Principles for secure design

Some of the slides and content are from Mike Hicks' Coursera course

Making secure software

- **Flawed approach**: Design and build software, and ***ignore security at first***
  - Add security once the functional requirements are satisfied

- **Better approach**: ***Build security in*** from the start
  - Incorporate security-minded thinking into all phases of the development process

Development process

<u>Four common **phases** of development</u>

- **Requirements**
- **Design**
- **Implementation**
- **Testing/assurance**

Security Requirements
Abuse Cases
Architectural Risk Analysis
Security-oriented Design
Code Review (with tools)
Risk-based Security Tests
Penetration Testing

Security activities apply to *all* phases

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Designing secure systems

- **Model** your threats
- Define your **security requirements**
  - What distinguishes a security requirement from a typical “software feature”?
- Apply good security **design principles**

Threat Modeling

Threat Model

- The **threat model** **makes explicit the adversary's assumed powers**
  - Consequence: The threat model must match reality, otherwise the risk analysis of the system will be wrong

- The threat model is **critically important**
  - If you are not explicit about what the attacker can do, how can you assess whether your design will repel that attacker?

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"This system is secure" means *nothing* in the absence of a threat model

A few different network threat models

Malicious user

A few different network threat models

A few different network threat models

A few different network threat models

Threat-driven Design

- Different threat models will elicit different responses

- **Only malicious users:** implies **message** traffic **is safe**
  - No need to encrypt communications
  - This is what `telnet` remote login software assumed

- **Snooping attackers:** means **message** traffic **is visible**
  - So use encrypted wifi (link layer), encrypted network layer (IPsec), or encrypted application layer (SSL)
    - Which is most appropriate for your system?

More on these when we get to networking

- **Co-located attacker:** can **access local files, memory**
  - Cannot store unencrypted secrets, like passwords
  - Likewise with a compromised server

In fact, even encrypting them might not suffice! (More later)

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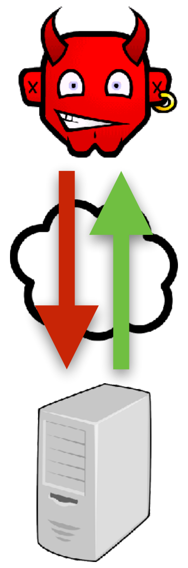

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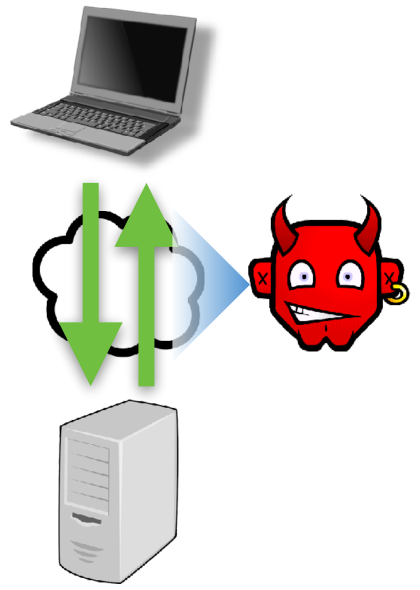

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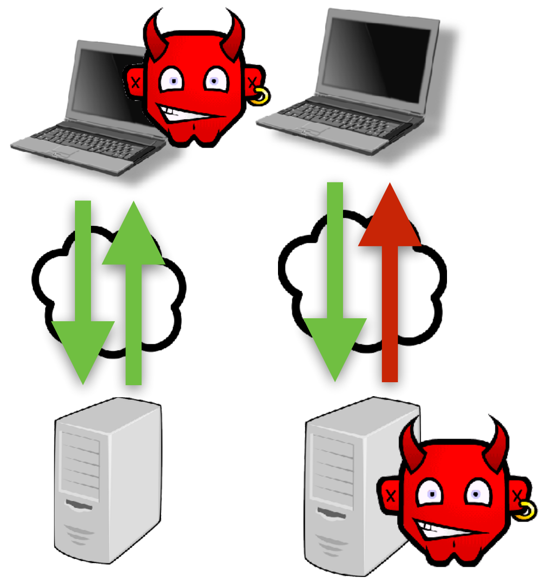

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- Other mistaken assumptions
  - **Assumption**: Encrypted traffic carries no information
    - Not true! By analyzing the size and distribution of messages, you can infer application state
  - **Assumption**: Timing channels carry little information
    - Not true! Timing measurements of previous RSA implementations could be used eventually reveal a remote SSL secret key

Bad Model = Bad Security

Assumption: Encrypted traffic carries no information

Skype encrypts its packets, so we're not revealing anything, right?

Language Identification of Encrypted VoIP Traffic:
Alejandra y Roberto or Alice and Bob?

Charles V. Wright *Lucas Ballard* *Fabian Monrose* *Gerald M. Masson*

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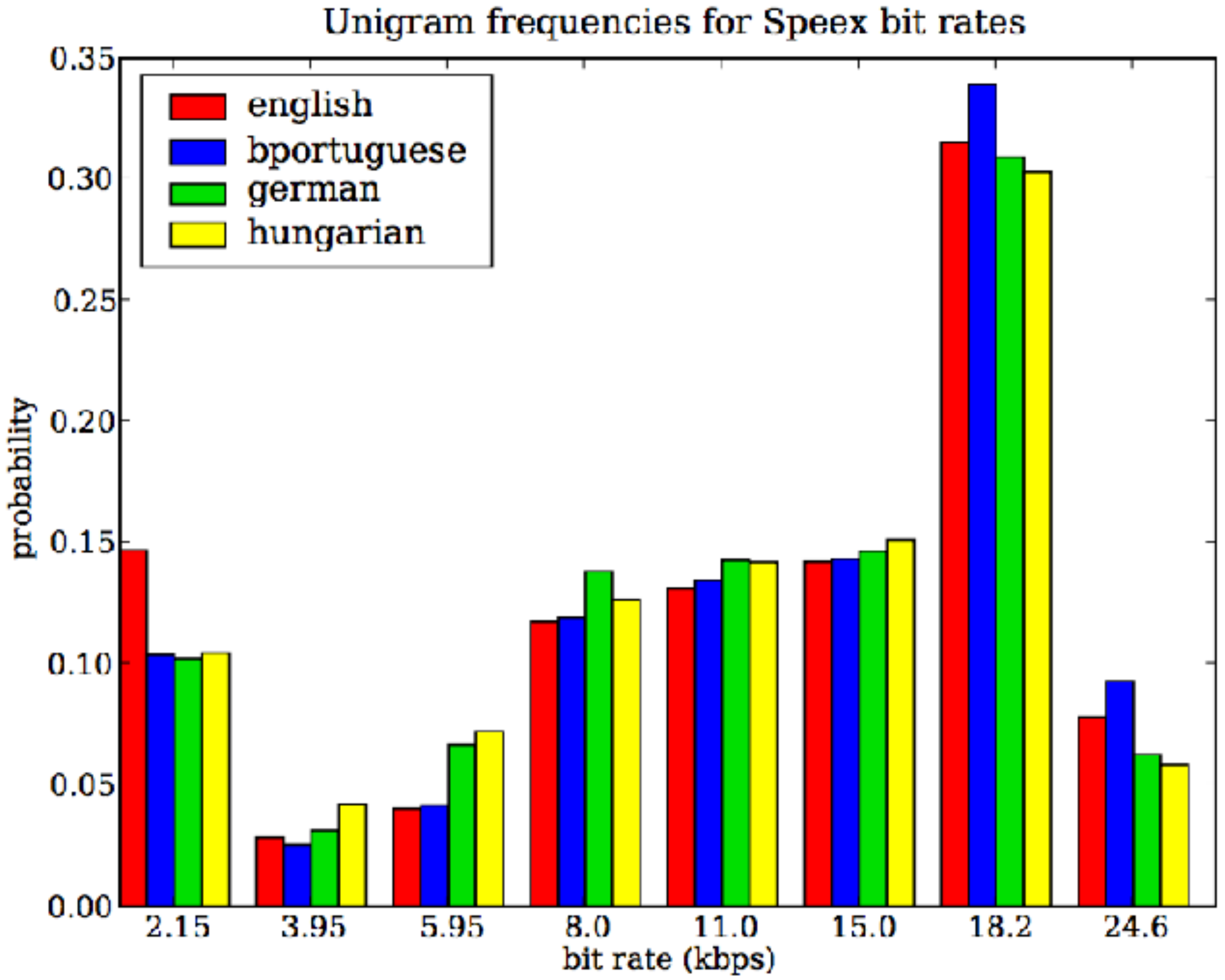

Figure 2: Unigram frequencies of bit rates for English, Brazilian Portuguese, German and Hungarian

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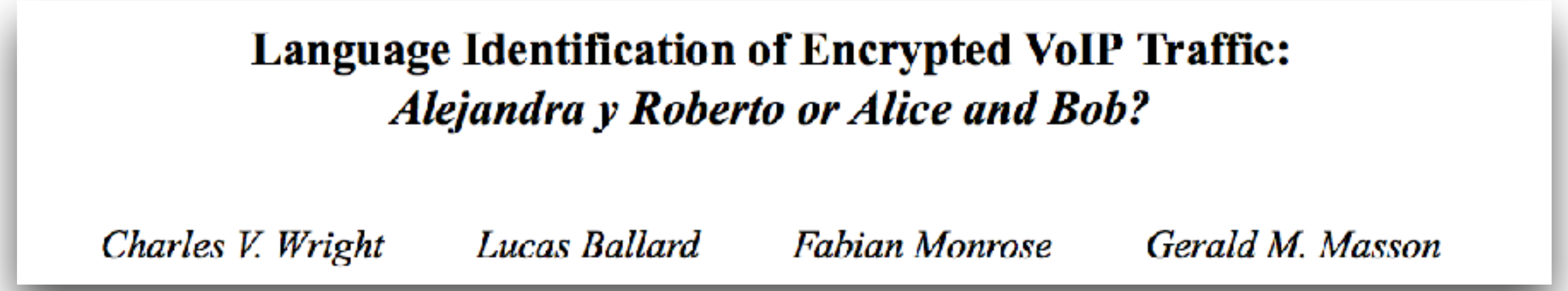

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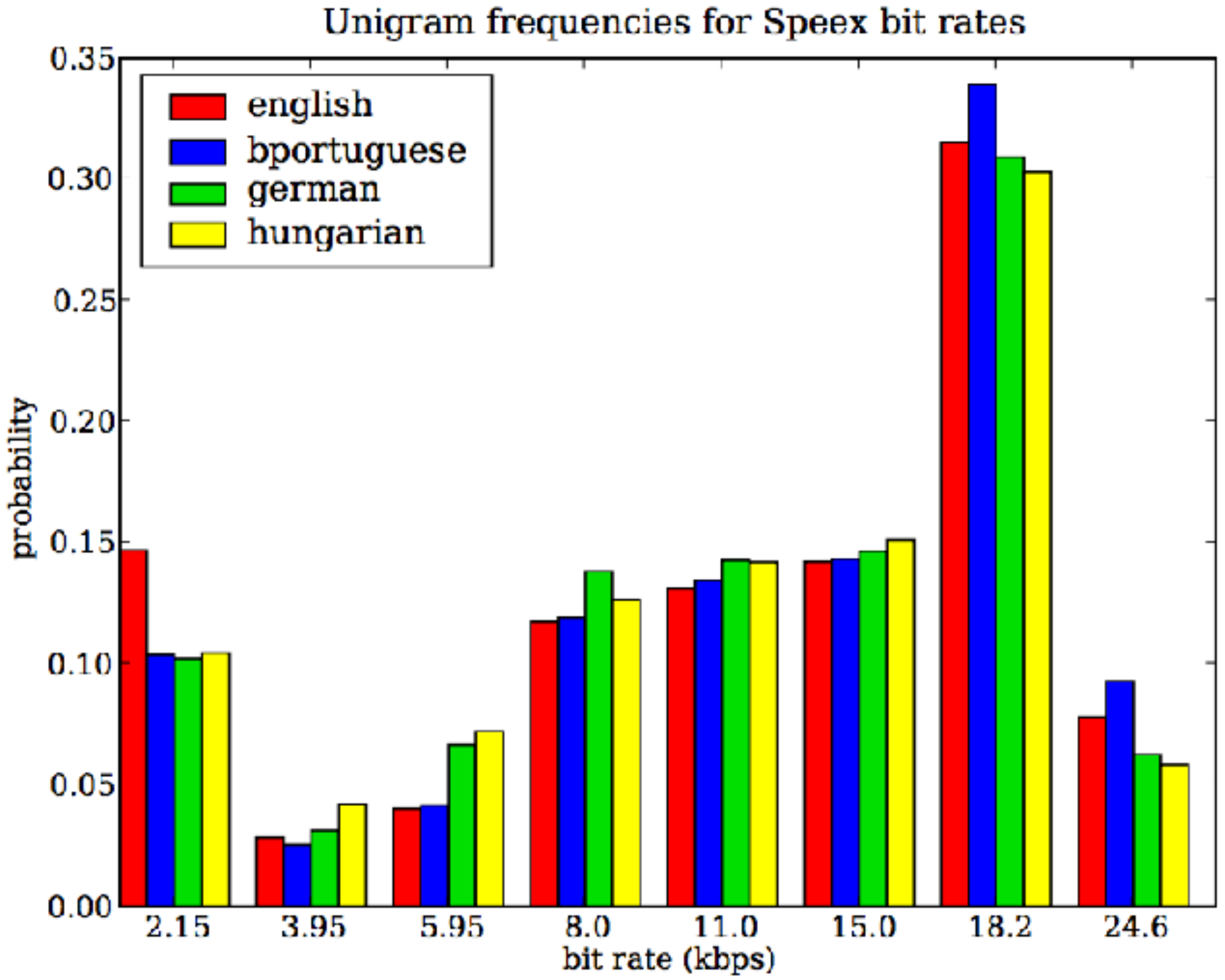

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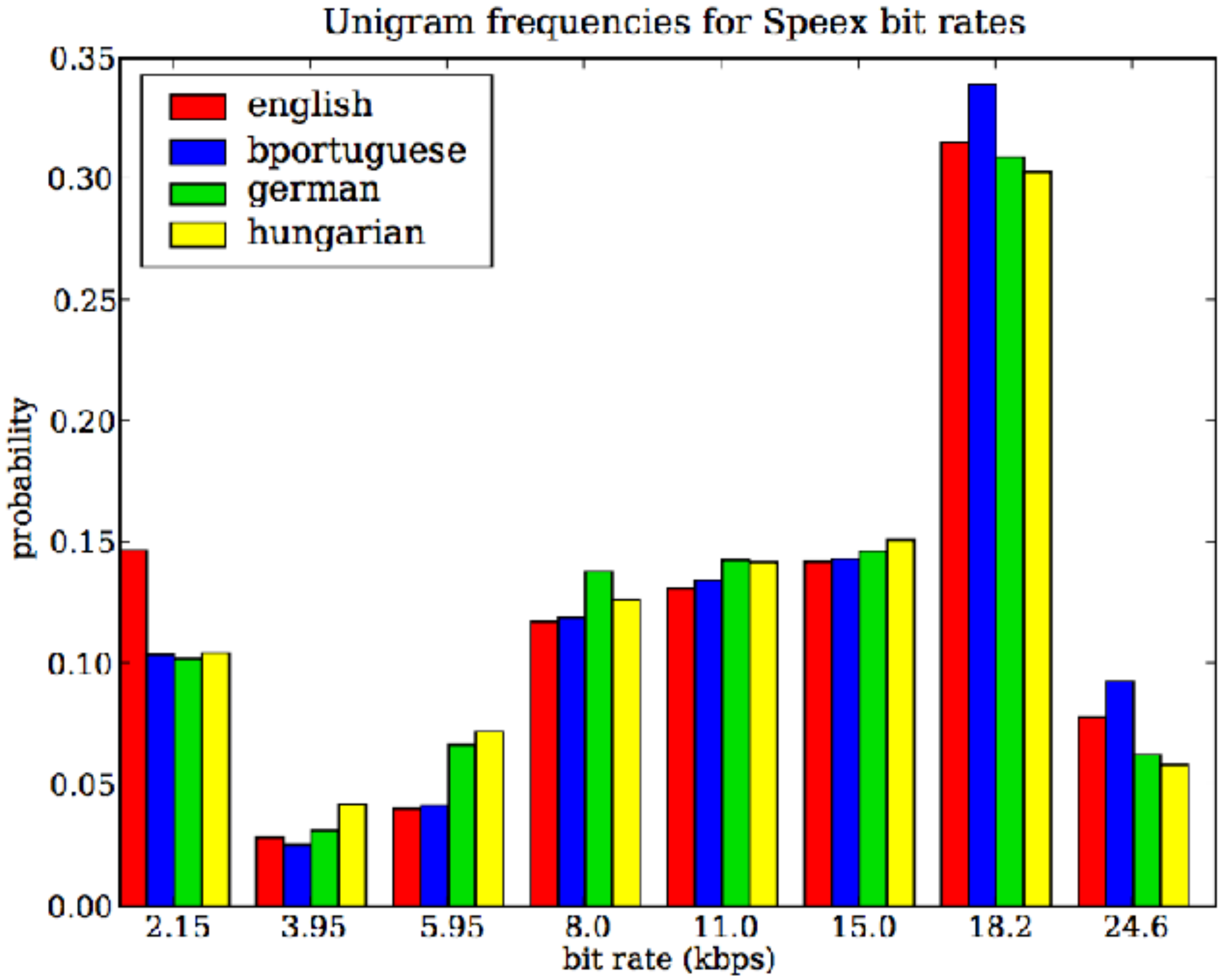
…and different languages have different word/unigram lengths…

…so you can infer *what language* two people are speaking based on **packet sizes**!



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Finding a good model

- **Compare against similar systems**
  - What attacks does their design contend with?
- **Understand past attacks and attack patterns**
  - How do they apply to your system?
- **Challenge assumptions in your design**
  - What happens if an assumption is untrue?
    - What would a breach potentially cost you?
  - How hard would it be to get rid of an assumption, allowing for a stronger adversary?
    - What would that development cost?

You have your threat model.

Now let's define what we need to defend against.

