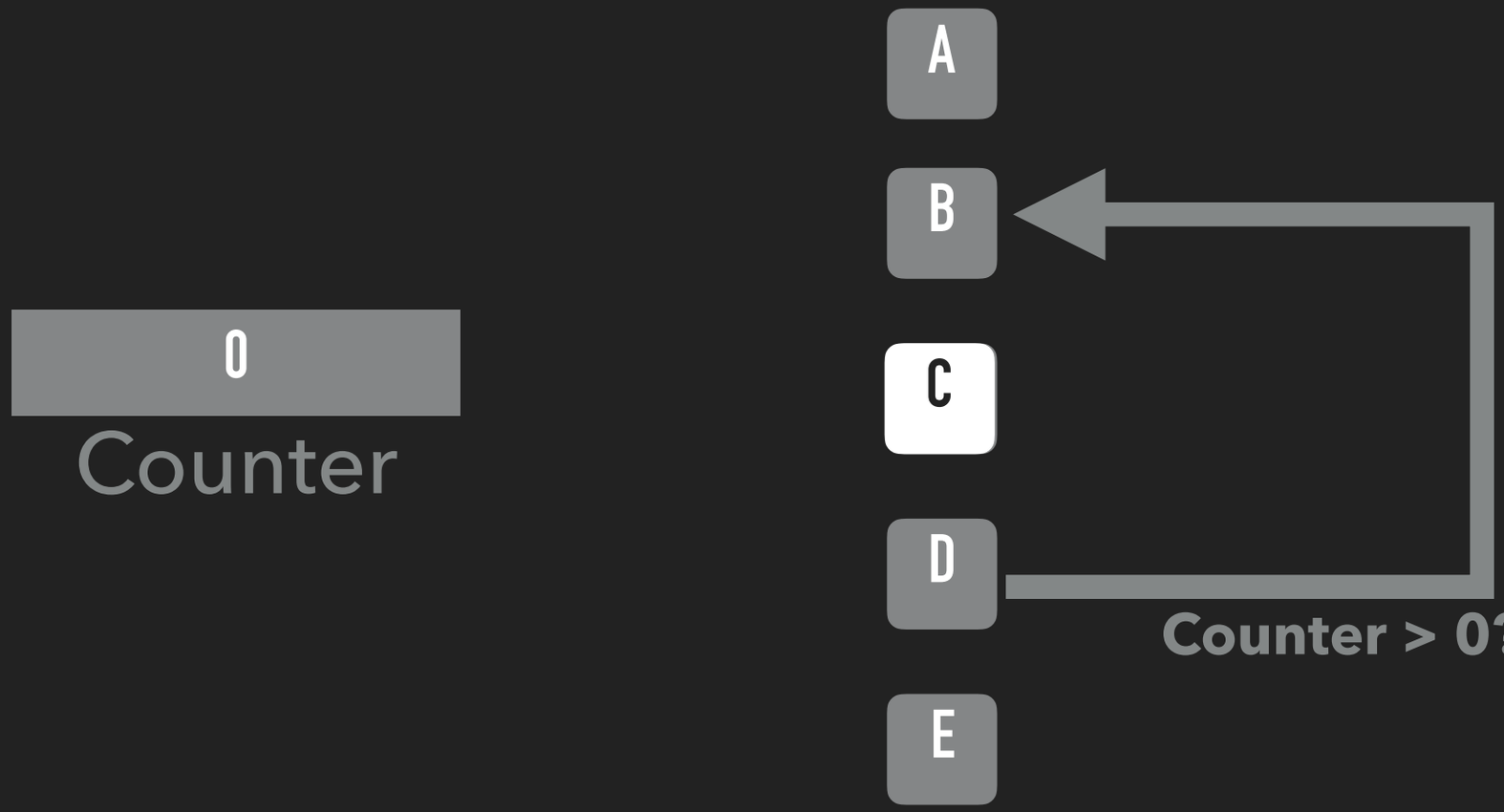

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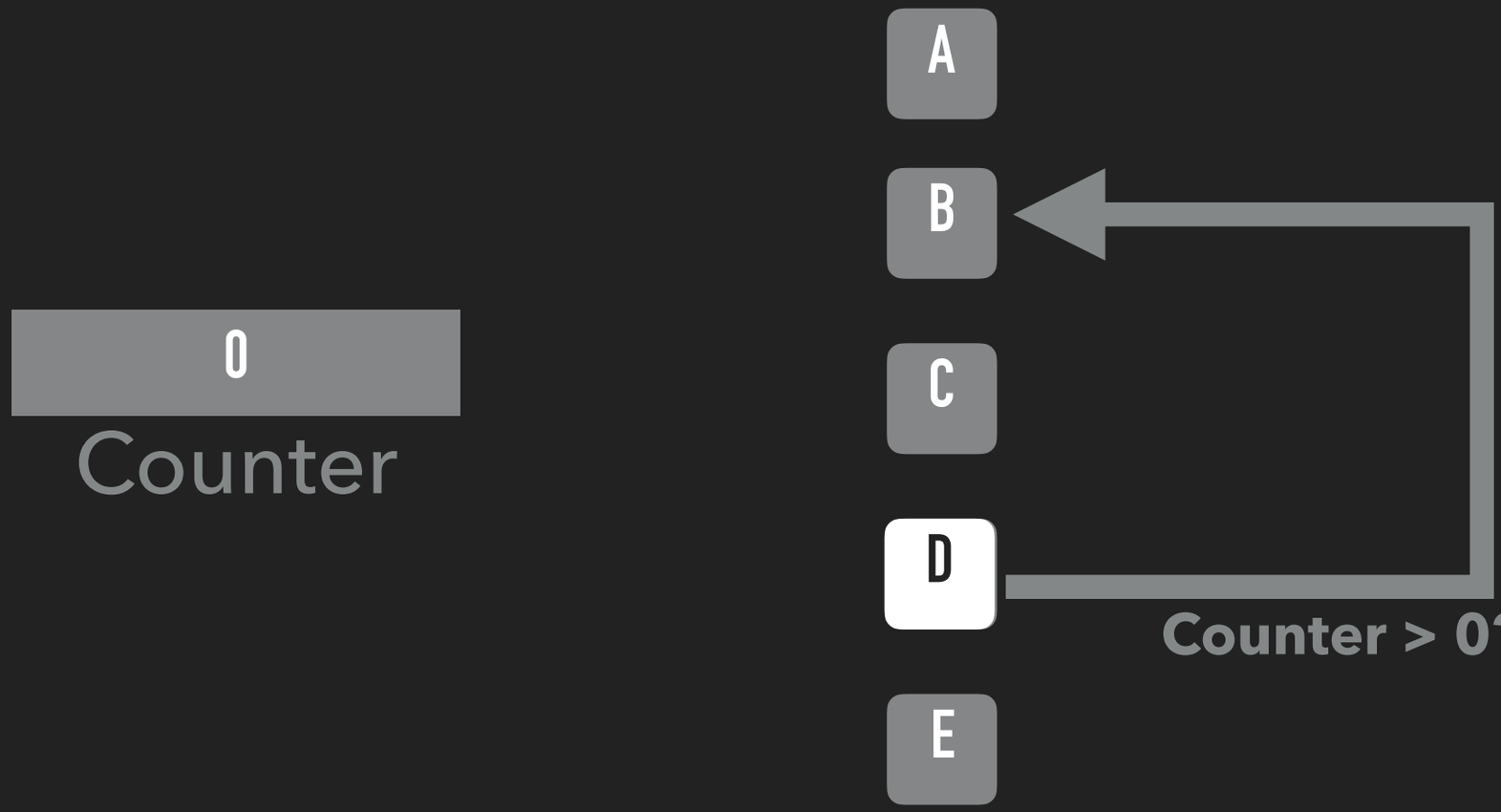