Security Requirements

Security Requirements

- **Software requirements** typically about **what** the **software should do**

- We also want to have **security requirements**
  - **Security-related goals** (or **policies**)
    - **Example**: One user's bank account balance should not be learned by, or modified by, another user, unless authorized
  - **Required mechanisms for enforcing them**
    - **Example**:
      1. Users identify themselves using passwords,
      2. Passwords must be "strong," and
      3. The password database is only accessible to login program.

Typical *Kinds* of Requirements

- **Policies**
  - **Confidentiality** (and Privacy and Anonymity)
  - **Integrity**
  - **Availability**

- Supporting **mechanisms**
  - **Authentication**
  - **Authorization**
  - **Audit-ability**
  - **Encryption**

Supporting mechanisms

These relate identities (“**principals**”) to **actions**

<u>Authentication</u> **<u>Authorization</u>** **<u>Audit-ability</u>**

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What we have
What we *are*
>1 of the above =
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Retain enough info to determine the circumstances of a breach

Defining Security Requirements

- Many processes for deciding security requirements

- Example: **General policy concerns**
  - Due to **regulations**/standards (HIPAA, SOX, etc.)
  - Due **organizational values** (e.g., valuing privacy)

- Example: **Policy arising from threat modeling**
  - Which **attacks** cause the **greatest concern**?
    - Who are the likely adversaries and what are their goals and methods?
  - Which **attacks** have **already occurred**?
    - Within the organization, or elsewhere on related systems?

Abuse Cases

- Abuse cases illustrate security requirements
- Where use cases describe what a system *should* do, **abuse cases describe what it should *not* do**
- Example **use case**: The system allows bank managers to modify an account's interest rate
- Example **abuse case**: A user is able to spoof being a manager and thereby change the interest rate on an account

Defining Abuse Cases

- Construct cases in which an **adversary's exercise of power** could **violate a security requirement**
  - Based on the threat model
  - What might occur if a security measure was removed?

- **Example**: *Co-located attacker* steals password file and learns all user passwords
  - Possible if password file is not encrypted
- **Example**: *Snooping attacker* **replays** a captured message, effecting a bank withdrawal
  - Possible if messages are have no *nonce* (a small amount of uniqueness/randomness - like the time of day or sequence number)

Security design principles

Design Defects = Flaws

- Recall that software defects consist of both flaws and bugs
  - **Flaws** are problems in the **design**
  - **Bugs** are problems in the **implementation**

- **We avoid flaws during the design phase**

- According to Gary McGraw,
  50% of security problems are flaws
  - So this phase is very important

Categories of Principles

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  - **Goal**: Eliminate software defects entirely
  - **Example**: Heartbleed bug would have been prevented by using a type-safe language, like Java

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  - **Example**: Run each browser tab in a separate process, so exploitation of one tab does not yield access to data in another

- **Detection** (and **Recovery**)
  - **Goal**: Identify and understand an attack (and undo damage)
  - **Example**: Monitoring (e.g., expected invariants), snapshotting

Principles for building secure systems

General rules of thumb that,
when neglected, result in design flaws

- Security is economics
- Principle of least privilege
- Use fail-safe defaults
- Use separation of responsibility
- Defend in depth
- Account for human factors
- Ensure complete mediation
- Kerkhoff's principle

- Accept that threat models change
- If you can't prevent, detect
- Design security from the ground up
- Prefer conservative designs
- Proactively study attacks

“Security is economics”

You can’t afford to secure against *everything*, so what *do* you defend against?
Answer: That which has the greatest “return on investment”

THERE ARE NO SECURE SYSTEMS, ONLY DEGREES OF INSECURITY

- In practice, need to **resist a certain level of attack**
  - Example: Safes come with security level ratings
  - “Safe against safecracking tools & 30 min time limit”

- Corollary: Focus energy & time on **weakest link**

- Corollary: Attackers follow the *path of least resistance*

“Principle of least privilege”

Give a program the access it legitimately needs to do its job. NOTHING MORE

- This doesn’t necessarily reduce probability of failure
- Reduces the EXPECTED COST

- **Example**: Unix does a BAD JOB:
  - Every program gets all the privileges of the user who invoked it
  - vim as root: it can do anything -- should just get access to file

- **Example**: Windows JUST AS BAD, MAYBE WORSE
  - Many users run as Administrator,
  - Many tools require running as Administrator

“Use fail-safe defaults”

Things are going to break. Break safely.

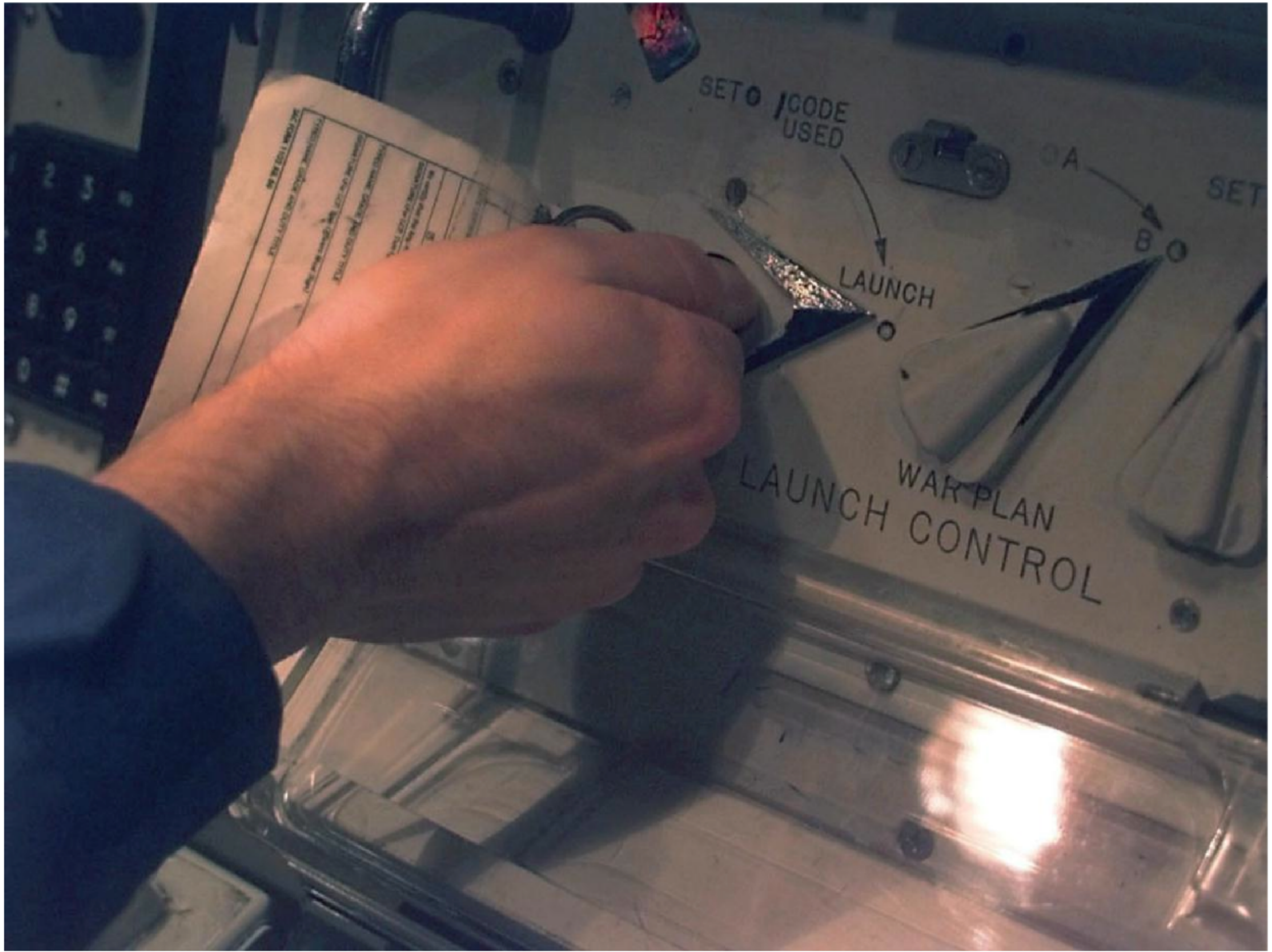
- **Default-deny policies**
  - Start by denying all access
  - Then allow only that which has been explicitly permitted

- **Crash => fail to secure behavior**
  - Example: firewalls explicitly decide to forward
  - Failure => packets don’t get through

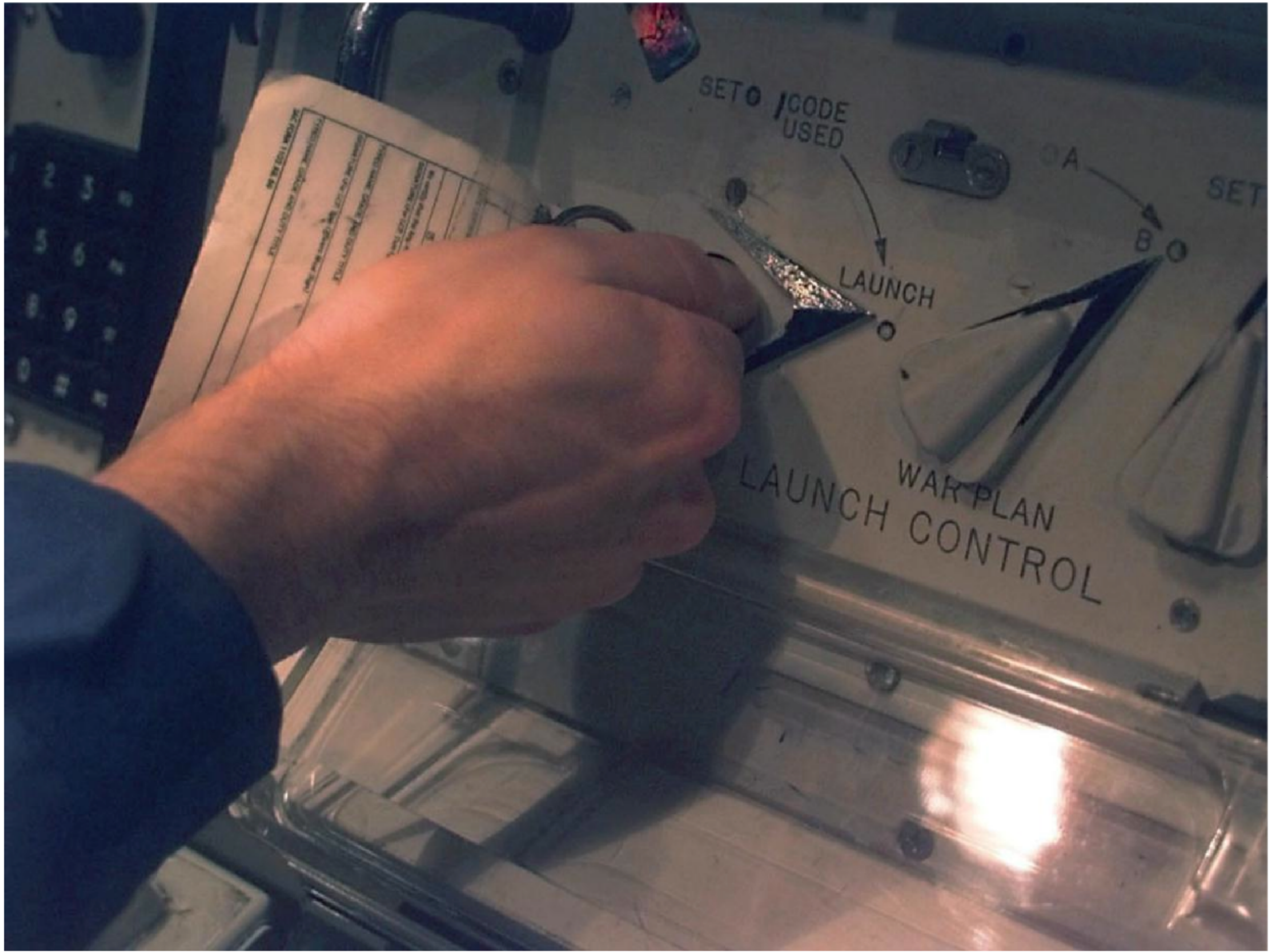
“Use separation of responsibility”

Split up privilege so no **one** person or program has total power.

- **Example**: US government
  - Checks and balances among different branches
- **Example**: Movie theater
  - One employee sells tickets, another tears them
  - Tickets go into lockbox
- **Example**: Nuclear weapons…


SET
CODE
USED
LAUNCH
A
B
SET
WAR PLAN
LAUNCH CONTROL

Use separation of responsibility



“Defend in depth”

Use multiple, redundant protections

- Only in the event that *all of them* have been breached should security be endangered.

- **Example**: Multi-factor authentication:
  - Some combination of password, image selection, USB dongle, fingerprint, iris scanner,… (more on these later)

- **Example**: “You can recognize a security guru who is particularly cautious if you see someone wearing both….”

…a belt and suspenders

Defense in depth

…a belt and suspenders

"Ensure complete mediation"

Make sure your reference monitor sees **every** access to **every** object

- Any **access control system** has some resource it needs to enforce
  - Who is allowed to access a files
  - Who is allowed to post to a message board…

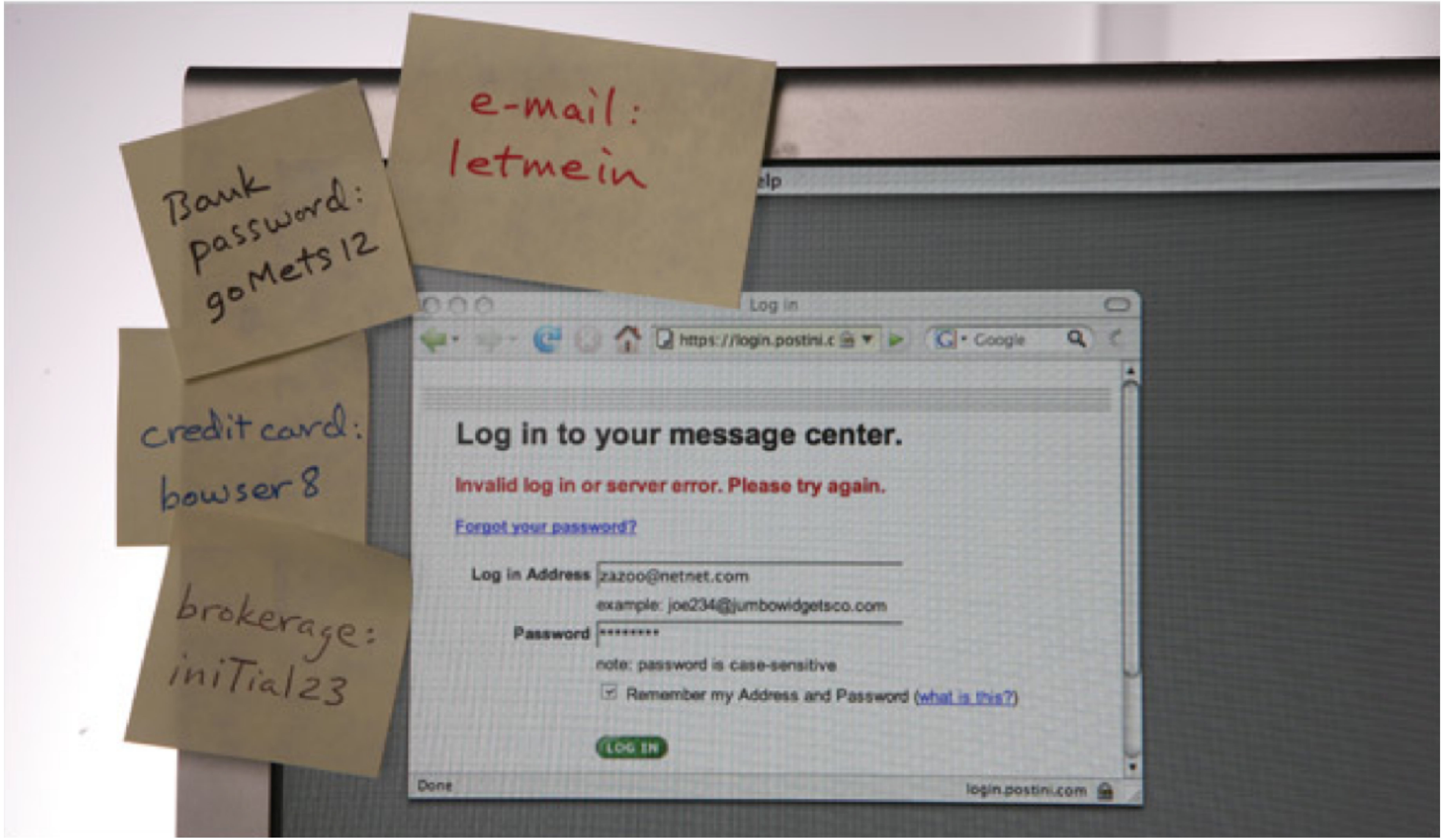
- **Reference Monitor:** The piece of code that checks for permission to access a resource

Ensure complete mediation

“Account for human factors”

(1) “Psychological acceptability”:
Users must buy into the security model

- The security of your system ultimately lies in the hands of those who use it.
- If they don’t believe in the system or the cost it takes to secure it, then they won’t do it.
- **Example**: “All passwords must have 15 characters, 3 numbers, 6 hieroglyphics, …”



Bank password: goMets12
e-mail: letmein
credit card: bowser8
brokerage: iniTial23
Log in
Log in to your message center.
Invalid log in or server error. Please try again.
Forgot your password?
Log in Address zazoo@netnet.com
example: joe234@jumbowidgetsco.com
Password
note: password is case-sensitive
Remember my Address and Password (what is this?)
LOG IN
Done
login.postini.com

Account for human factors ("psychological acceptability")
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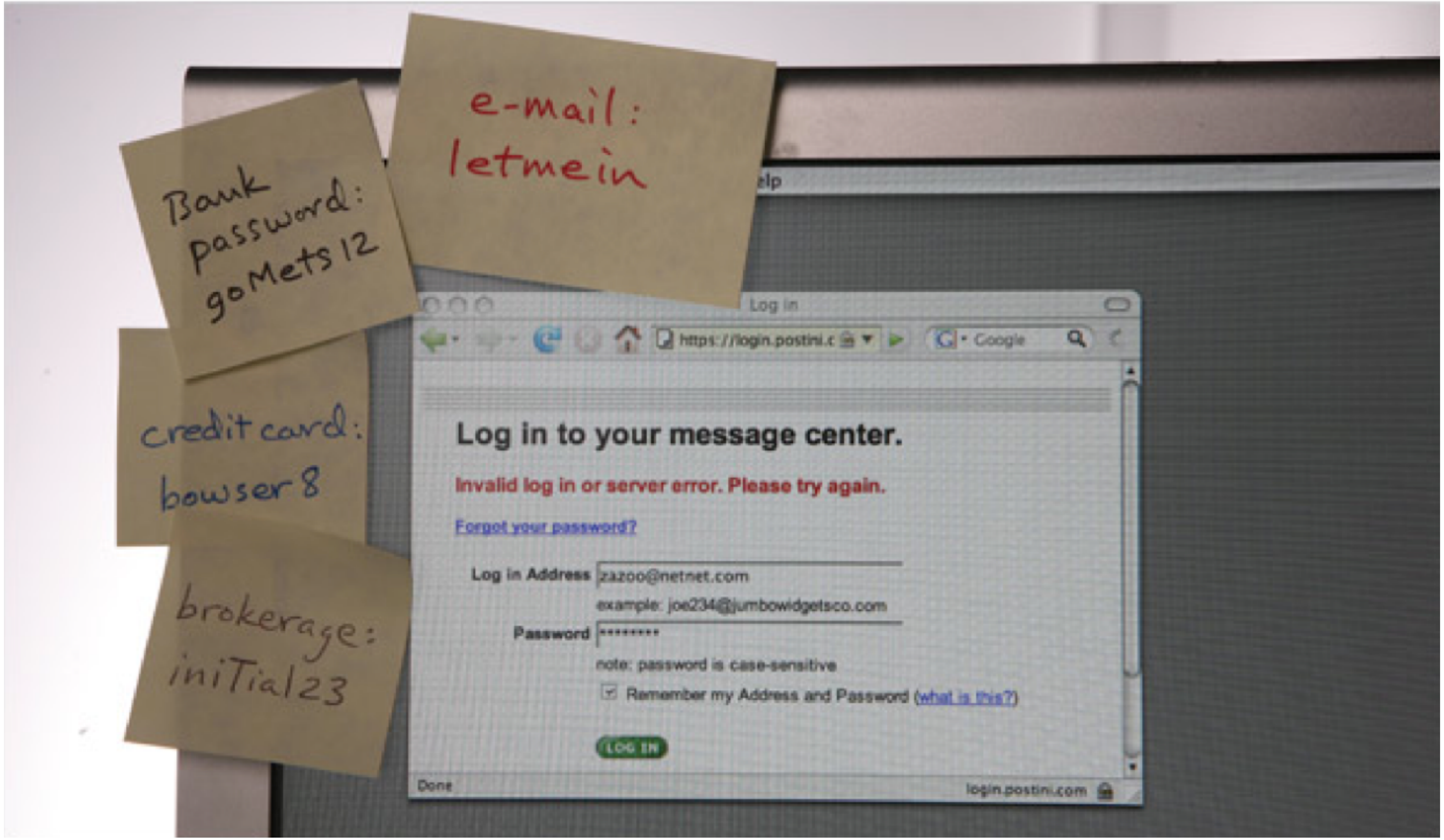

“Account for human factors”

(2) The security system must be usable

- The security of your system ultimately lies in the hands of those who use it.
- If it is too hard to act in a secure fashion, then they won’t do it.
- **Example**: Popup dialogs

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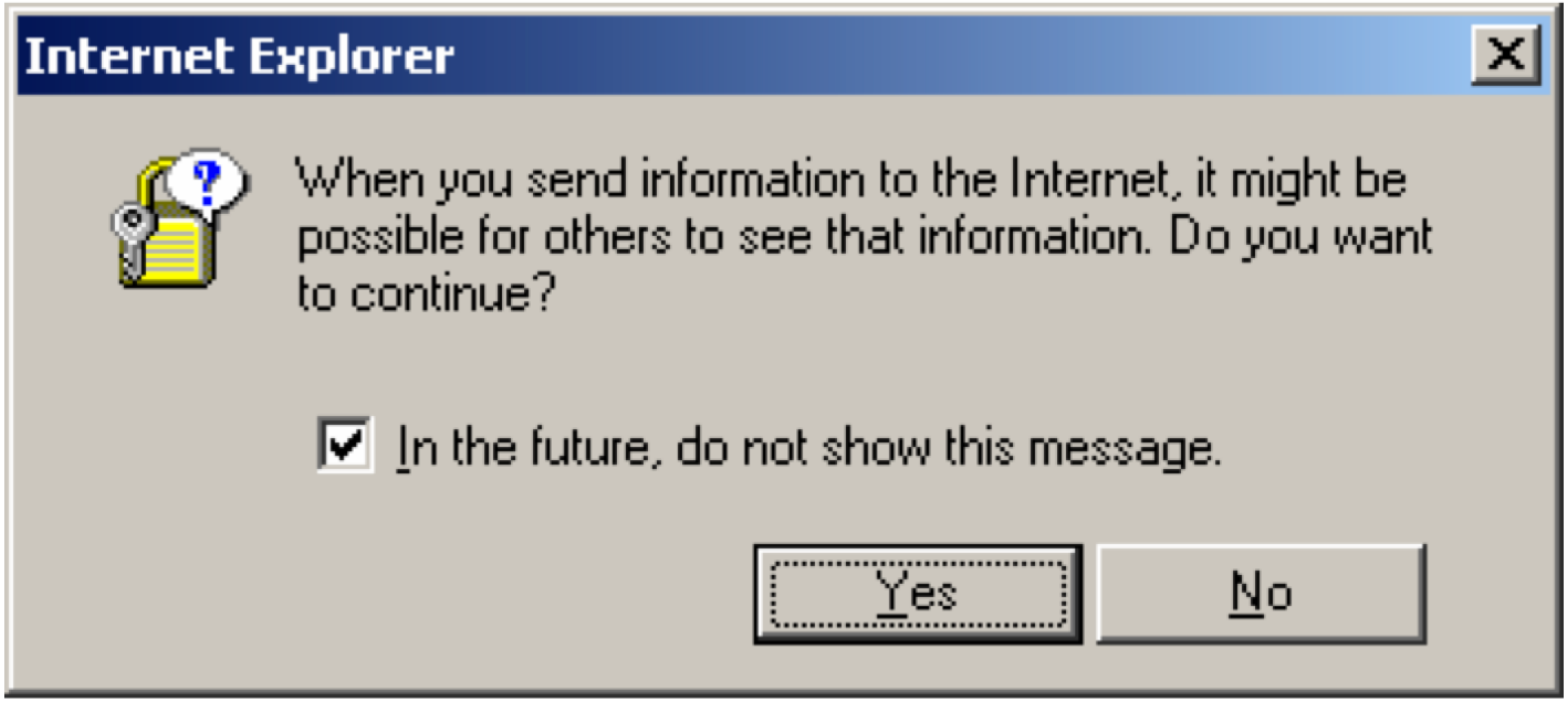

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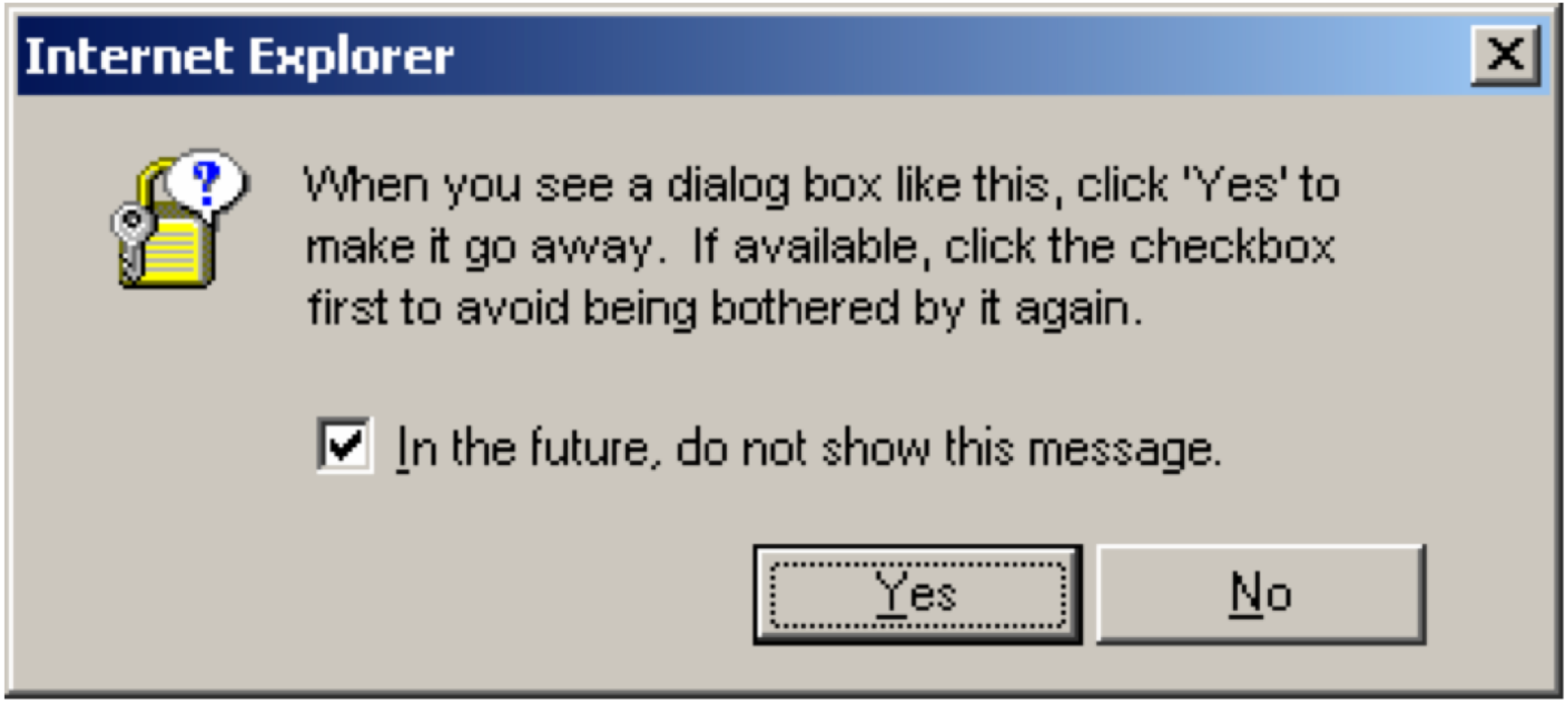

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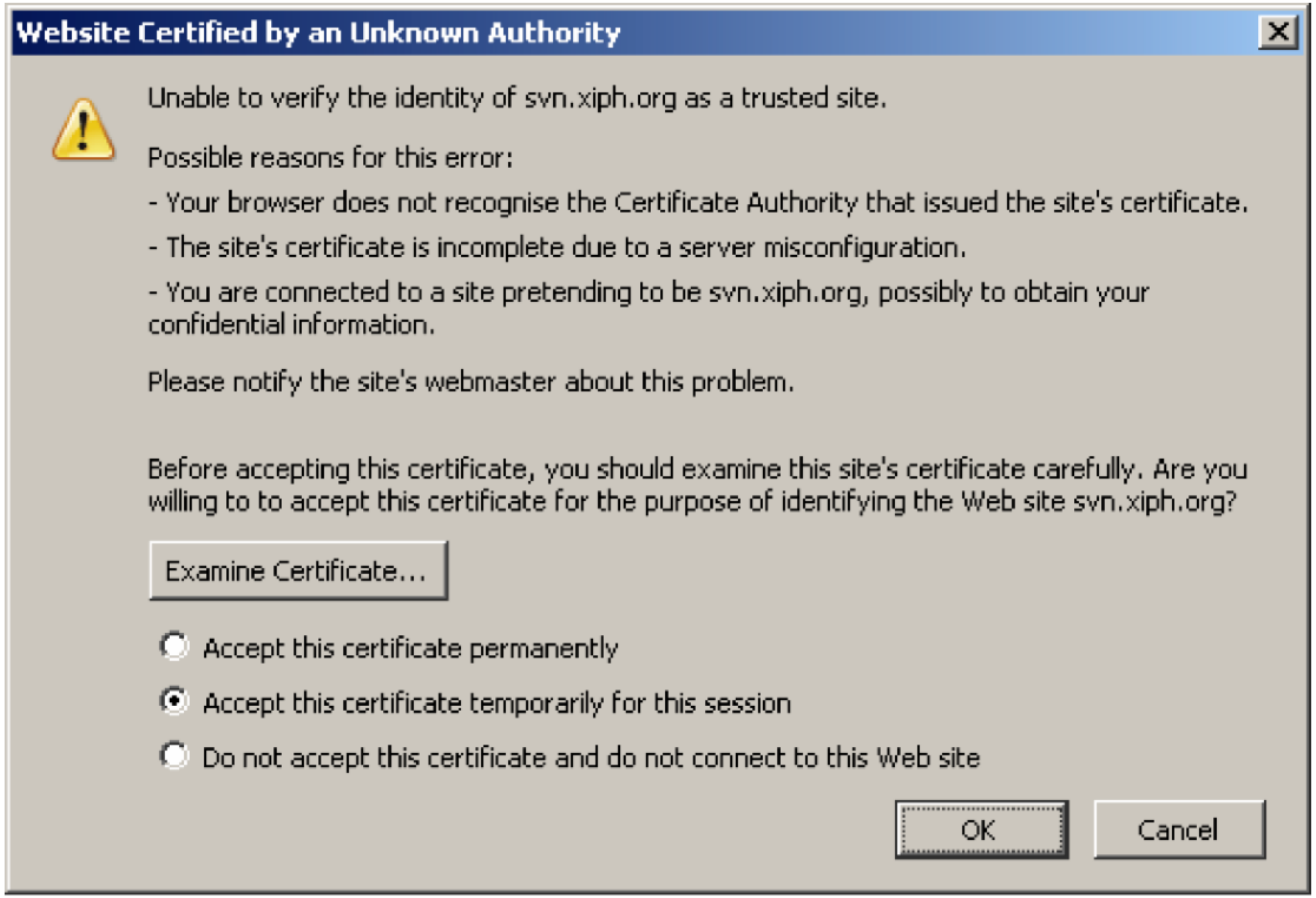

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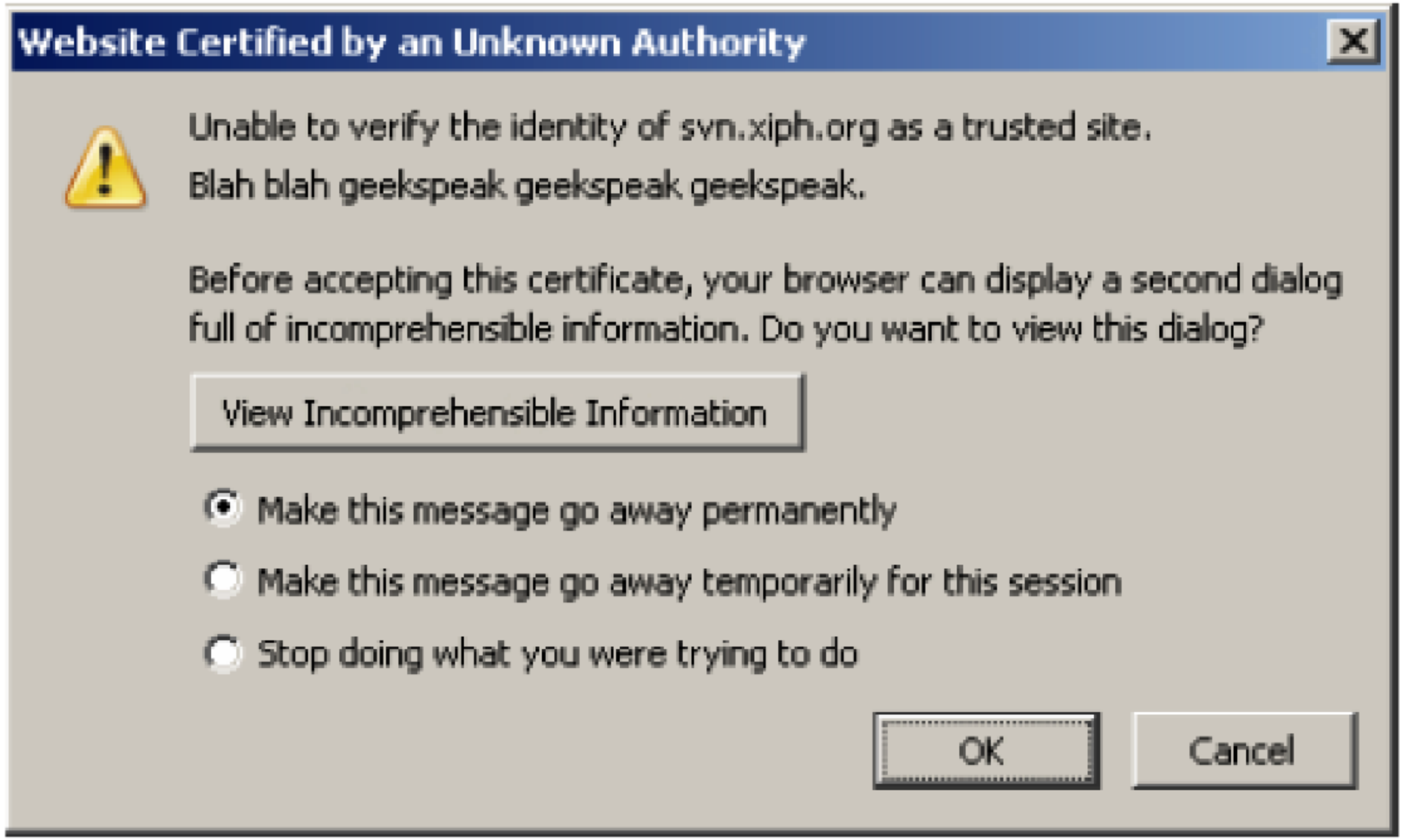