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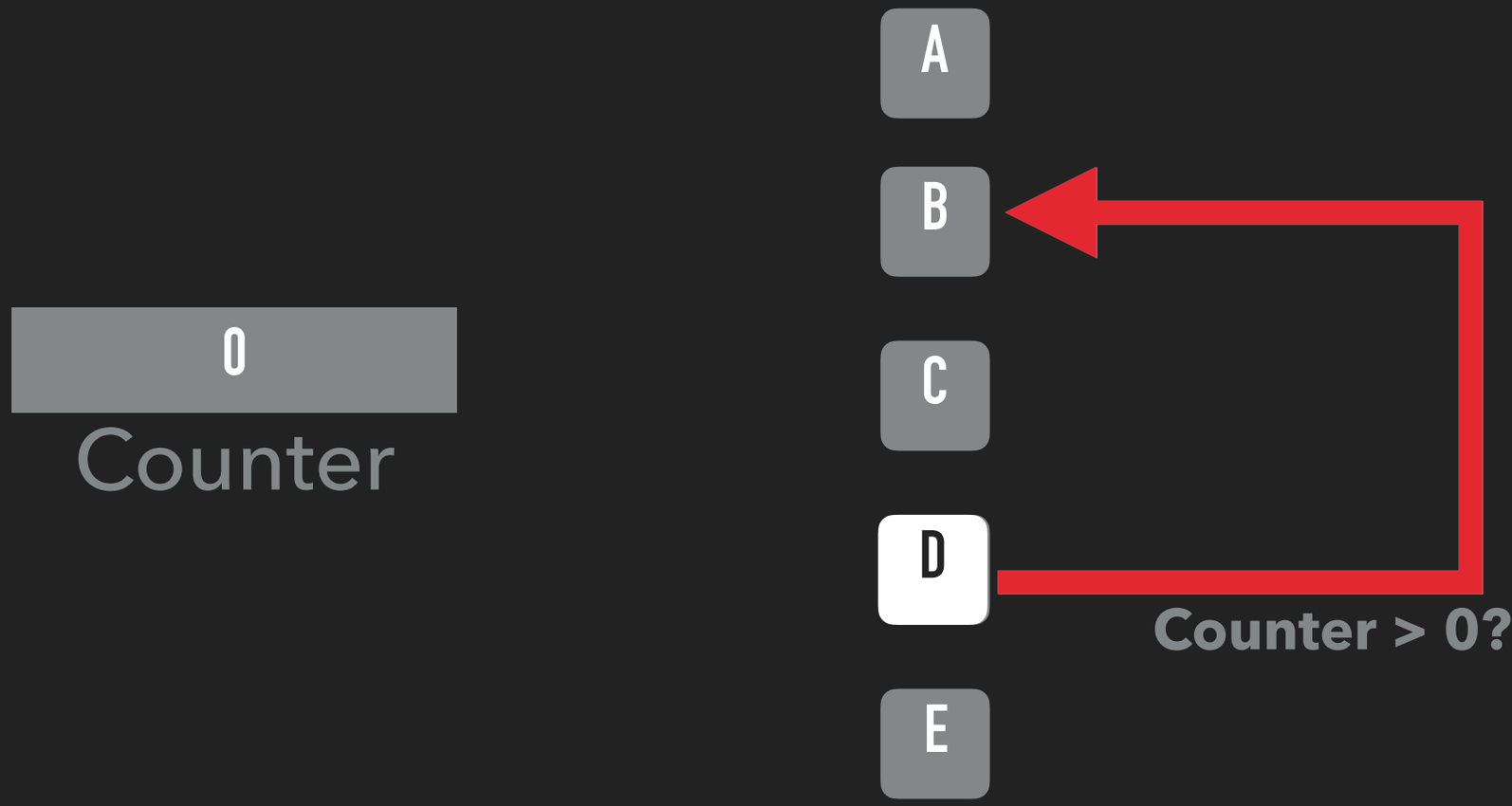

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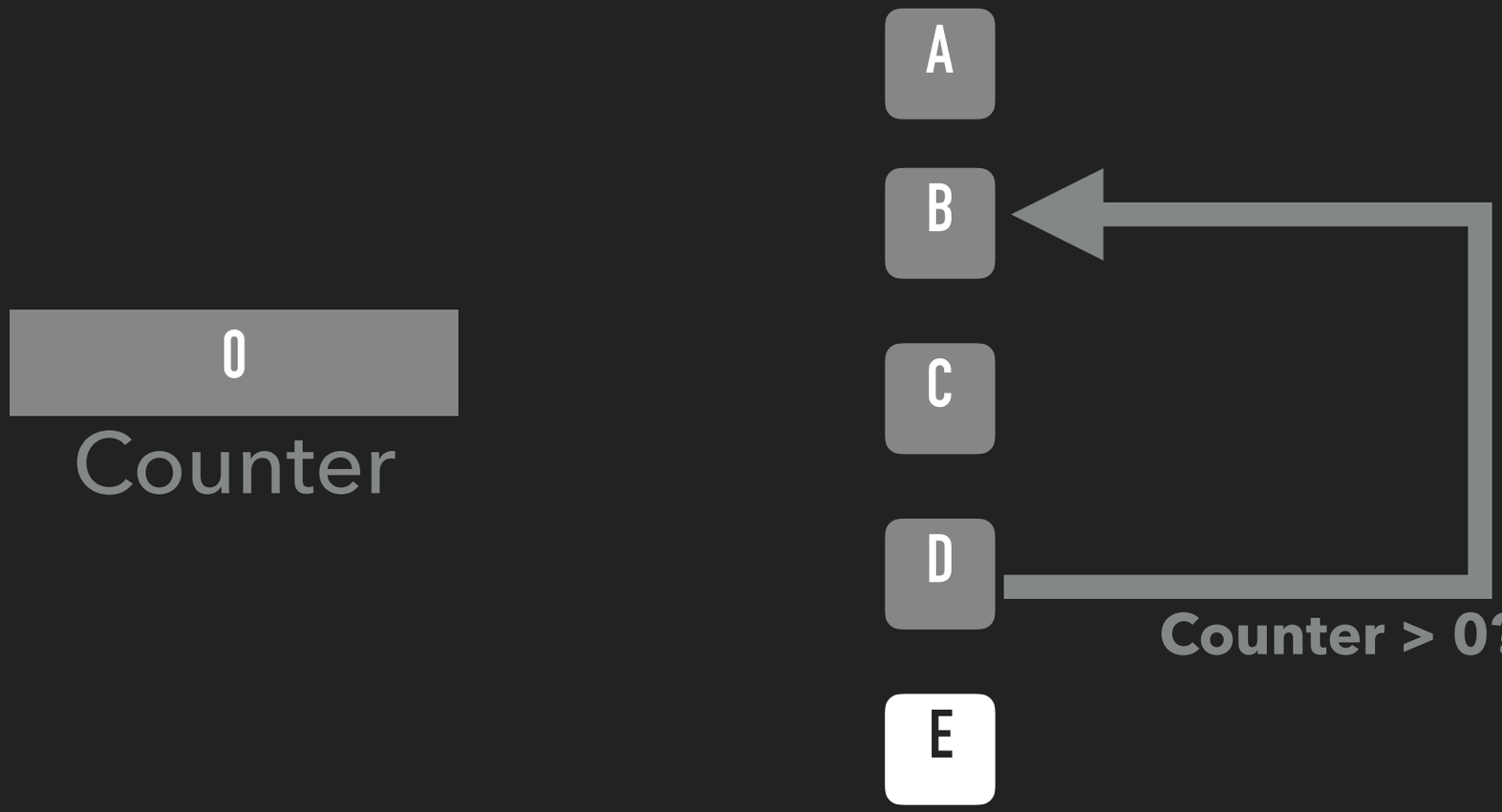

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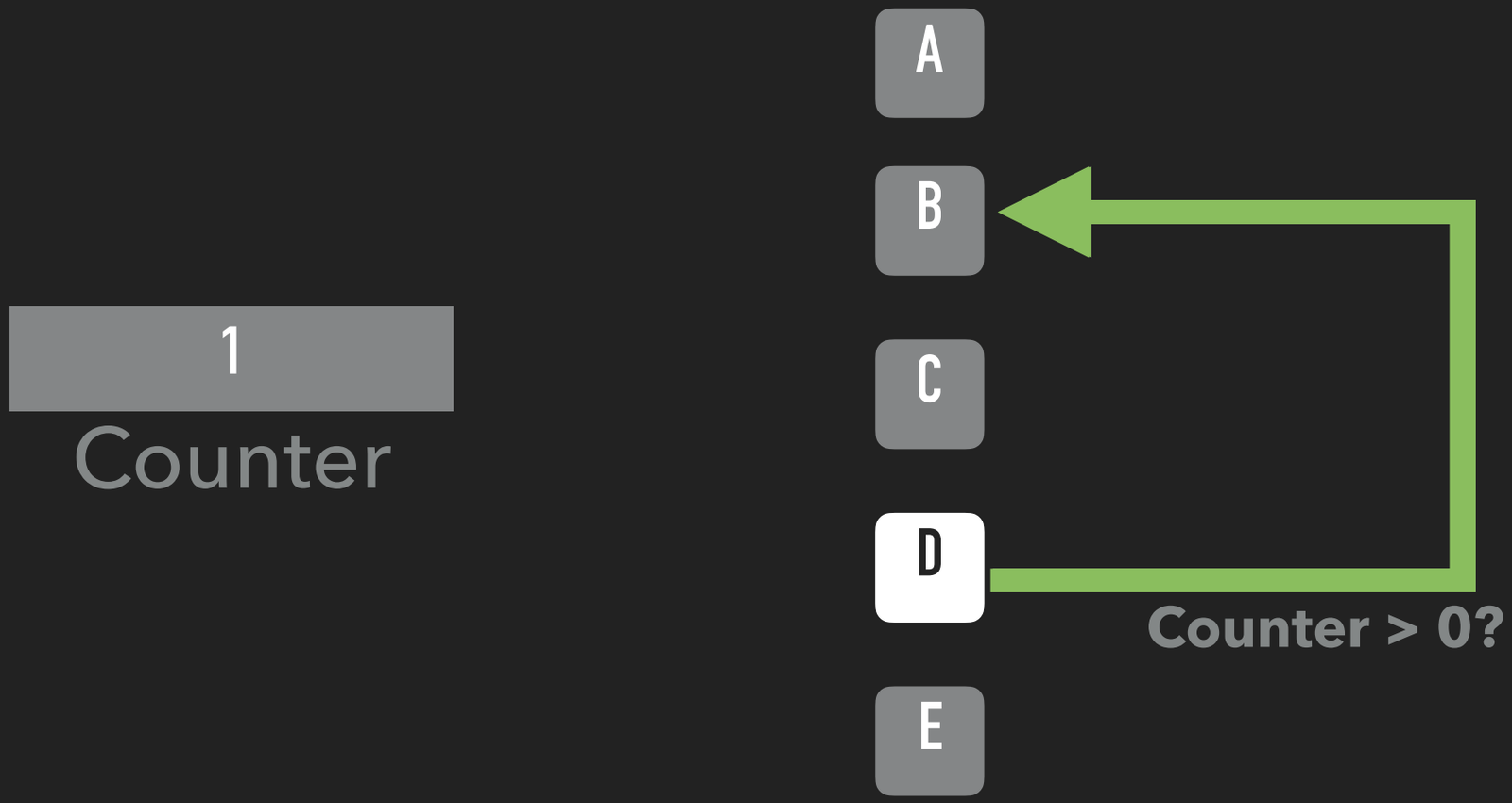