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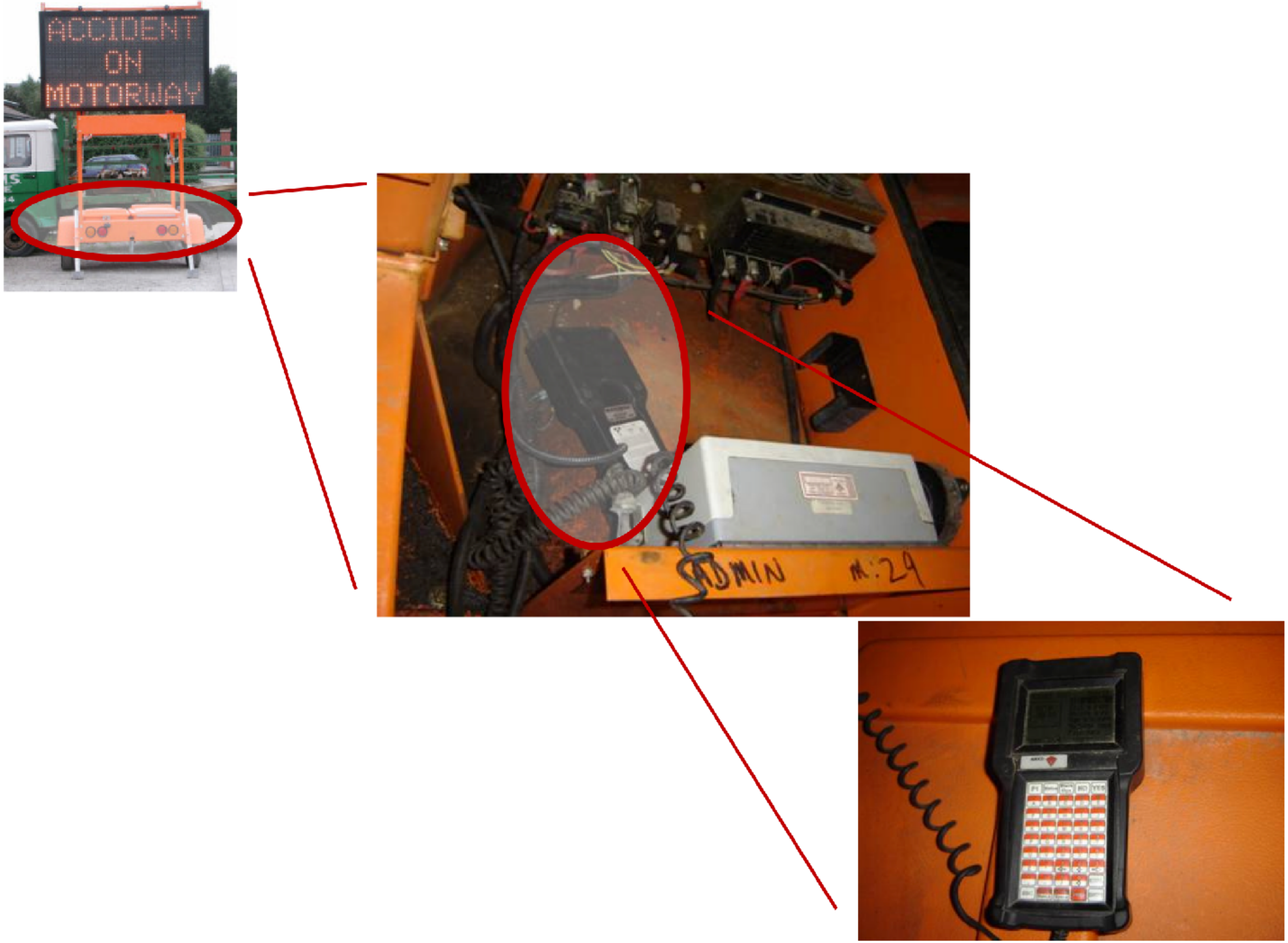
“Kerkhoff’s principle”

Don’t rely on **security through obscurity**

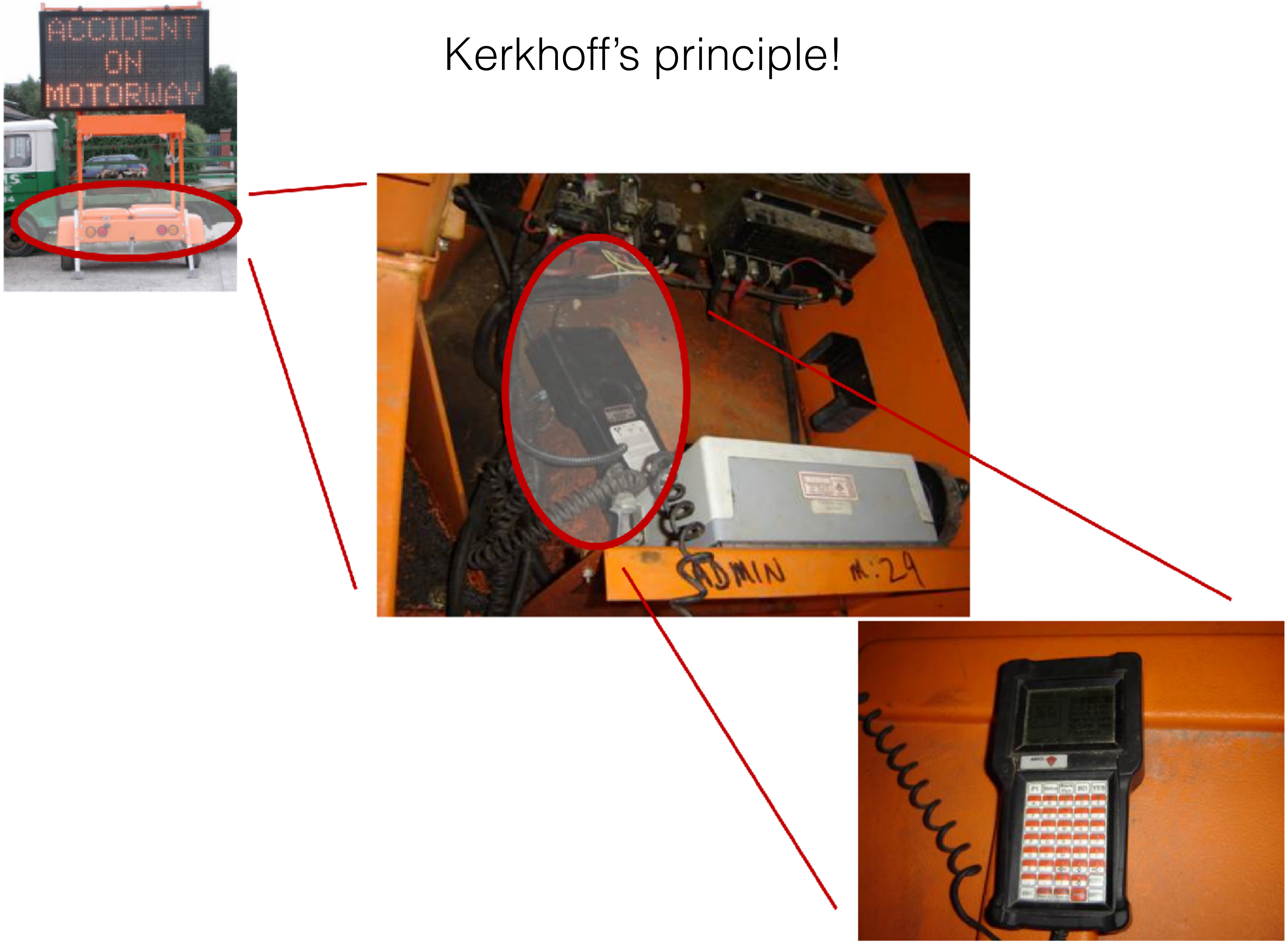
- Originally defined in the context of crypto systems (encryption, decryption, digital signatures, etc.):
- Crypto systems should remain *secure even when an attacker knows all of the internal details*
  - It is easier to change a compromised key than to update all code and algorithms
- The best security is the light of day


RAPTORS
AHEAD
CAUTION

Kerkhoff’s principle??


ACCIDENT
ON
MOTORWAY
ADMIN

Kerkhoff's principle!



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Self-explanatory:

- Accept that threat models change; adapt your designs over time
- If you can't prevent, detect
- Design security from the ground up
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SANDBOXES

Execution environment that restricts what an application running in it can do

NaCl's restrictions

Takes arbitrary x86, runs it in a sandbox in a browser

- Restrict applications to using a narrow API
- Data integrity: No reads/writes outside of sandbox
- No unsafe instructions
- CFI

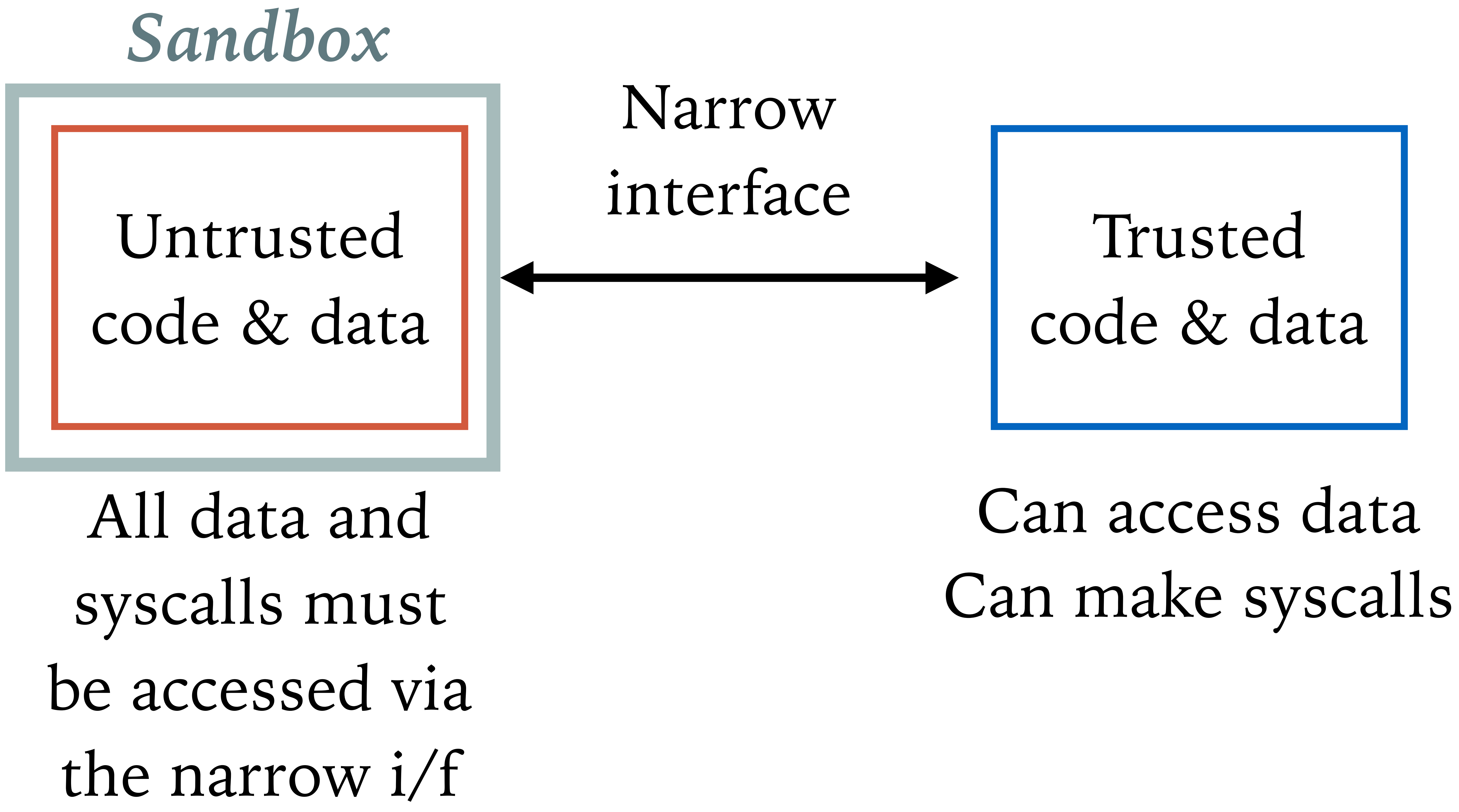
Chromium's restrictions

Runs each webpage's rendering engine in a sandbox

- Restrict rendering engines to a narrow "kernel" API
- Data integrity: No reads/writes outside of sandbox (incl. the desktop and clipboard)


What have I done
to deserve this?

Sandbox mental model



- Even the untrusted code needs input and output
- The goal of the sandbox is to constrain what the untrusted program can execute, what data it can access, what system calls it can make, etc.

Example sandboxing mechanism: SecComp

- Linux system call enabled since 2.6.12 (2005)
  - Affected process can subsequently **only perform `read`, `write`, `exit`, and `sigreturn` system calls**
    - No support for `open` call: Can only use already-open file descriptors
  - **Isolates a process by limiting possible interactions**

- Follow-on work produced **seccomp-bpf**
  - **Limit process to policy-specific set of system calls**, subject to a policy handled by the kernel
    - Policy akin to *Berkeley Packet Filters (BPF)*
  - Used by *Chrome*, *OpenSSH*, *vsftpd*, and others

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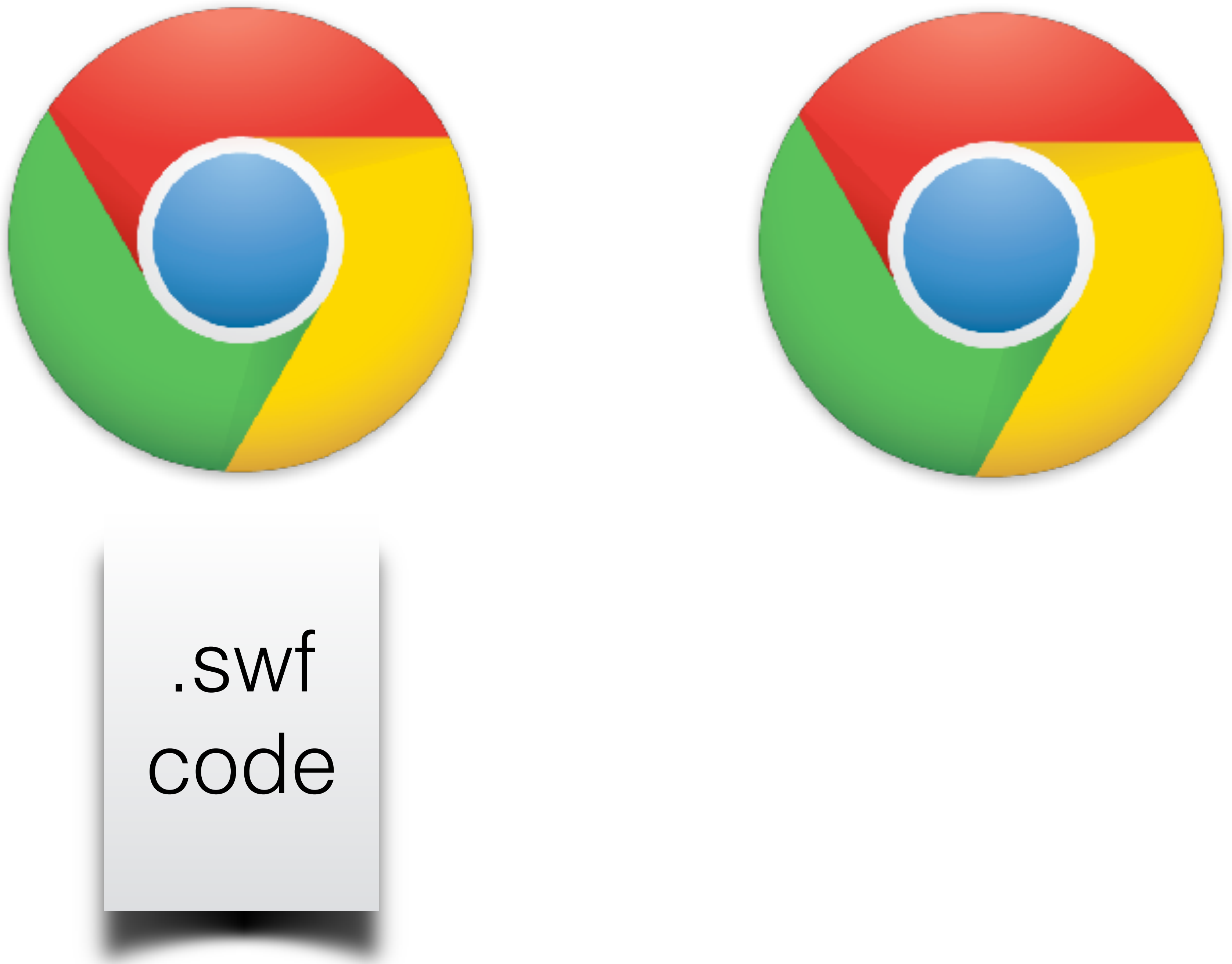

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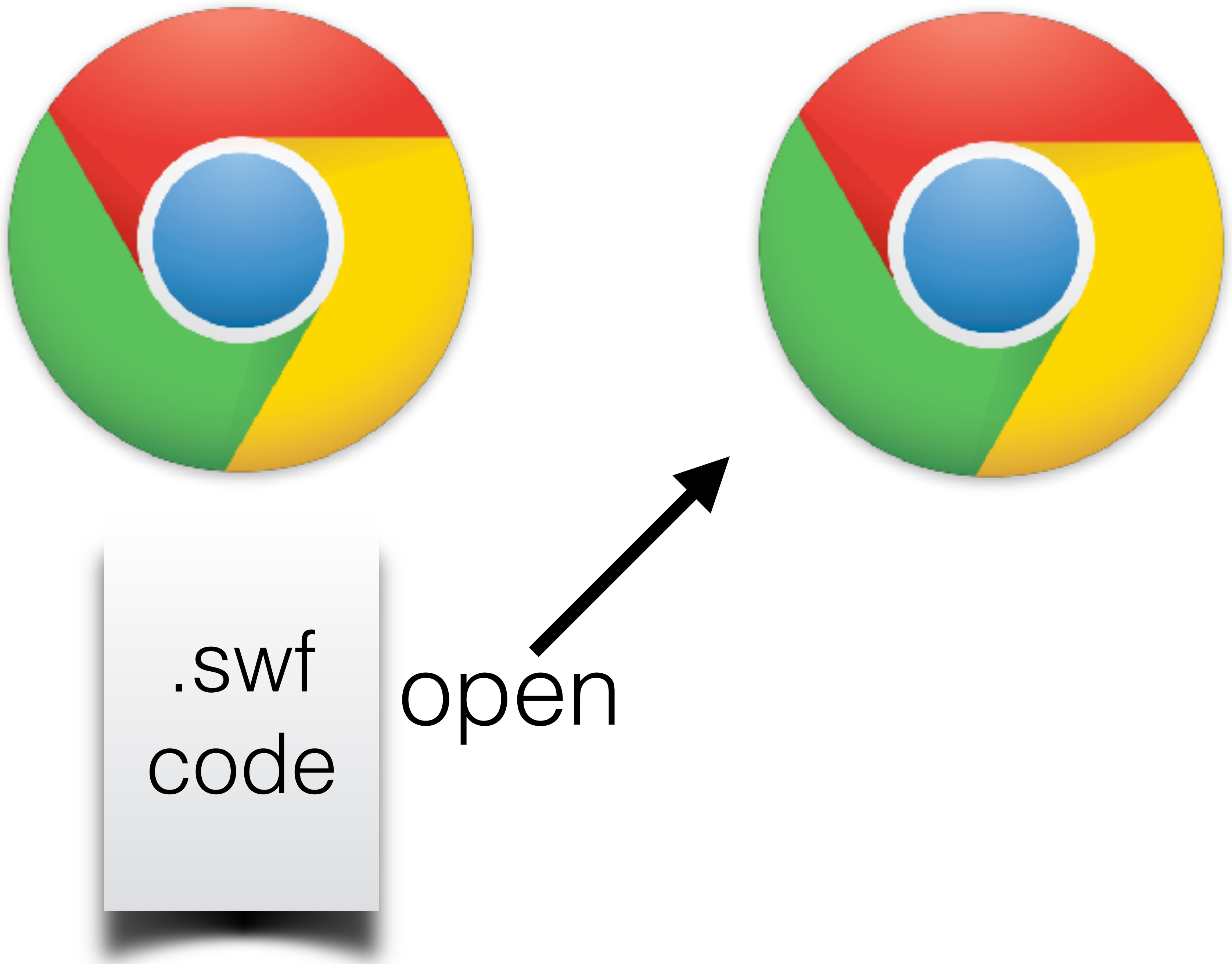

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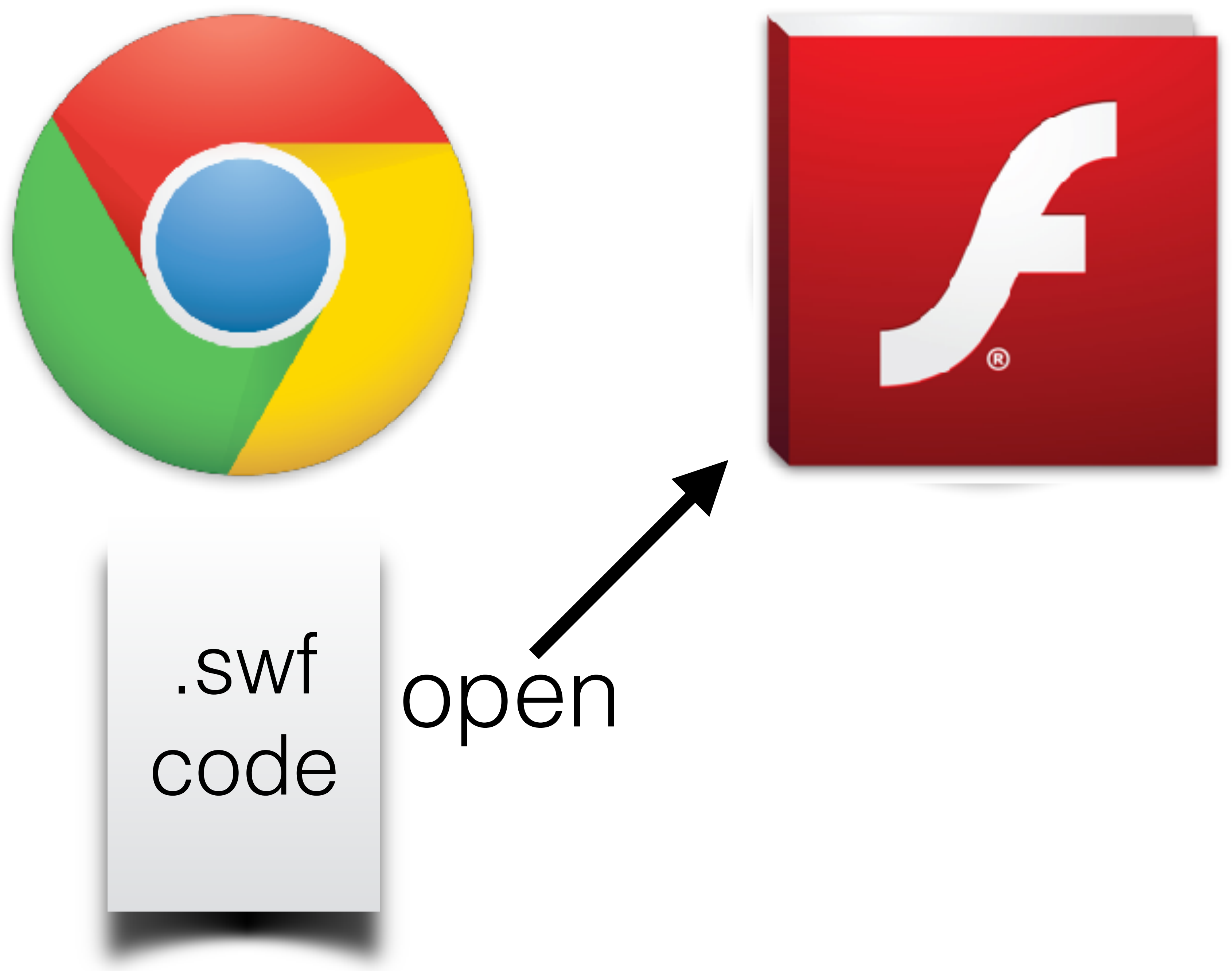
- Call `exec` to run Flash player



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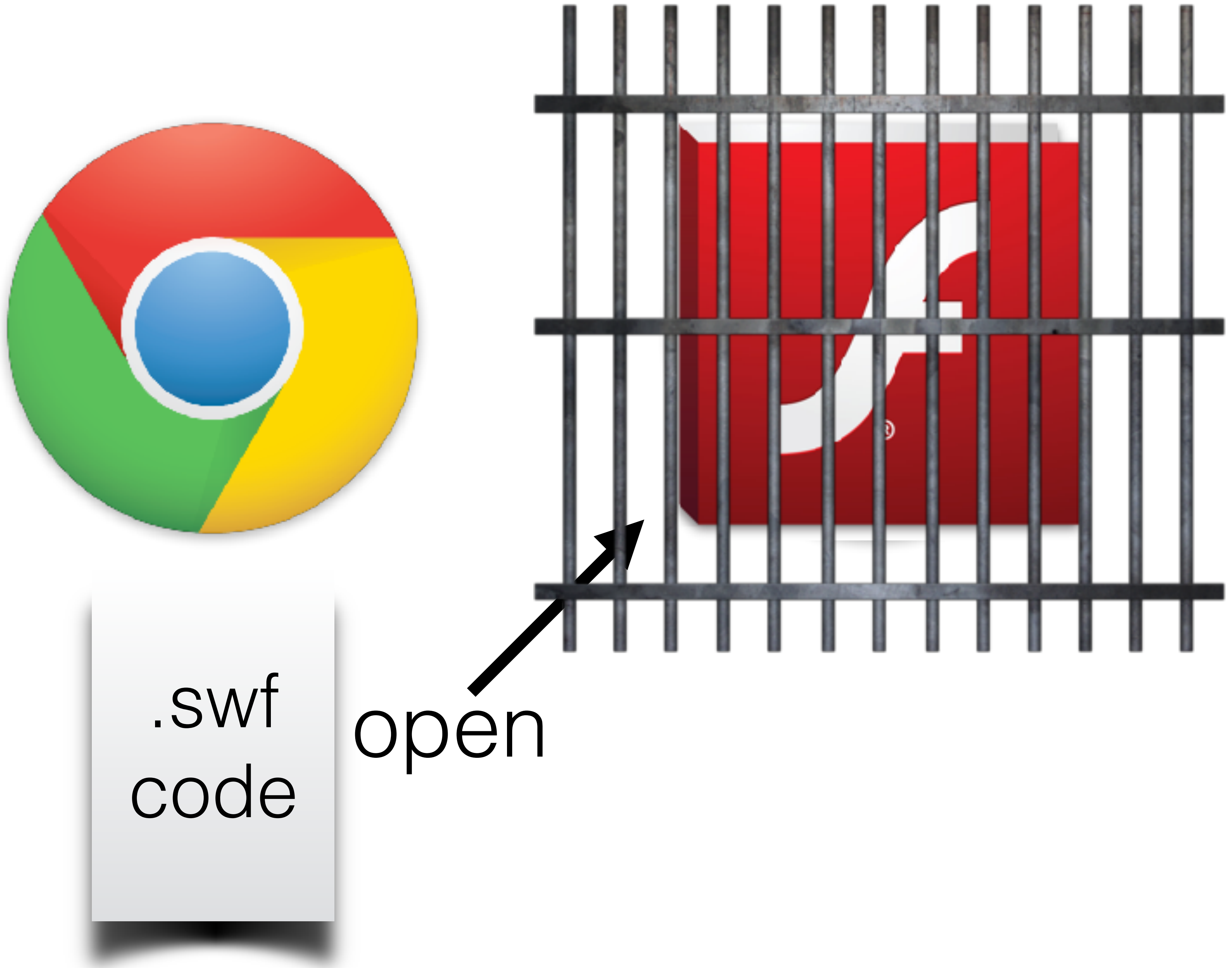
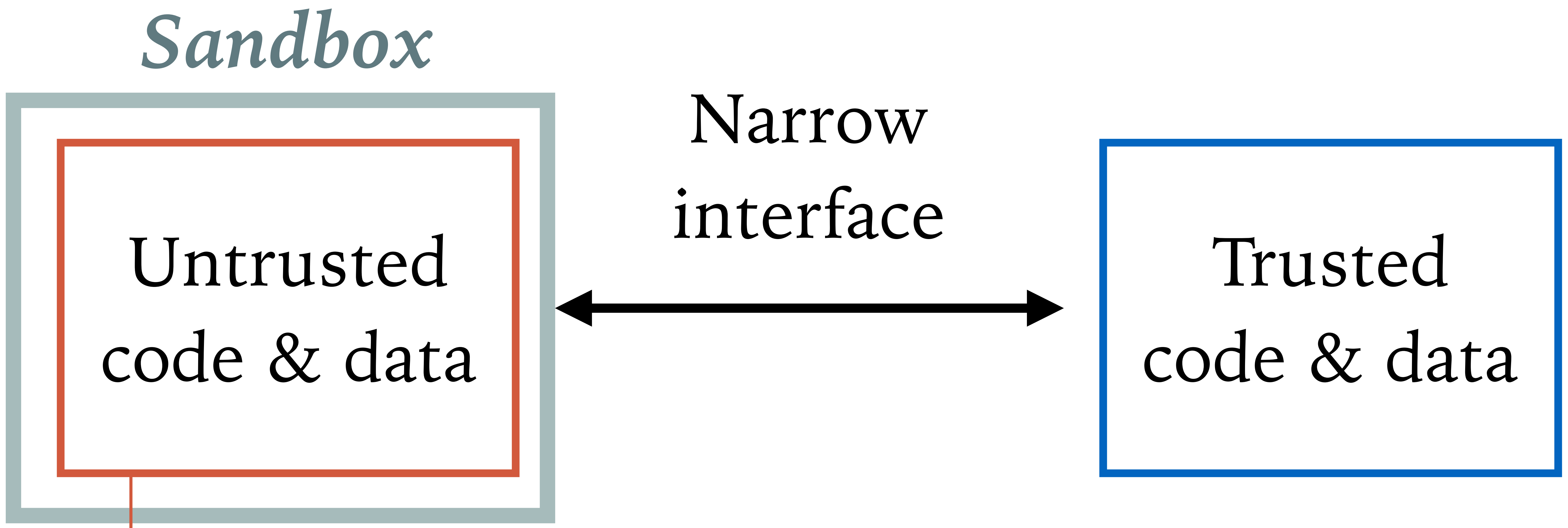
- In the new process, open the file
- Call **`exec`** to run Flash player
- Call **`seccomp-bpf`** to compartmentalize



Sandboxing as a design principle



- 3rd party binaries (NaCl)
- Webpages (Chromium)
- *Modules of your own code:*

Mitigate the impact of the inevitability that your code has an exploitable bug

- It's not just *3rd-party* code that should be sandboxed: sandbox your own code, too!
- Break up your program into modules that **separate responsibilities** (what you should be doing anyway)
- Give each module the **least privileges** it needs to do its job
- Use the sandbox to enforce what exactly a given module can/can't do

Case study: VSFTPD

Very Secure FTPD

- **FTP**: File Transfer Protocol
  - More popular before the rise of HTTP, but still in use
  - 90's and 00's: **FTP daemon compromises were frequent and costly**, e.g., in Wu-FTPD, ProFTPd, …

- **Very thoughtful design** aimed to **prevent** and **mitigate security defects**

- But also to **achieve good performance**
  - Written in C

- Written and maintained by Chris Evans since 2002
  - **No security breaches that I know of**

https://security.appspot.com/vsftpd.html

VSFTPD Threat model

- **Clients untrusted, until authenticated**

- Once authenticated, **limited** trust:
  - According to user's **file access control policy**
  - For the files being served FTP (and not others)

- Possible attack goals
  - **Steal** or **corrupt resources** (e.g., files, malware)
  - **Remote code injection**

- Circumstances:
  - **Client attacks server**
  - **Client attacks** another **client**

Defense: Secure Strings

```
struct mystr
{
  char* PRIVATE_HANDS_OFF_p_buf;
  unsigned int PRIVATE_HANDS_OFF_len;
  unsigned int PRIVATE_HANDS_OFF_alloc_bytes;
};
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Size of buffer returned by **`malloc`**

```c
void
private_str_alloc_memchunk(struct mystr* p_str, const char* p_src,
                           unsigned int len)
{
  ...
}
```

```c
struct mystr
{
  char* p_buf;
  unsigned int len;
  unsigned int alloc_bytes;
};
```

```c
void
str_copy(struct mystr* p_dest, const struct mystr* p_src)
{
  private_str_alloc_memchunk(p_dest, p_src->p_buf, p_src->len);
}
```

replace uses of `char*` with `struct mystr*`
and uses of `strcpy` with `str_copy`

```c
void
private_str_alloc_memchunk(struct mystr* p_str, const char* p_src,
                           unsigned int len)
{
  /* Make sure this will fit in the buffer */
  unsigned int buf_needed;
  if (len + 1 < len)
  {
    bug("integer overflow");
  }
  buf_needed = len + 1;
  if (buf_needed > p_str->alloc_bytes)
  {
    str_free(p_str);
    s_setbuf(p_str, vsf_sysutil_malloc(buf_needed));
    p_str->alloc_bytes = buf_needed;
  }
  vsf_sysutil_memcpy(p_str->p_buf, p_src, len);
  p_str->p_buf[len] = '\0';
  p_str->len = len;
}
```

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struct mystr
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Copy in at most `len` bytes from `p_src` into `p_str`

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consider NUL terminator when computing space

allocate space, if needed

copy in p_src contents

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- Example: `malloc()`
  - What if argument is non-positive?
    - We saw earlier that integer overflows can induce this behavior
    - Leads to buffer overruns
  - What if returned value is NULL?
    - Oftentimes, a de-reference means a crash
    - On platforms without memory protection, a dereference can cause corruption

```c
void*
vsf_sysutil_malloc(unsigned int size)
{
  void* p_ret;
  /* Paranoia - what if we got an integer overflow/underflow? */
  if (size == 0 || size > INT_MAX)
  {
    bug("zero or big size in vsf_sysutil_malloc");
  }
  p_ret = malloc(size);
  if (p_ret == NULL)
  {
    die("malloc");
  }
  return p_ret;
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fails if it receives malformed argument or runs out of memory

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small trusted computing base

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Connection Establishment

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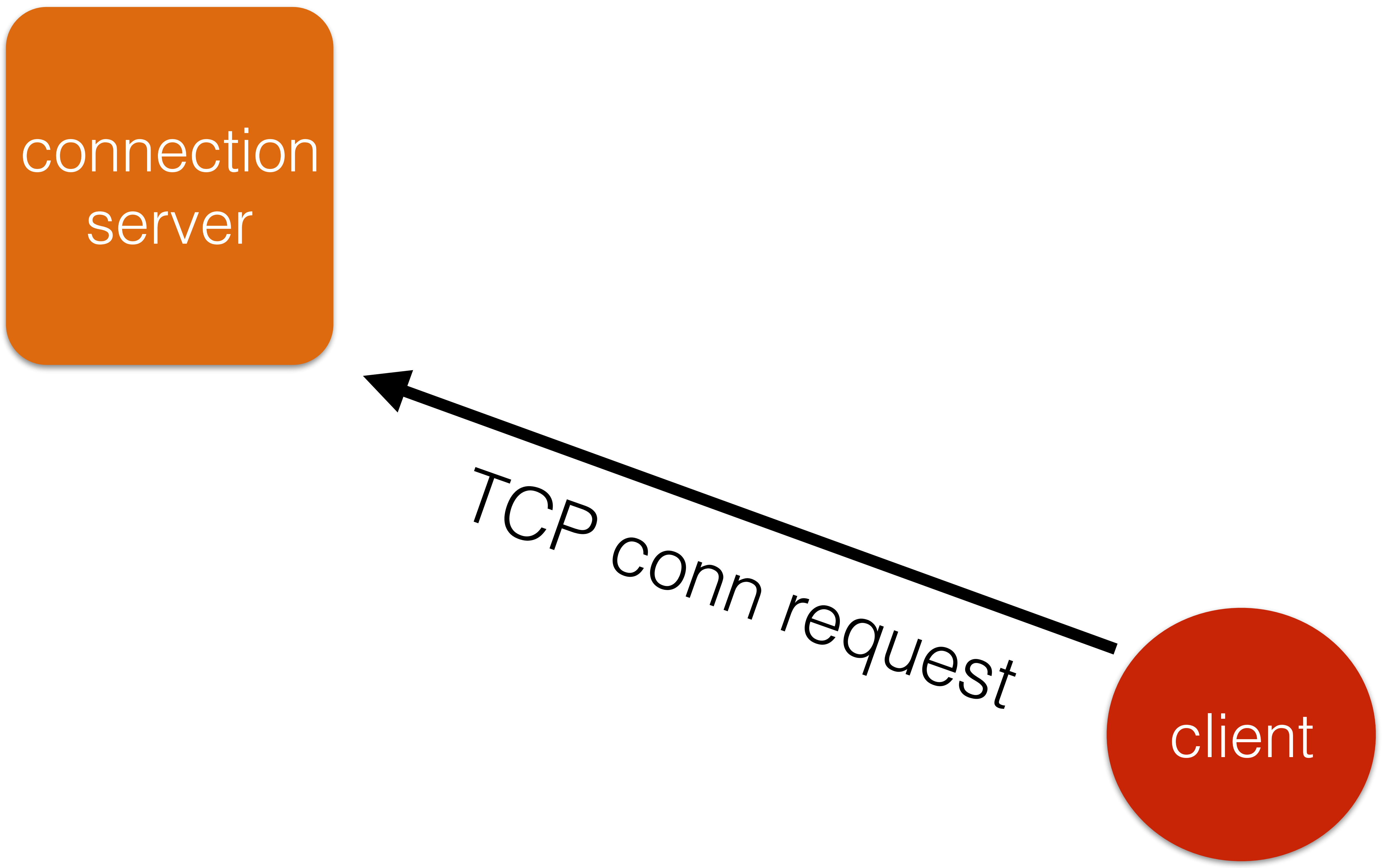