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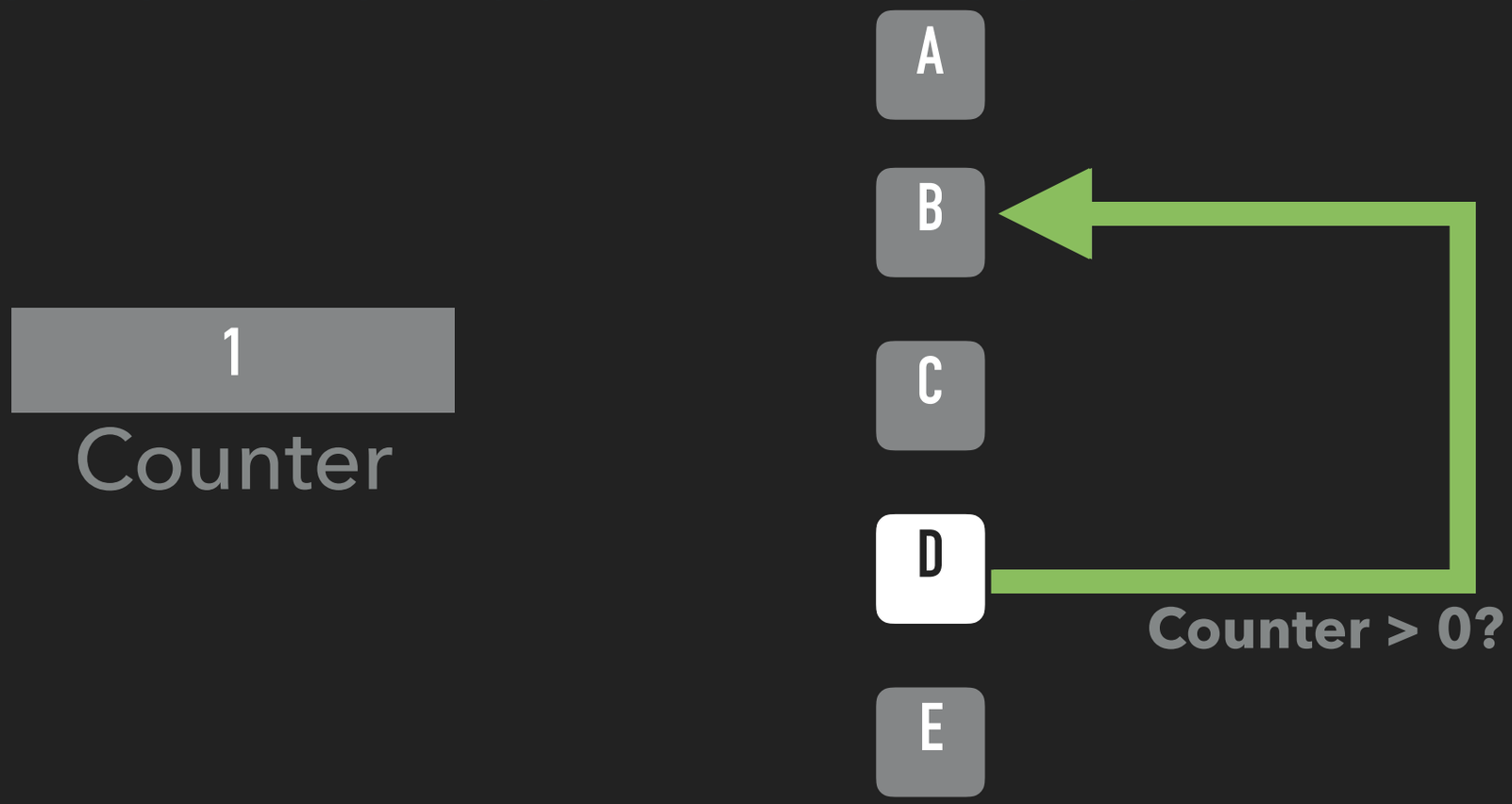

The CPU has learned that Counter *probably* is > 0

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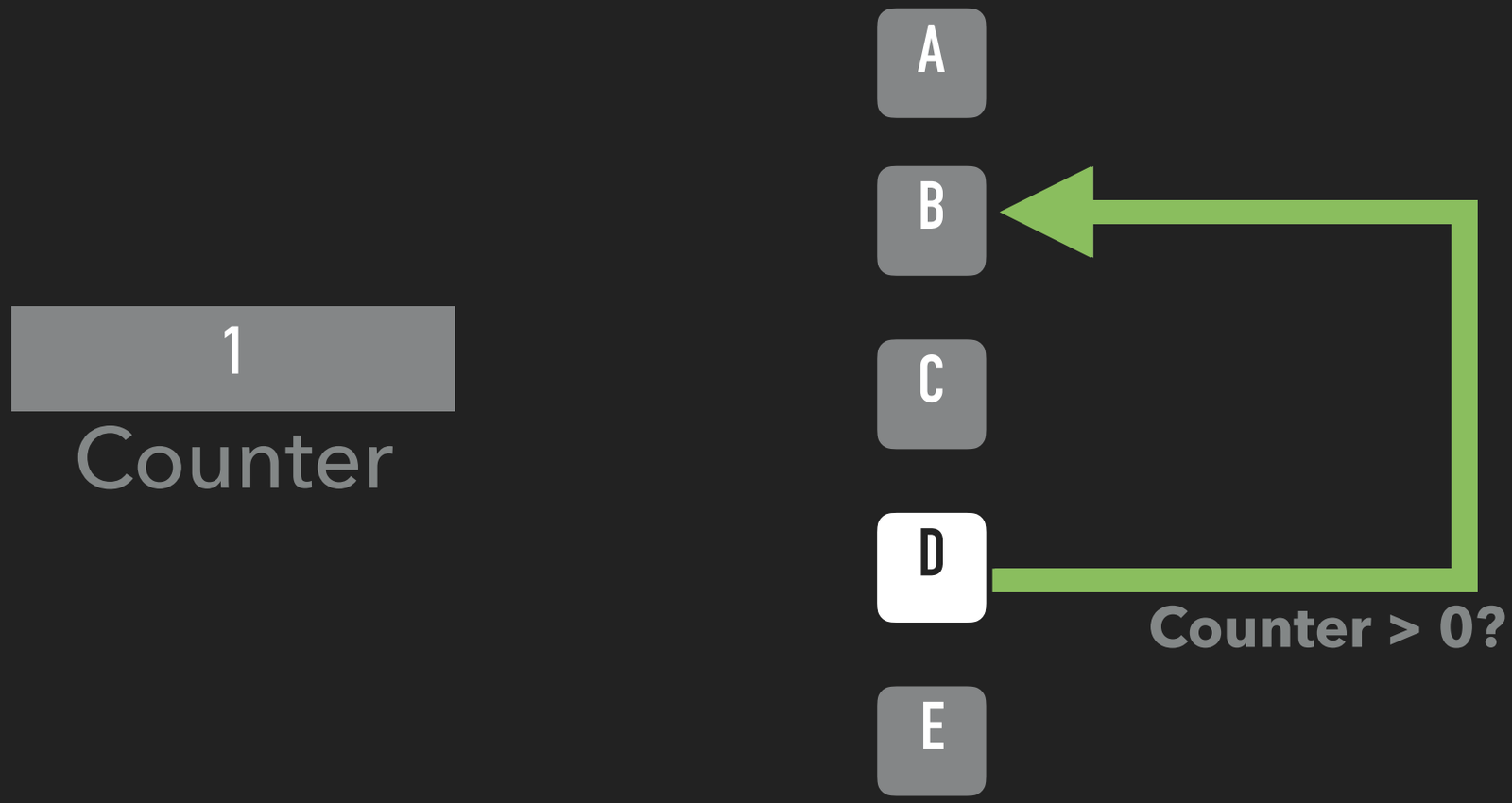

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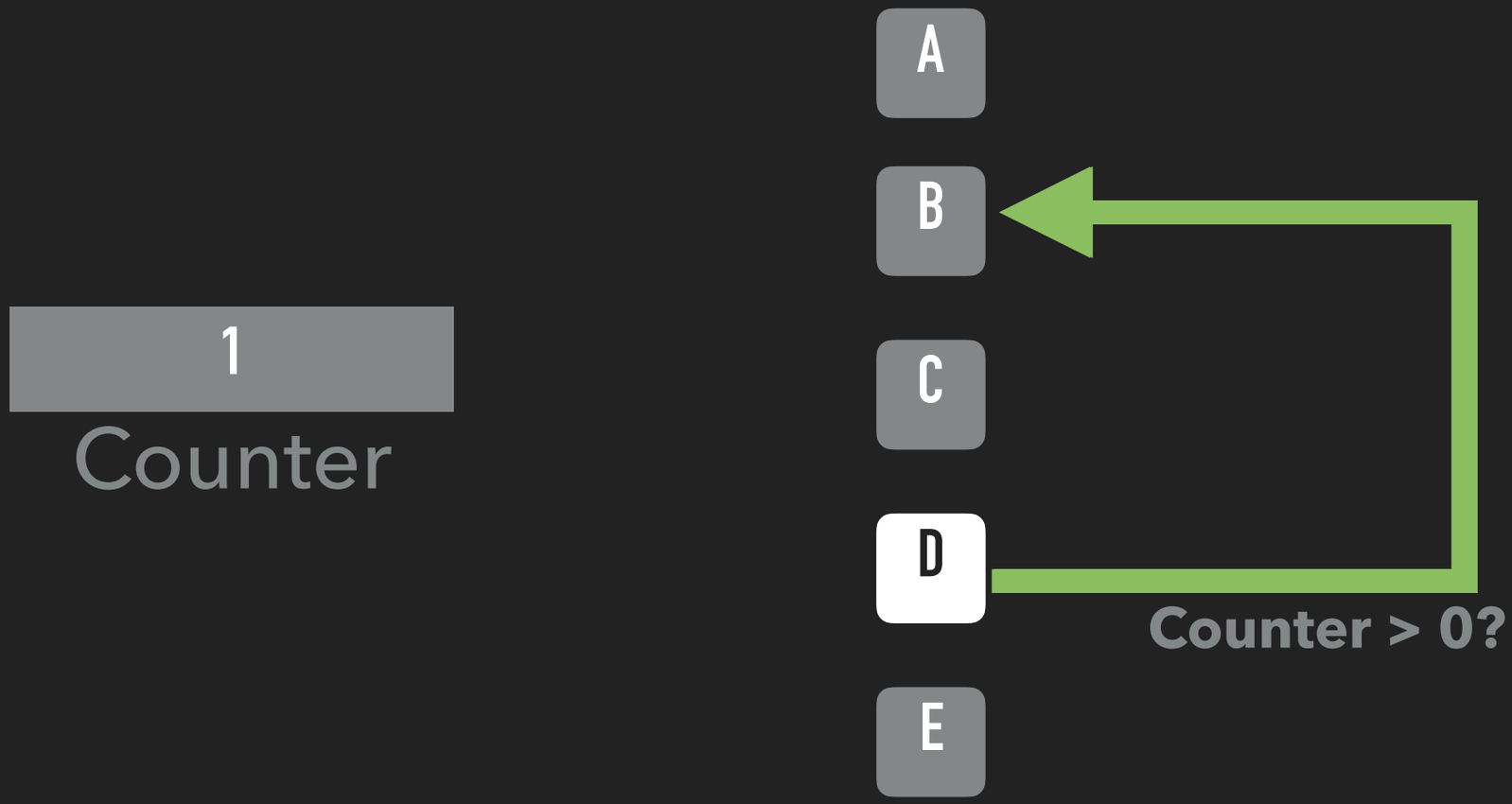

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The CPU *speculatively* executes B C to improve performance

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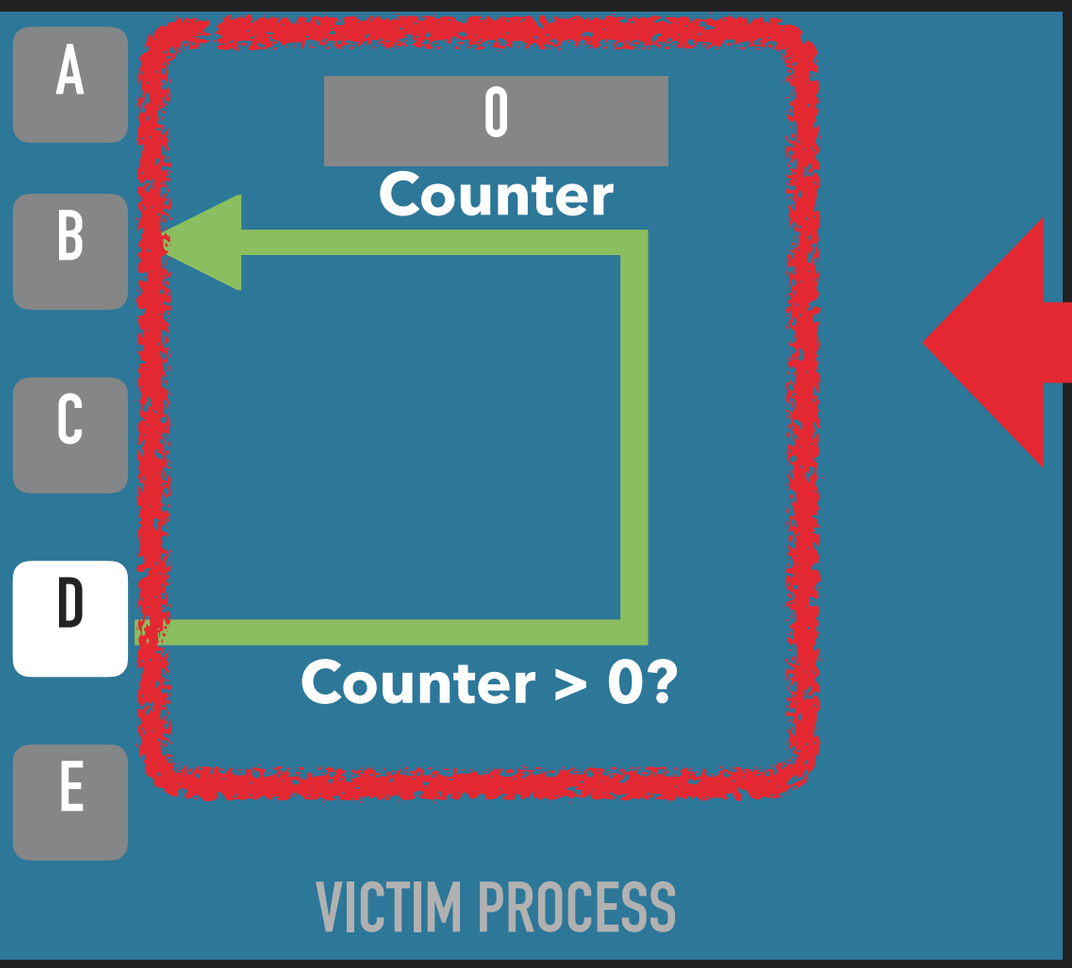

1. **Prime the branch prediction to expect a loop**
2. **Make sure *Counter* is not cached so the CPU is more likely to *speculatively* run the code**
3. **Find a way victim leaks data when B &C are executed speculatively**

ATTACKER PROCESS

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];
```

- 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
2. speculatively runs even when x > array1_size

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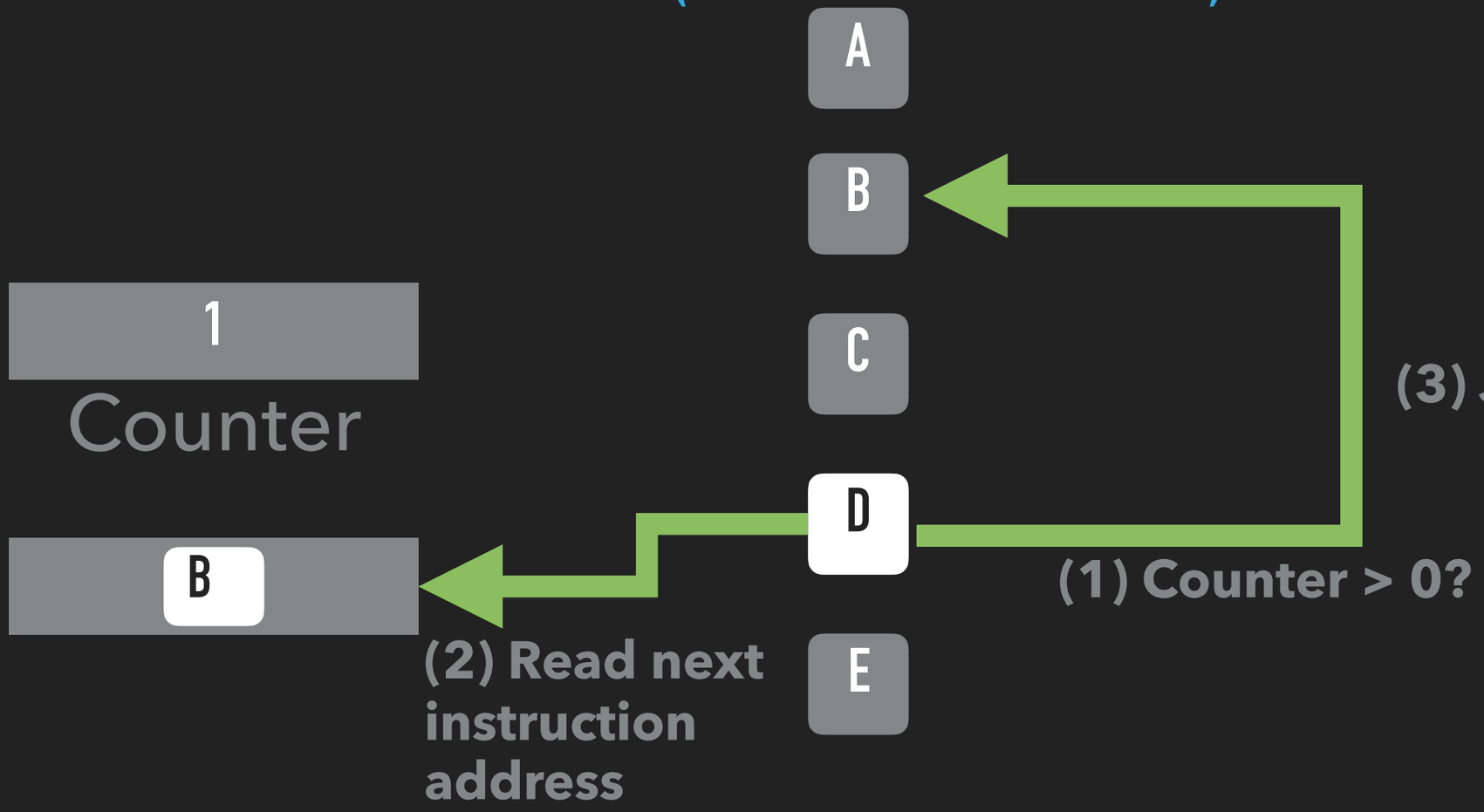
```