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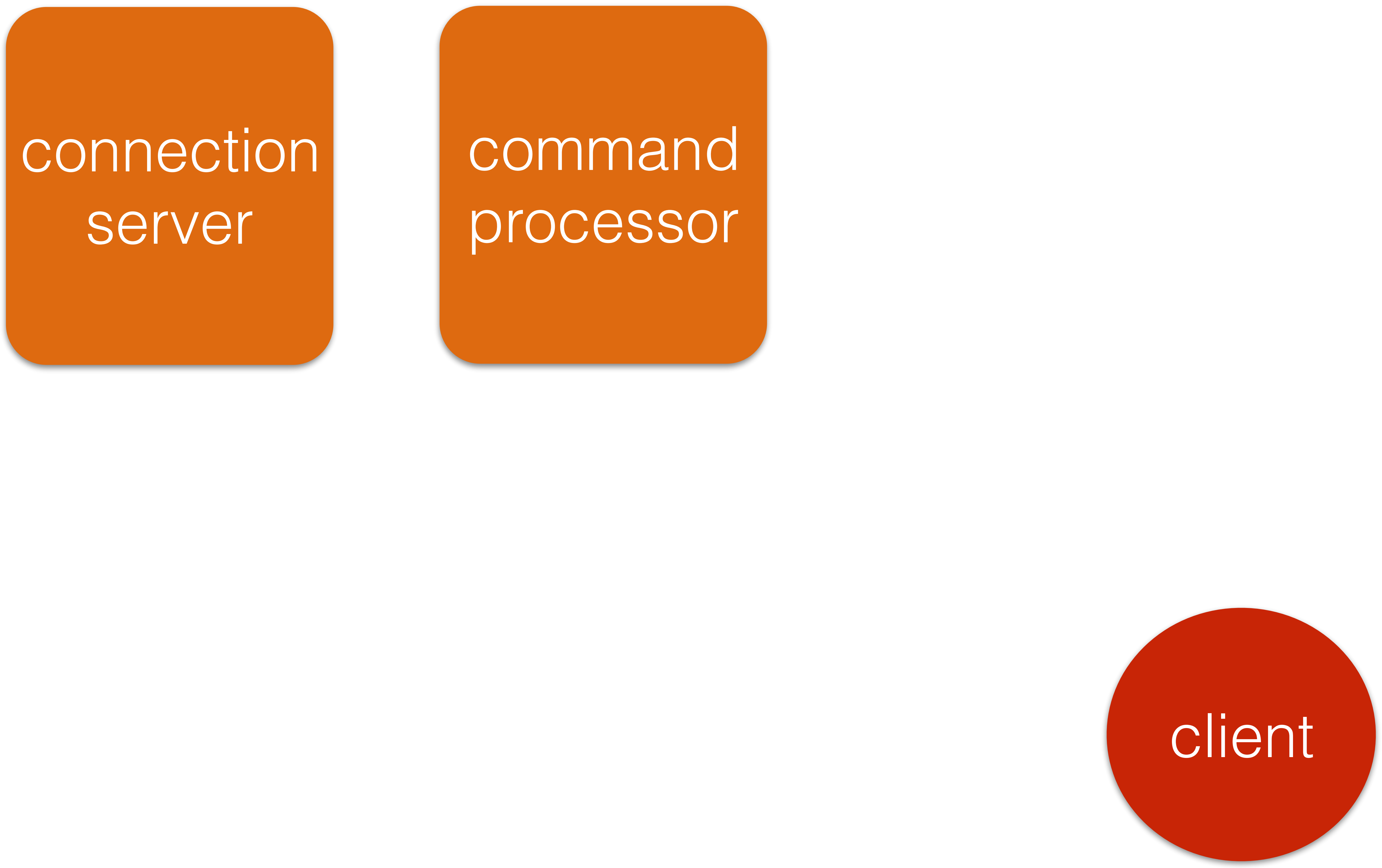

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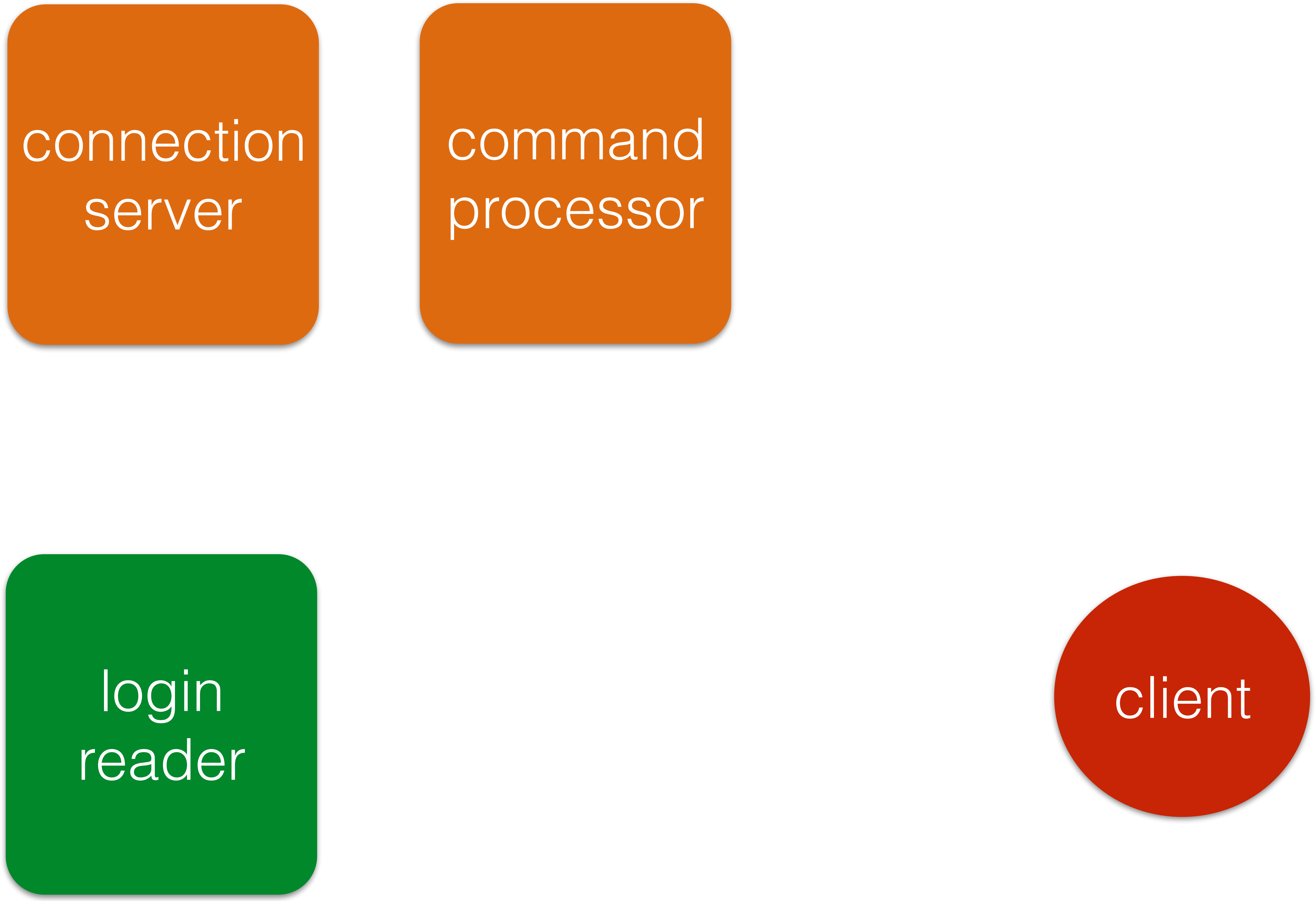

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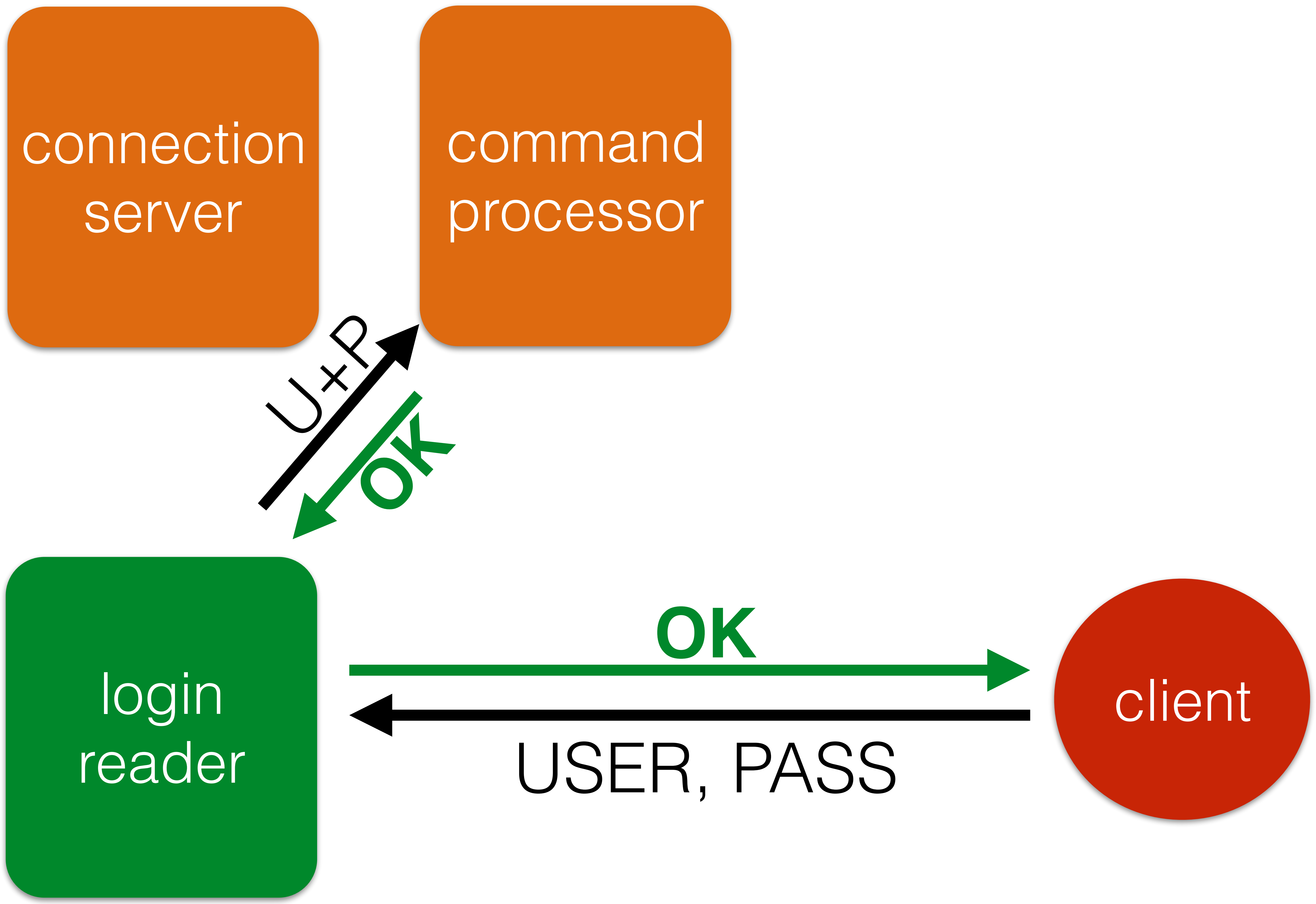

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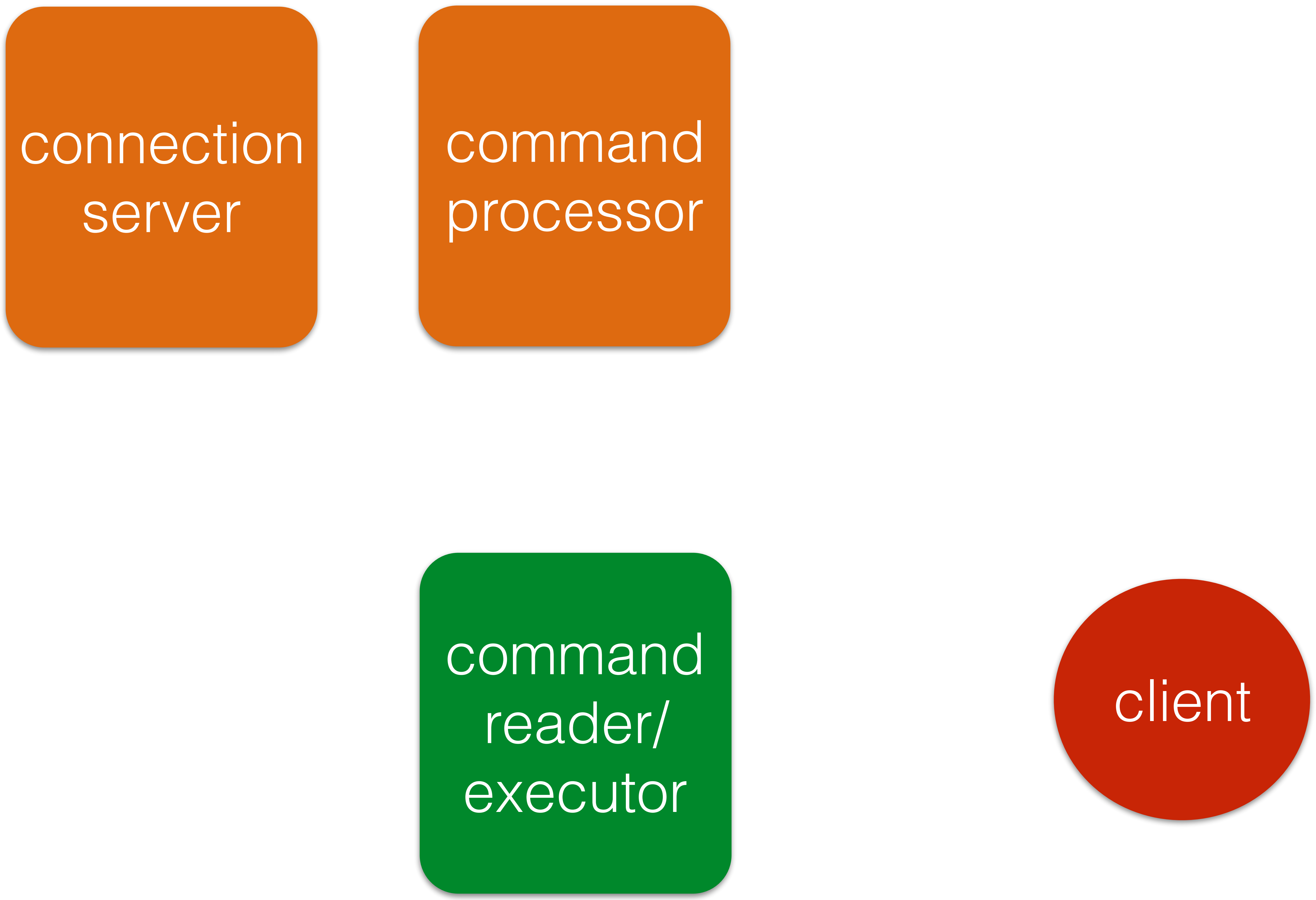
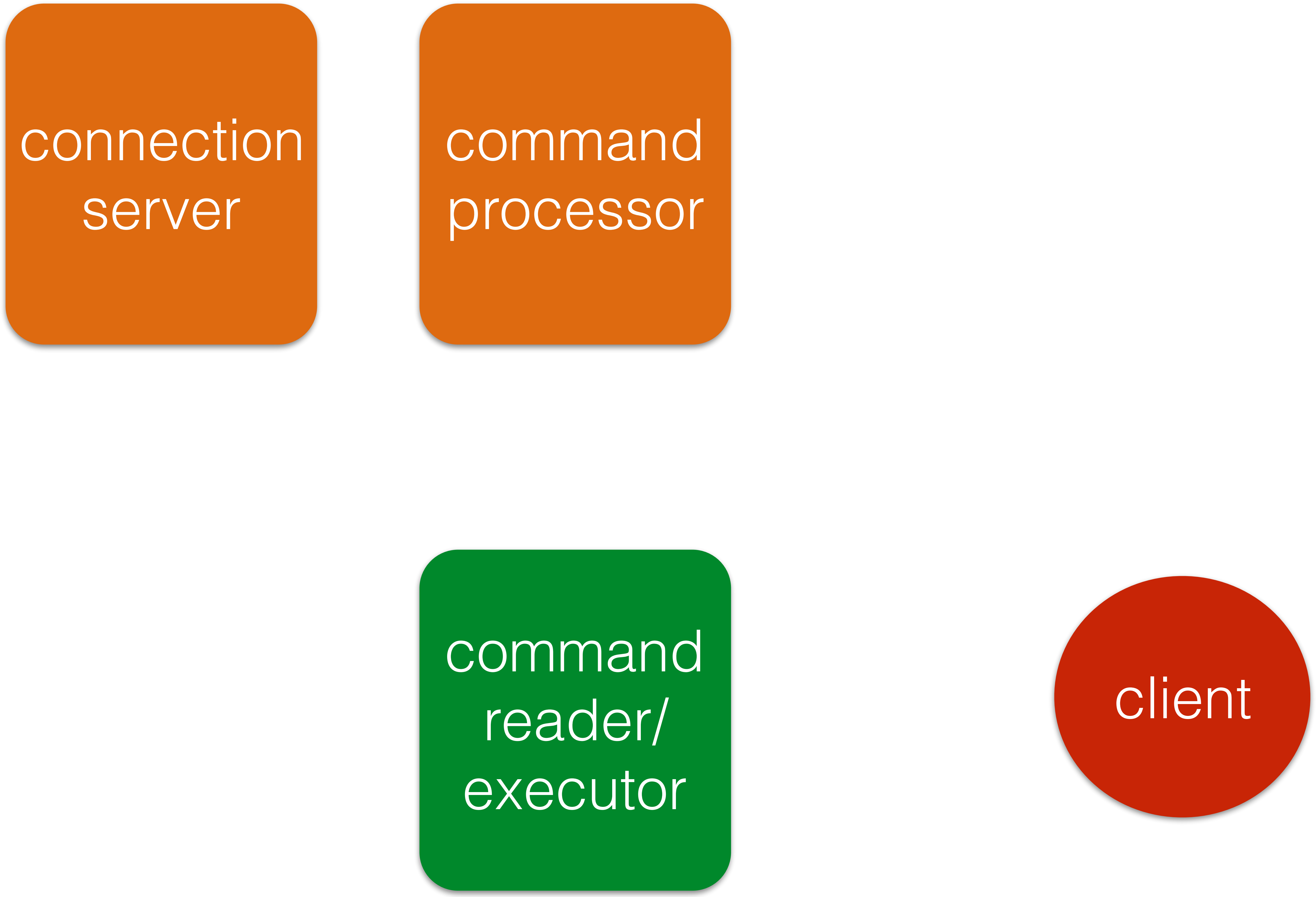


Performing Commands



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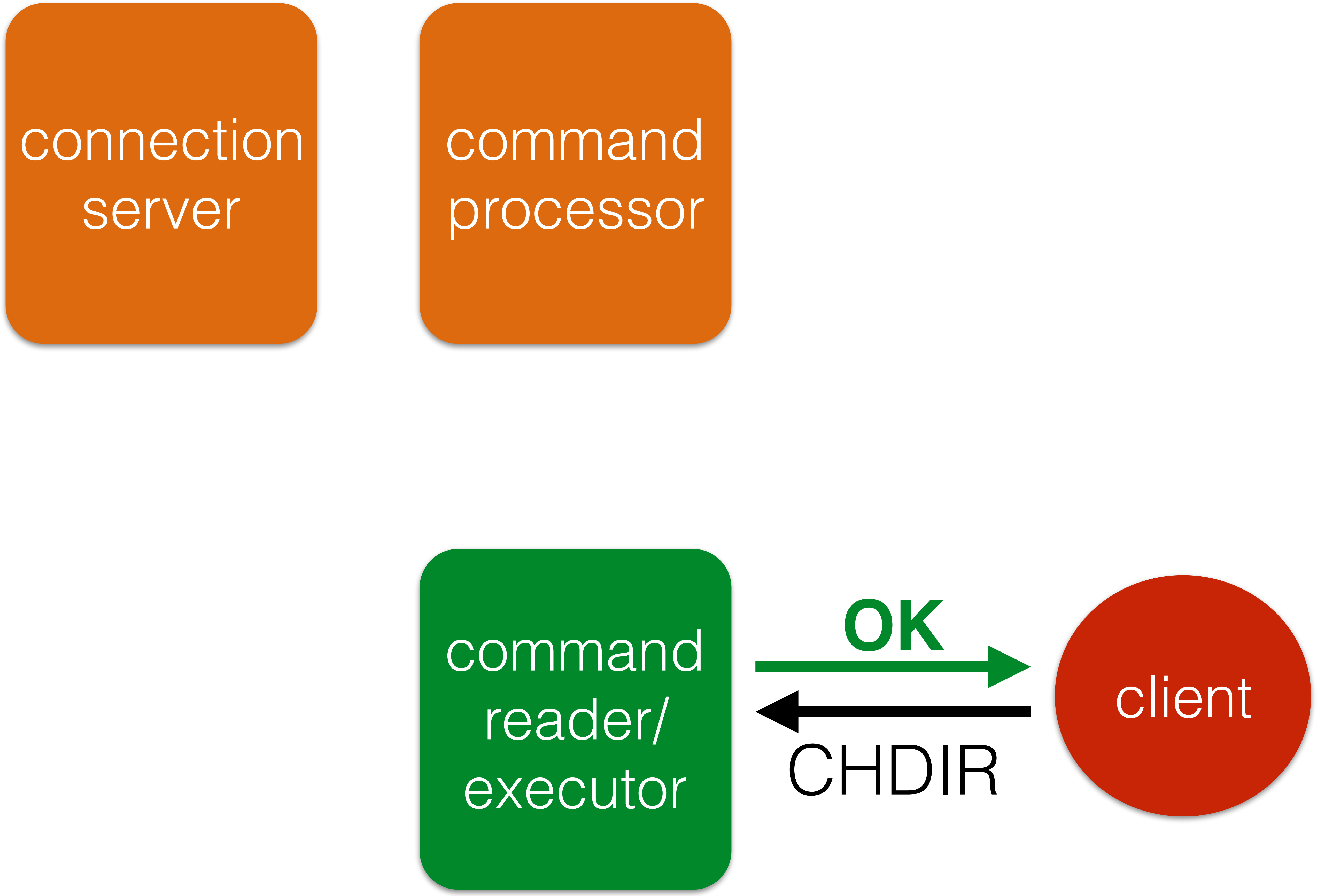

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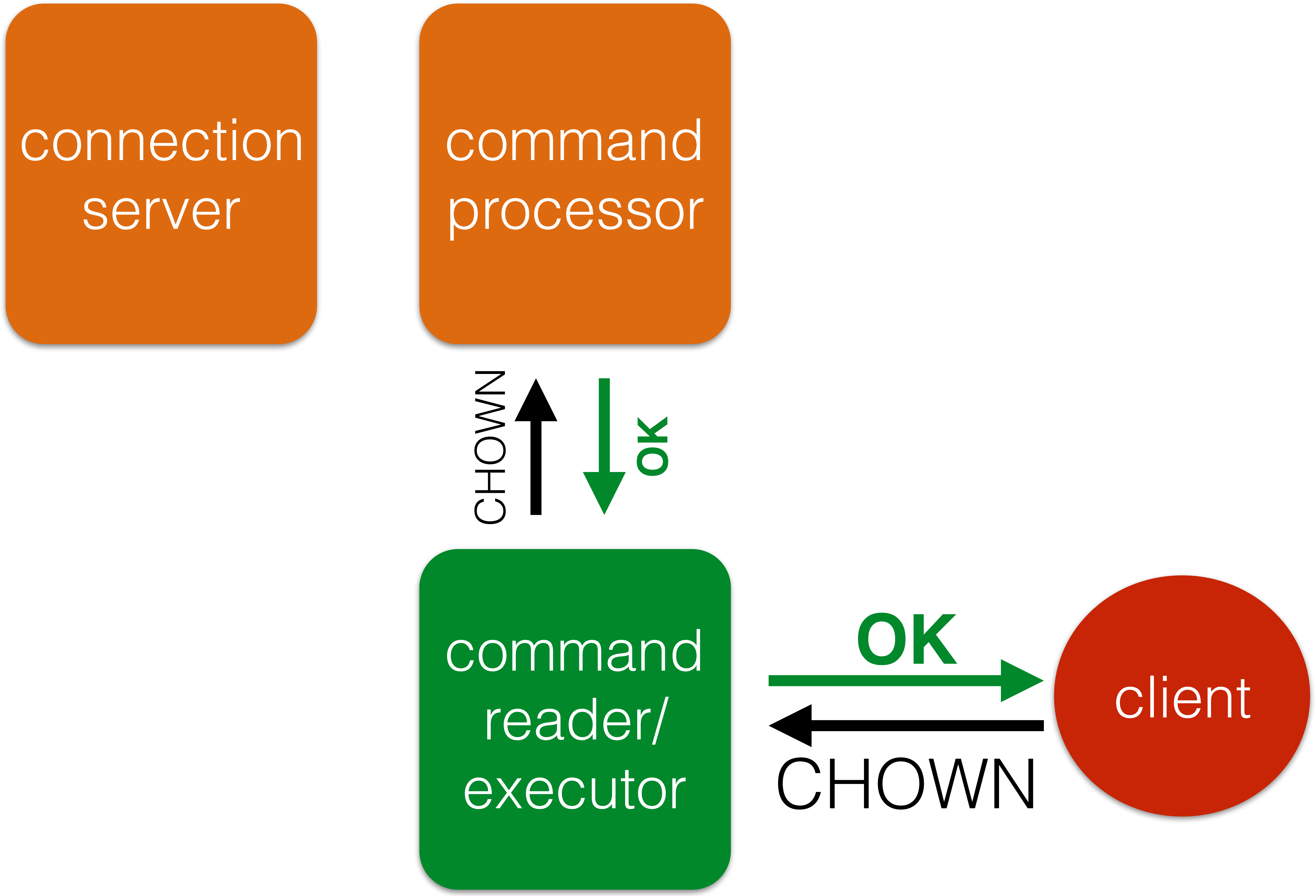
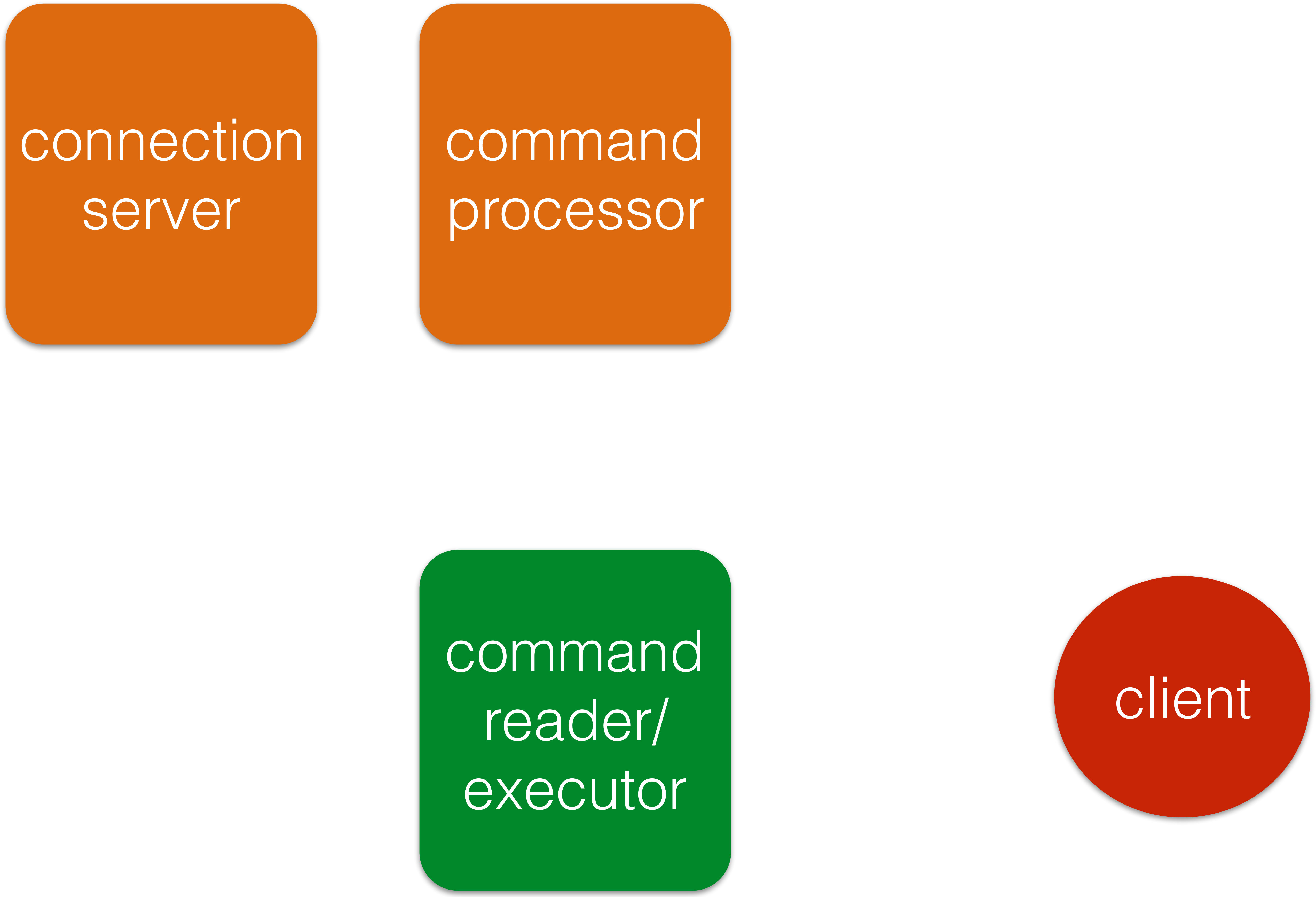
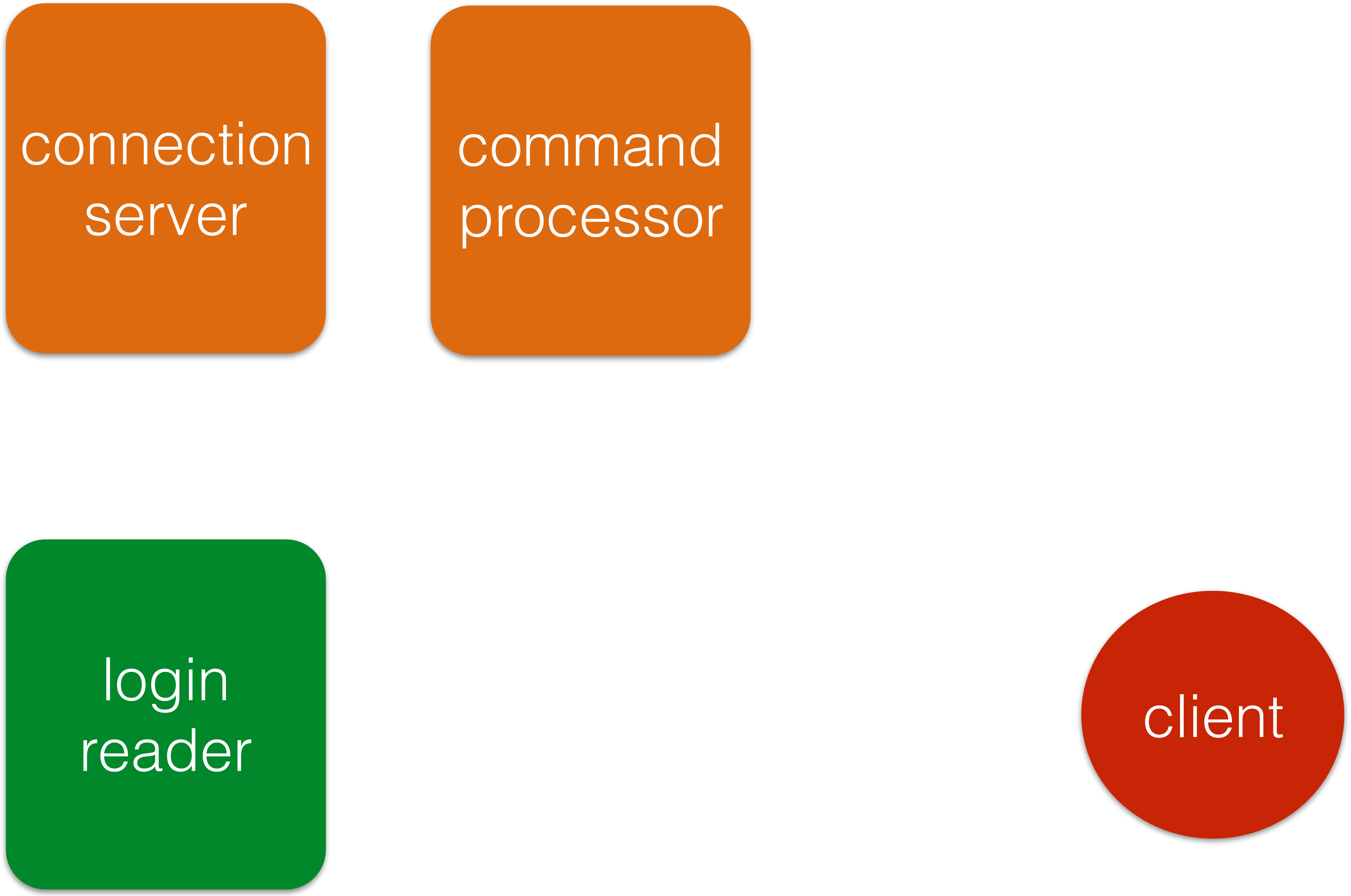