- 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)

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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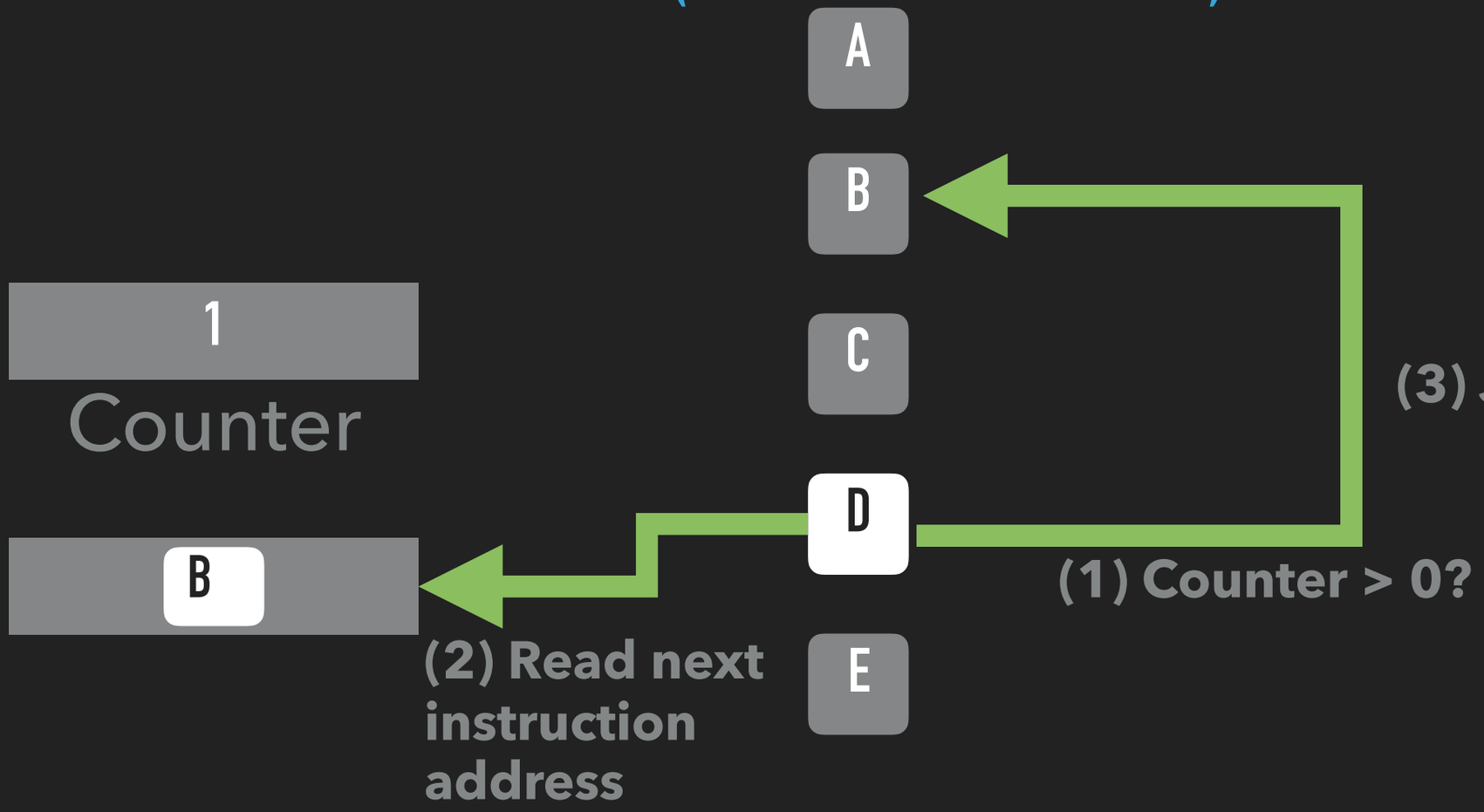

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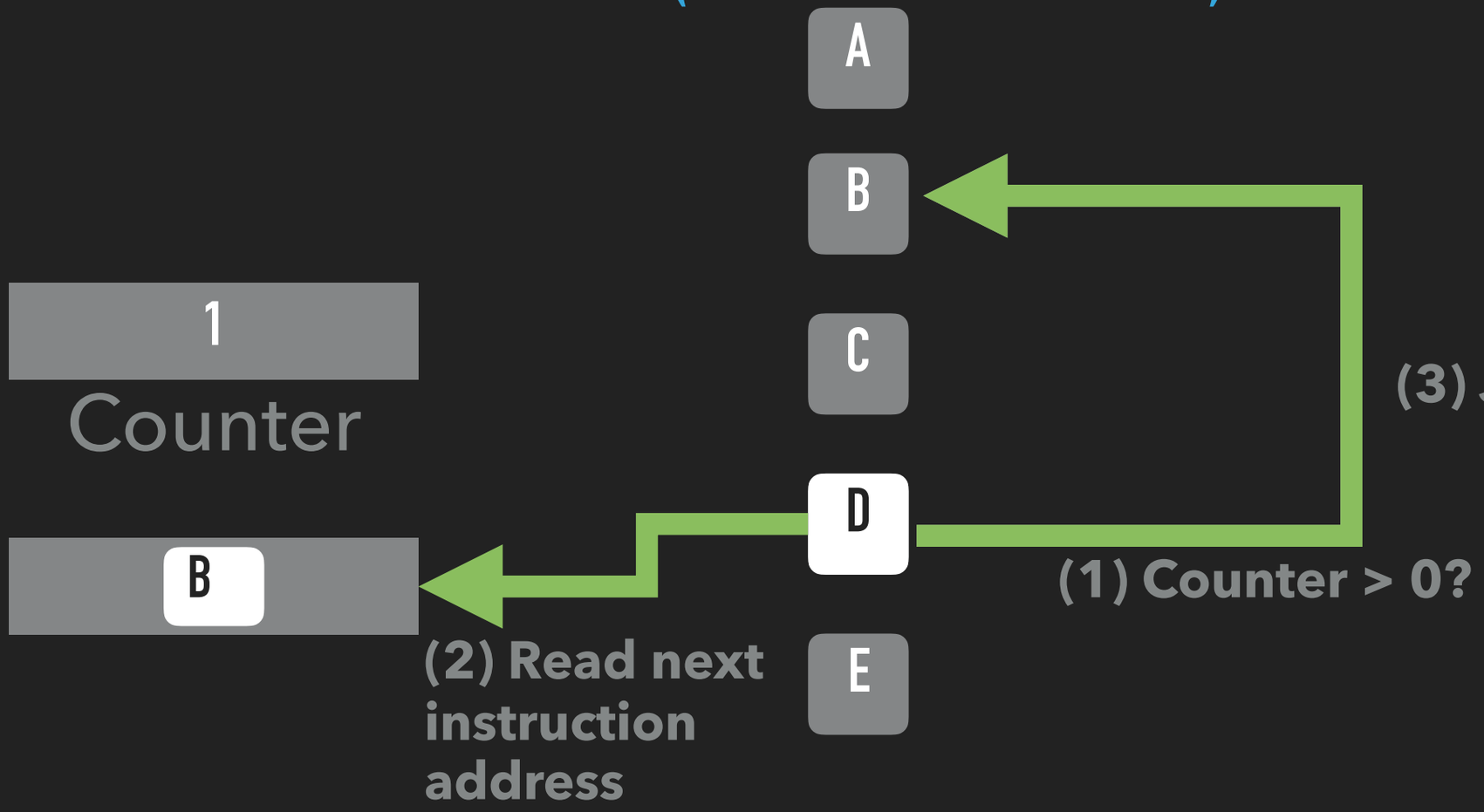

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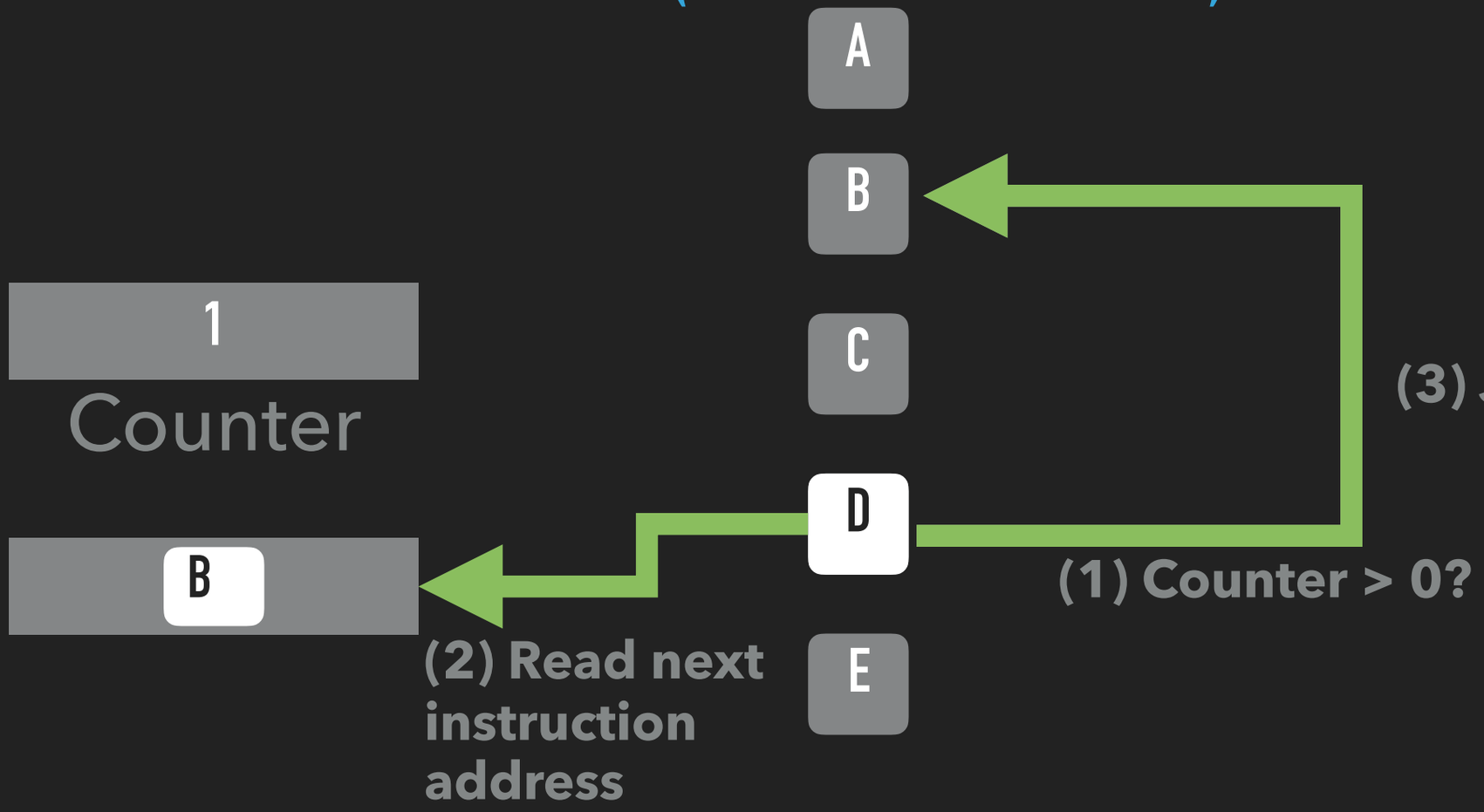

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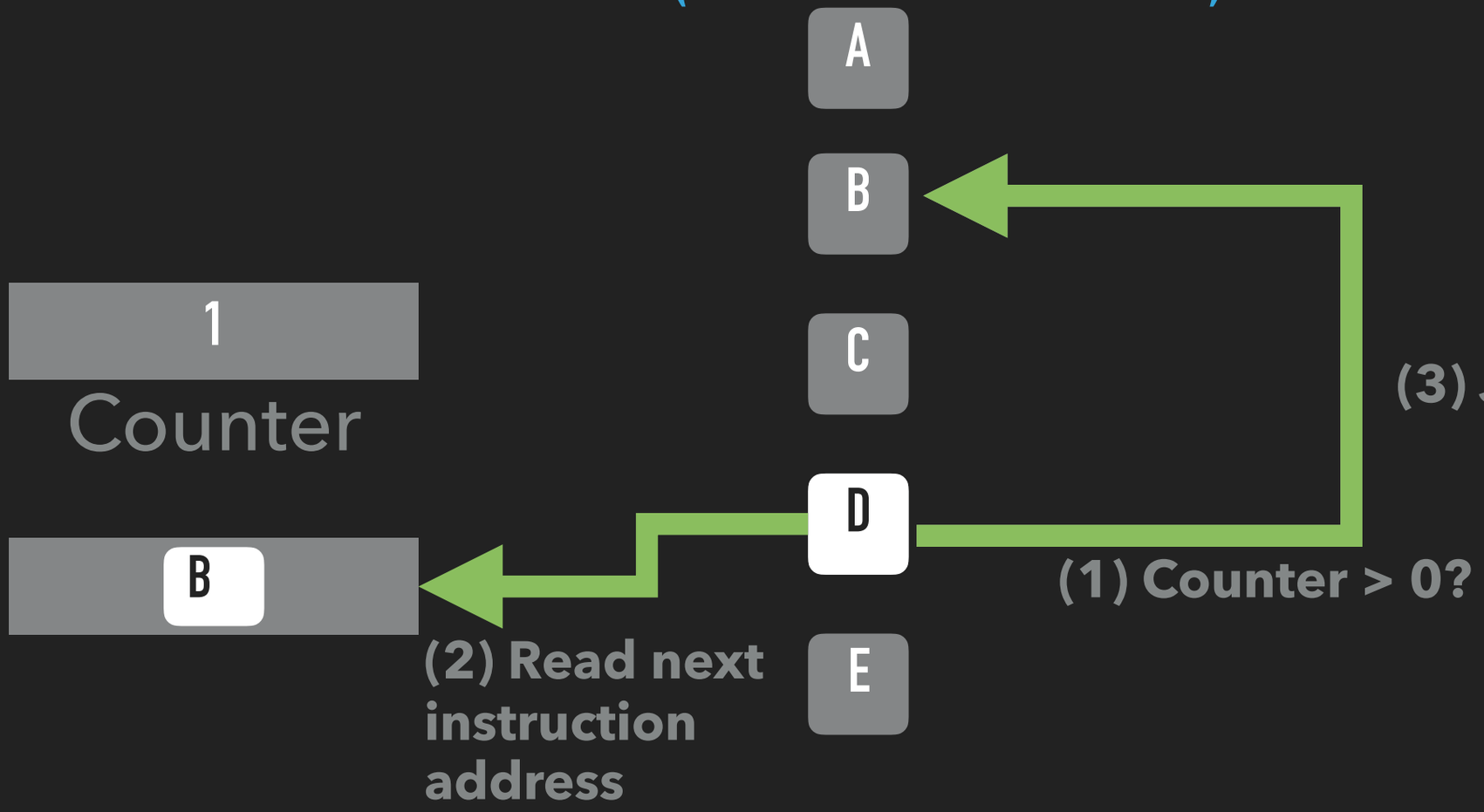

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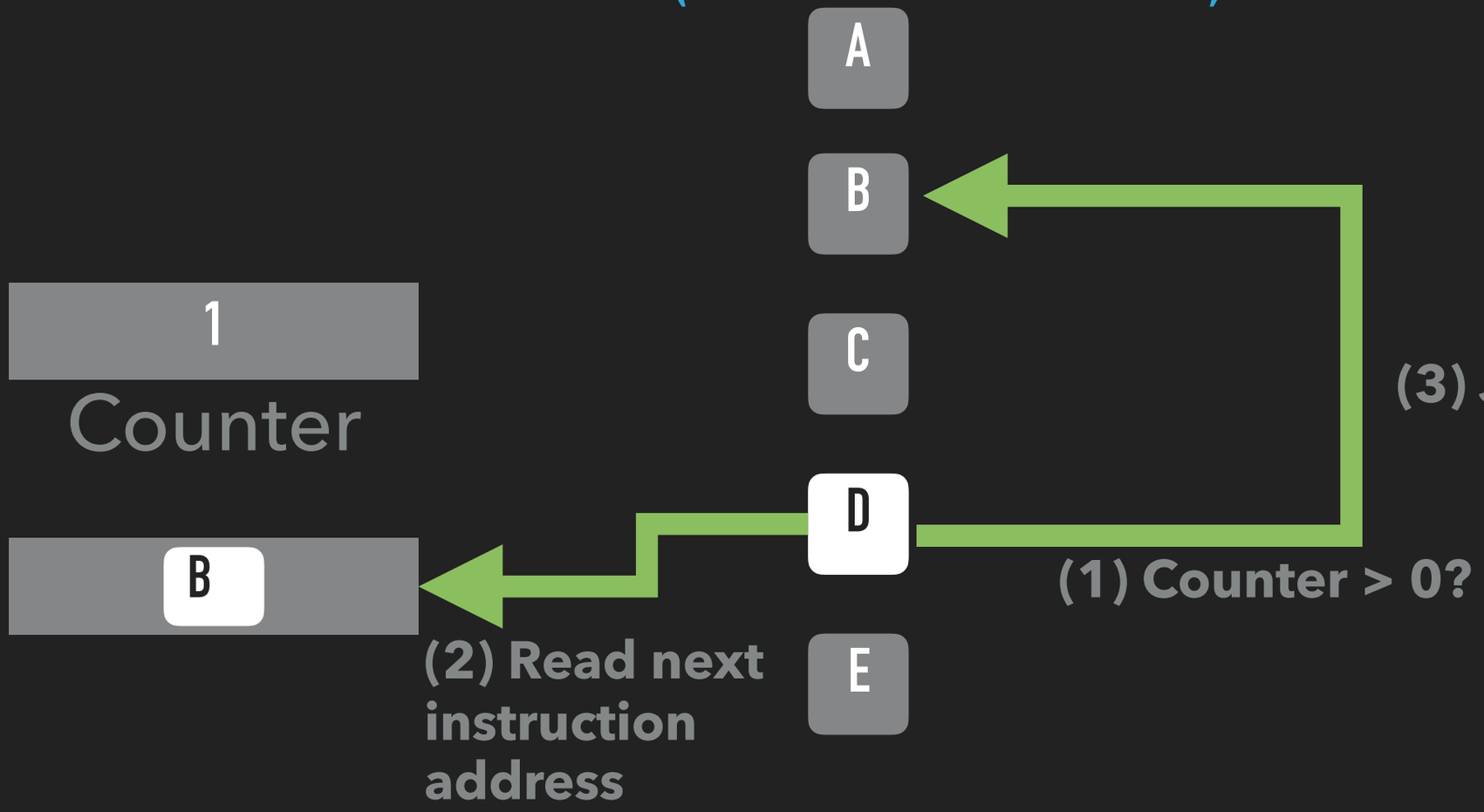

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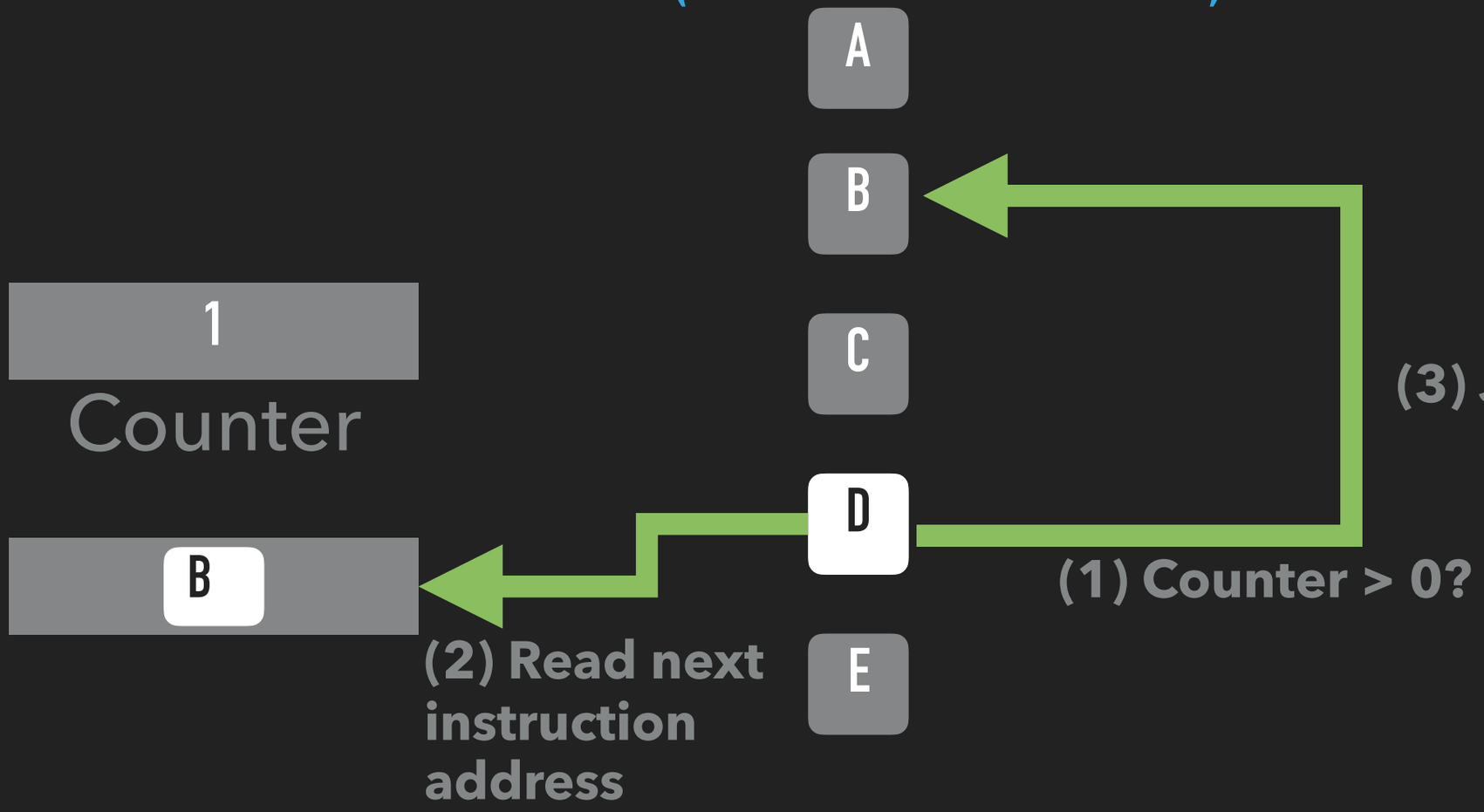

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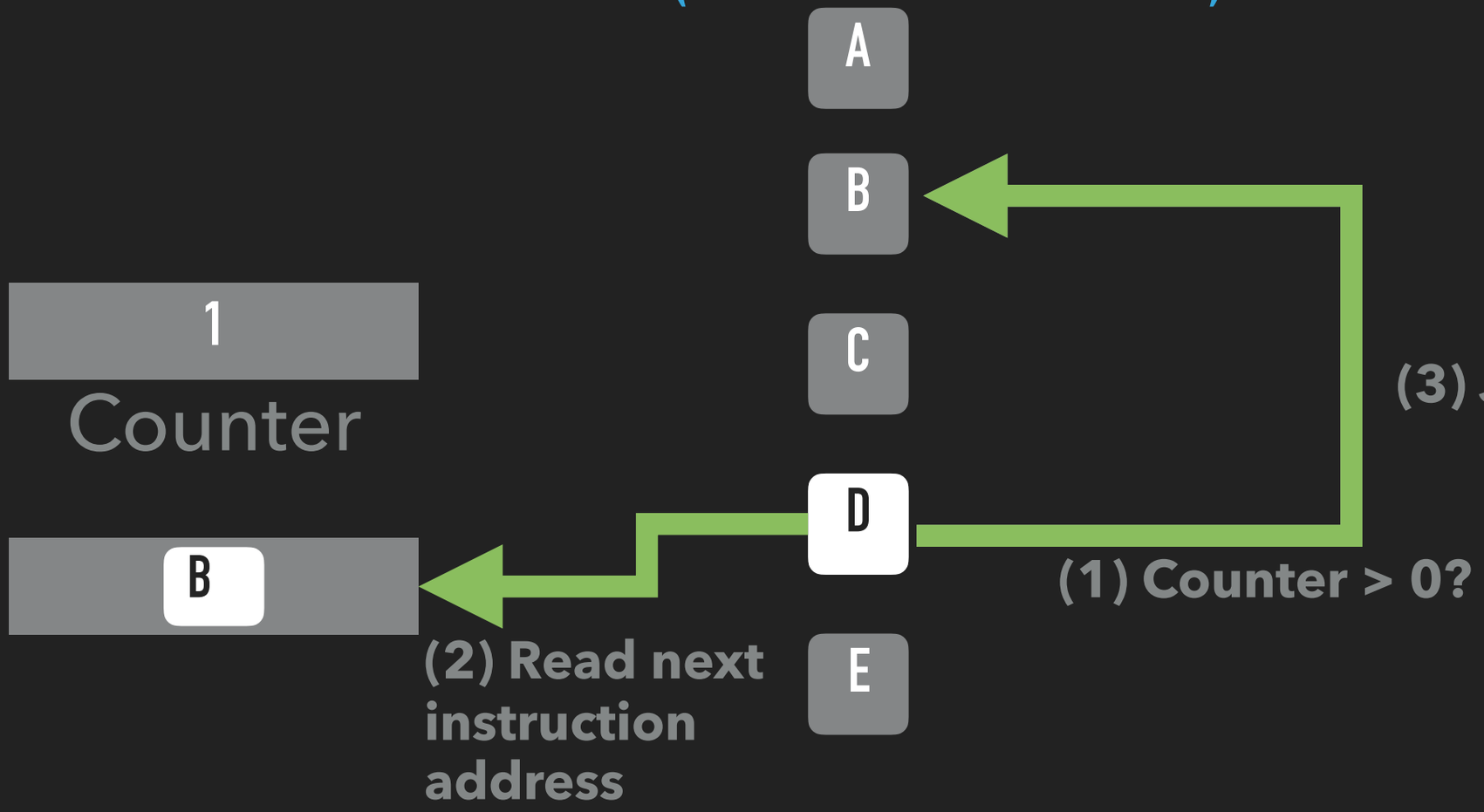

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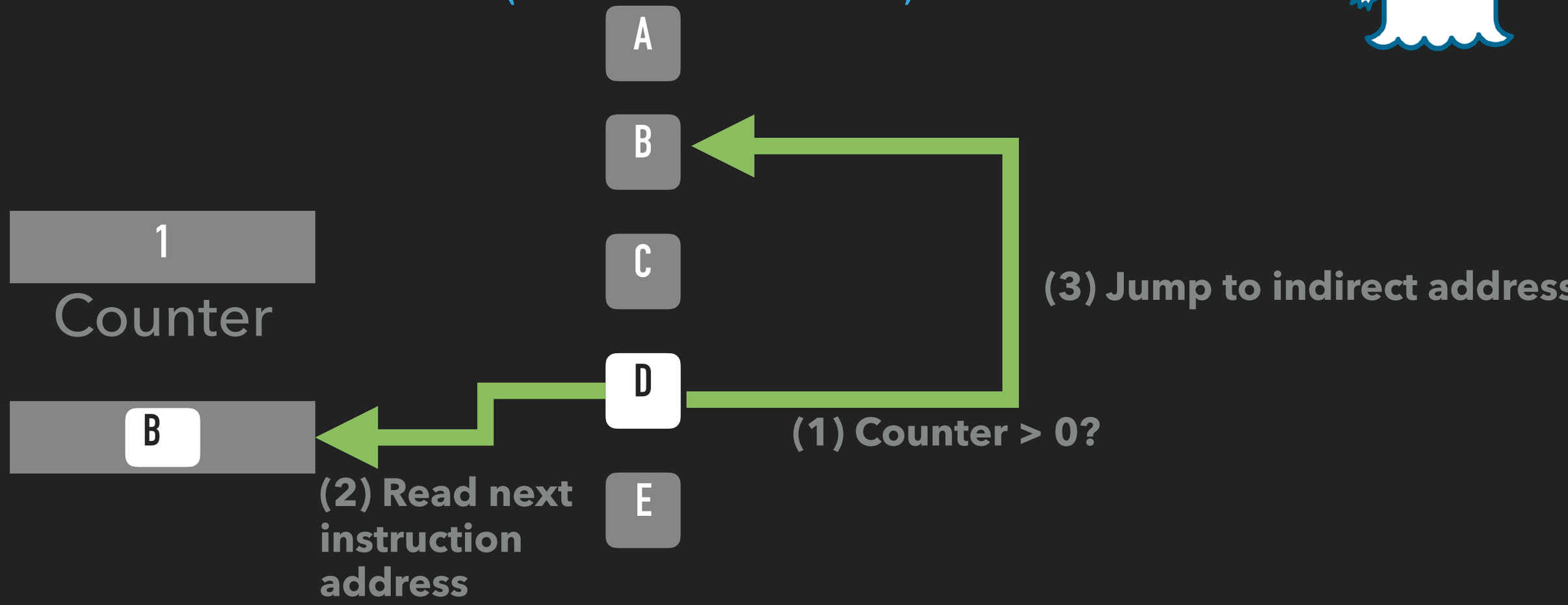

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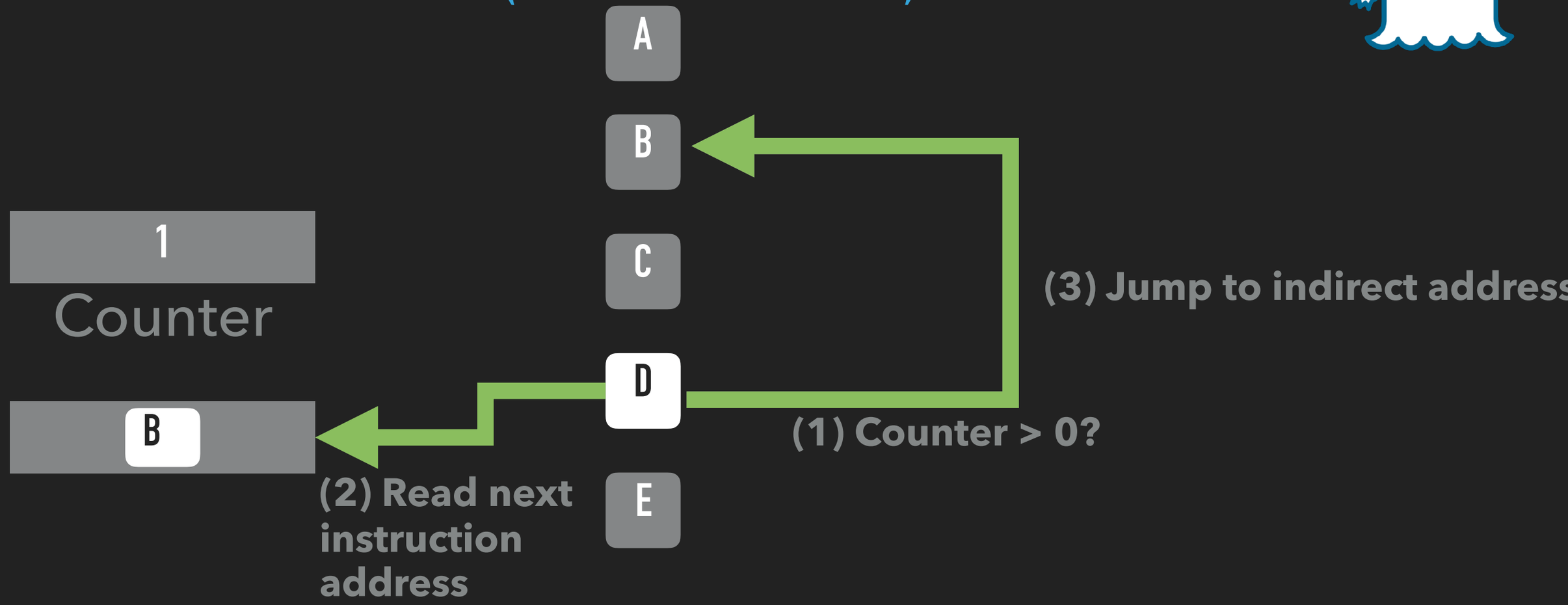

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MELTDOWN AND SPECTRE

CONCLUSION

THREAT-O-METER

LOW RISK

Exploit unlikely or running untrusted code already worst case

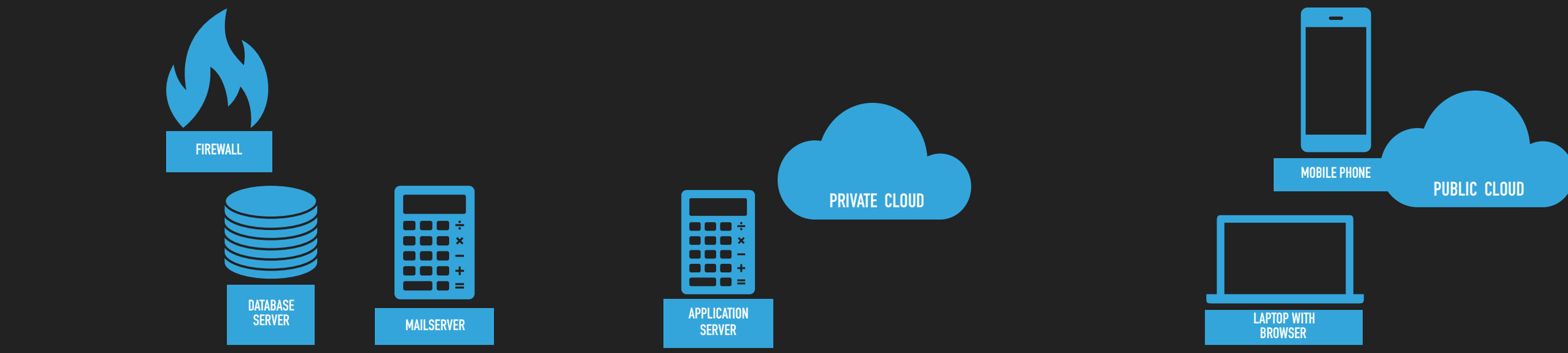
MEDIUM RISK

Exploit possible but needs another successful attack to run attackers code

HIGH RISK

Exploit possible and runs untrusted code “by design”

THREAT-O-METER



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Meltdown and Spectre exploit side effects of modern CPU architectures.

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Meltdown and Spectre exploit side effects of modern CPU architectures.

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

BLIC CLOUD

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Expect new “bugs” of this type!

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Q & A

https://github.com/neuhalje/presentation_meltdown_spectre

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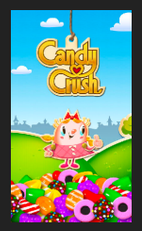
HTTPS://SPECTREATTACK.COM/



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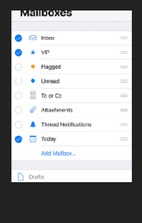

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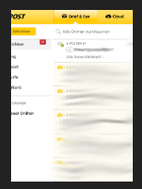

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ASSETS

ABANDONED SLIDES