Logging out


connection server
command processor
command reader/ executor
client

Logging out

Attack: Login



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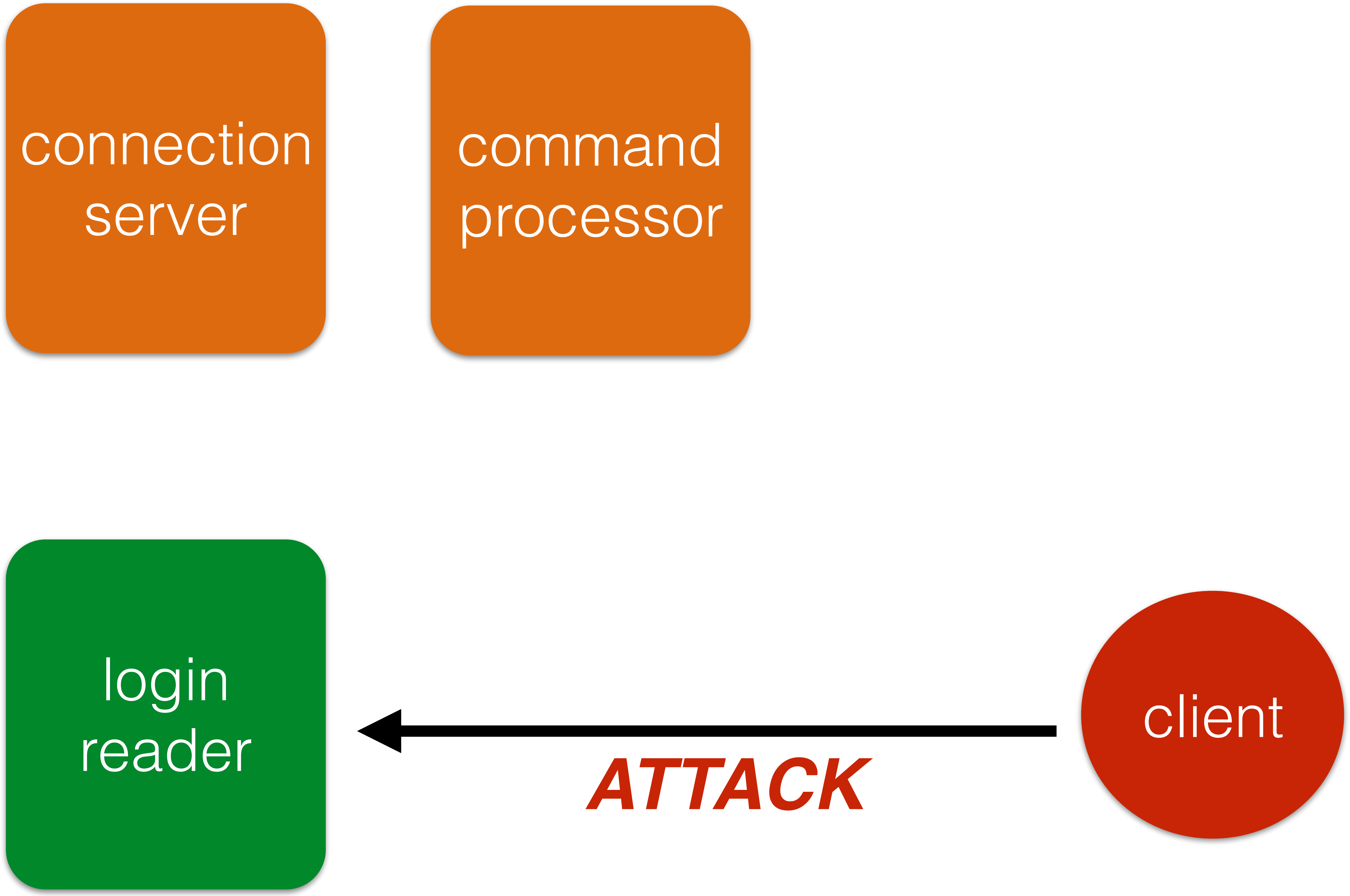

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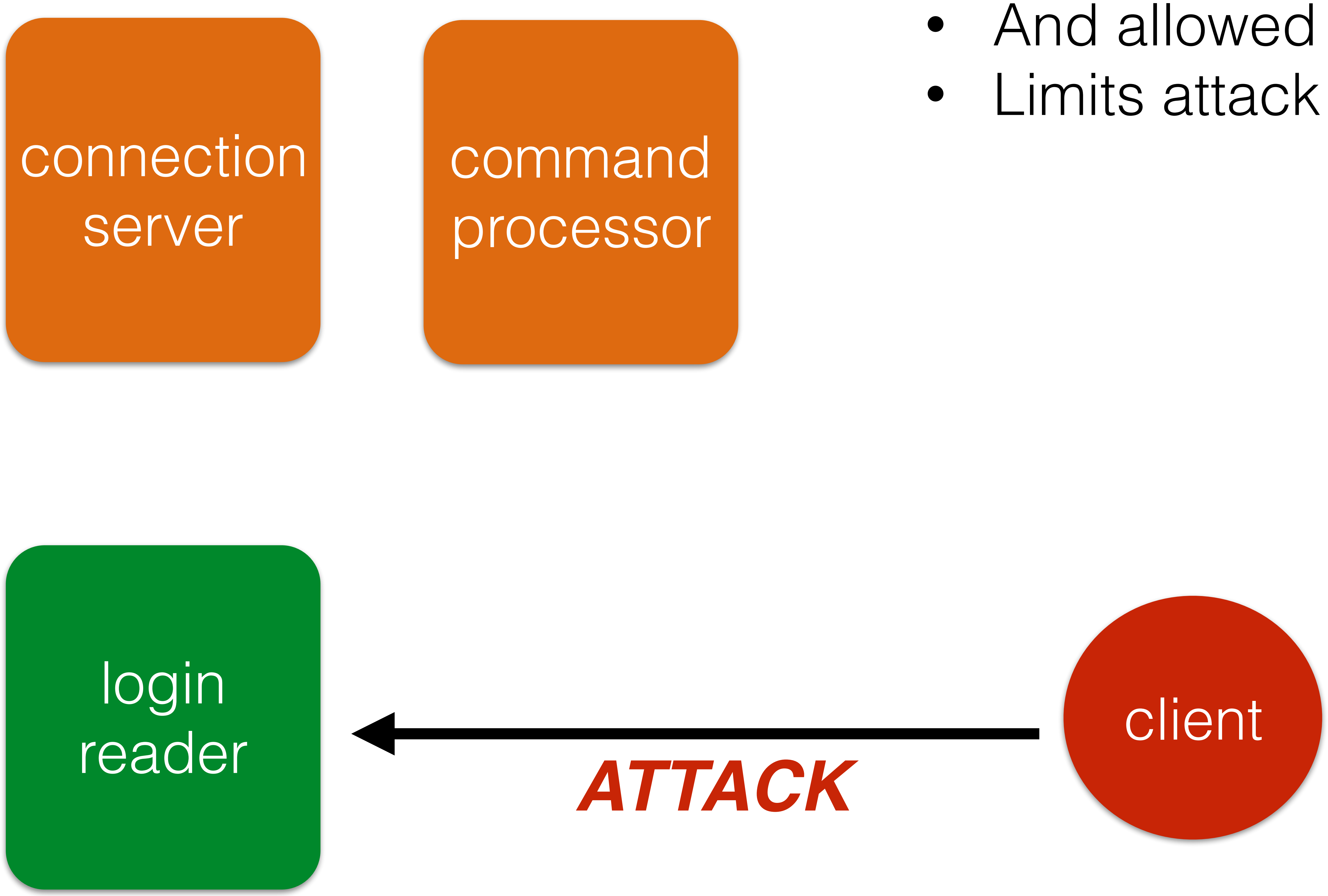

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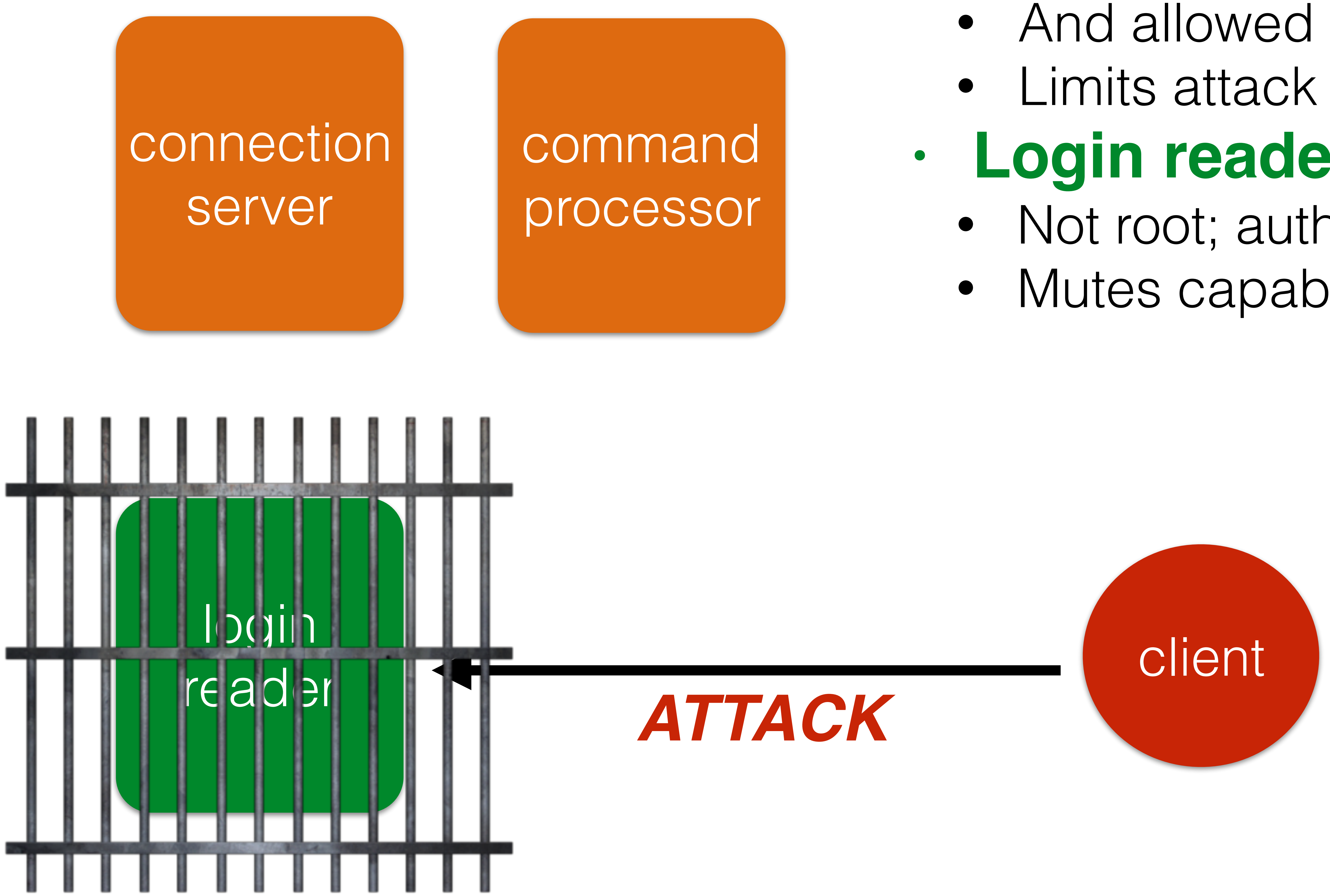

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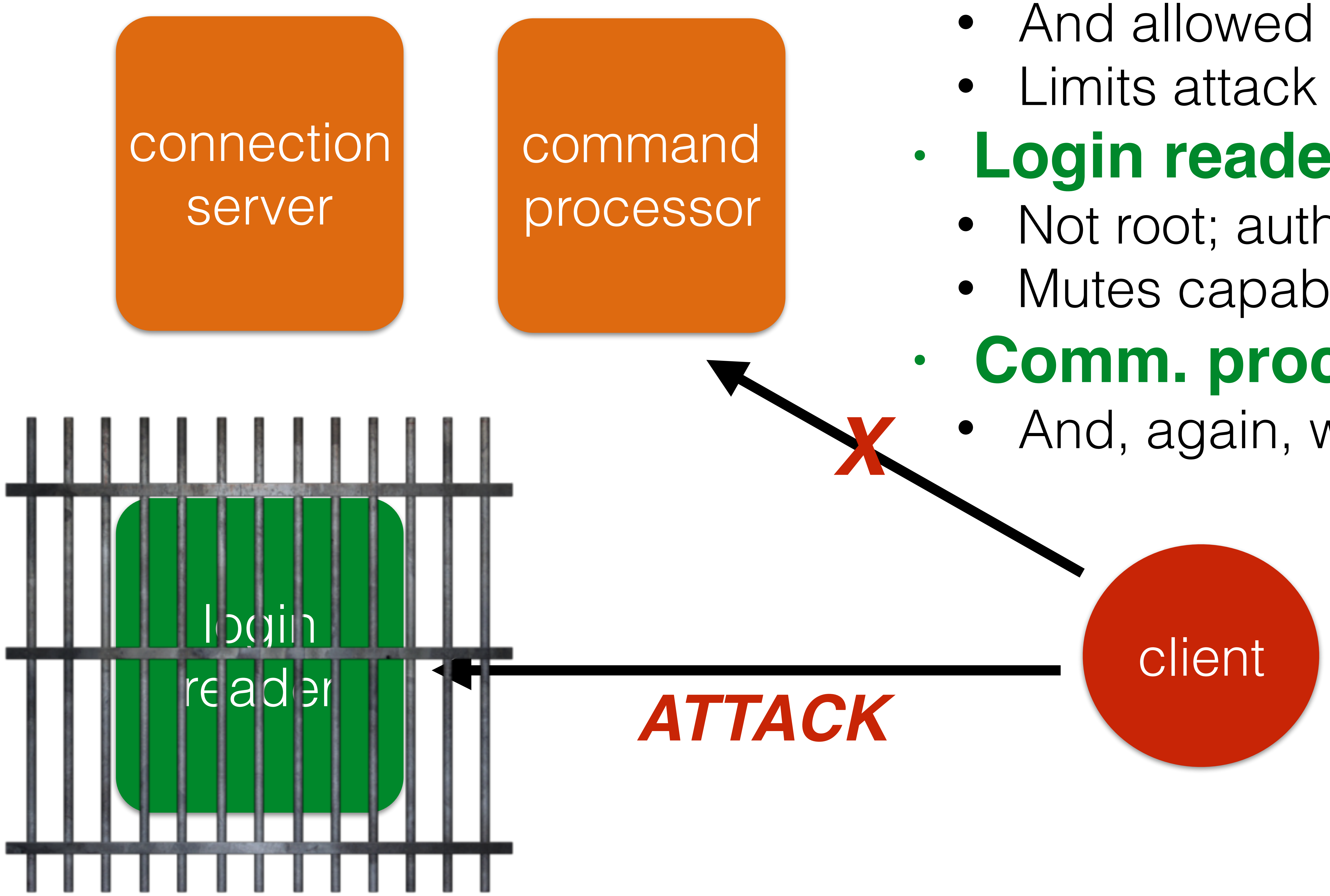

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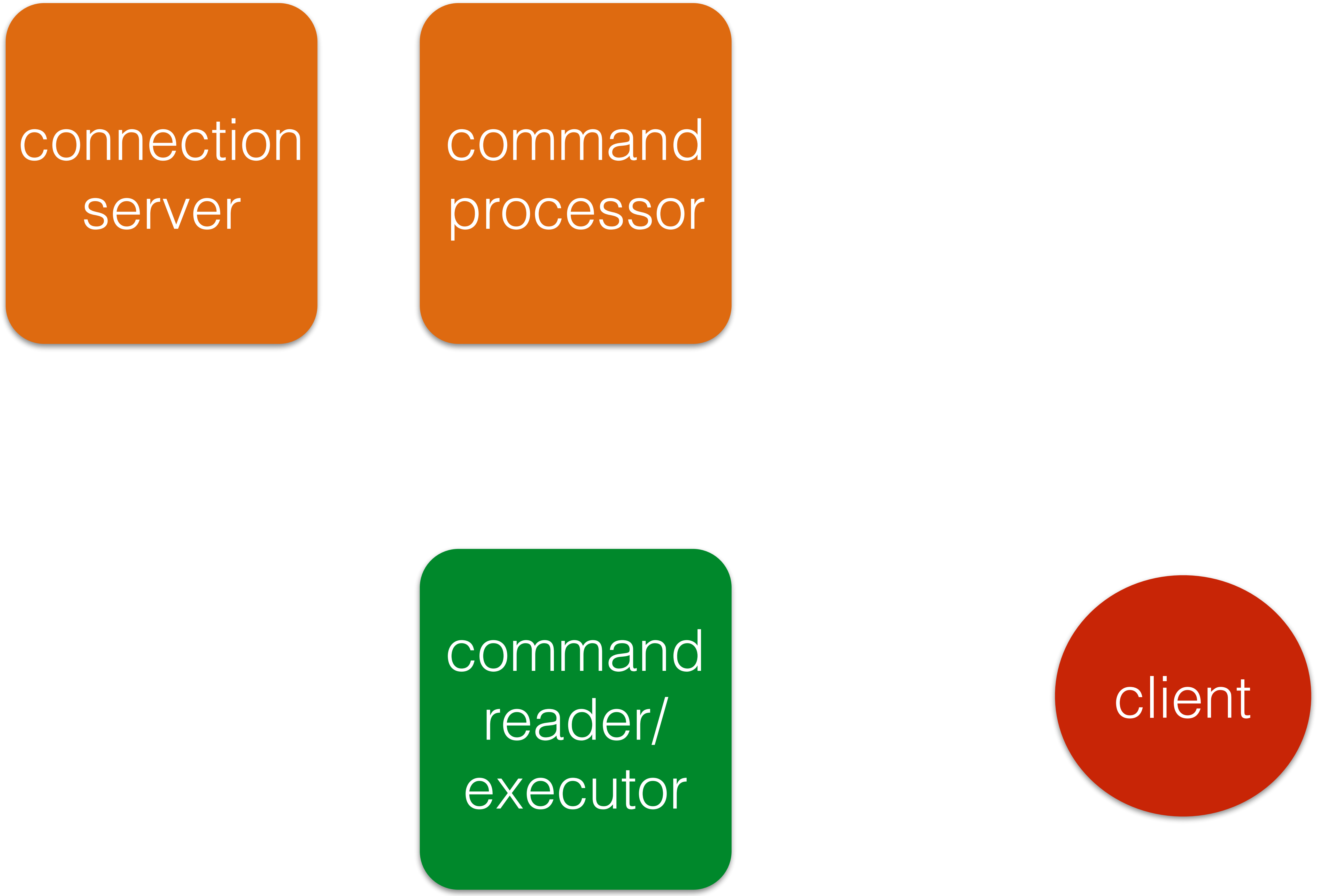

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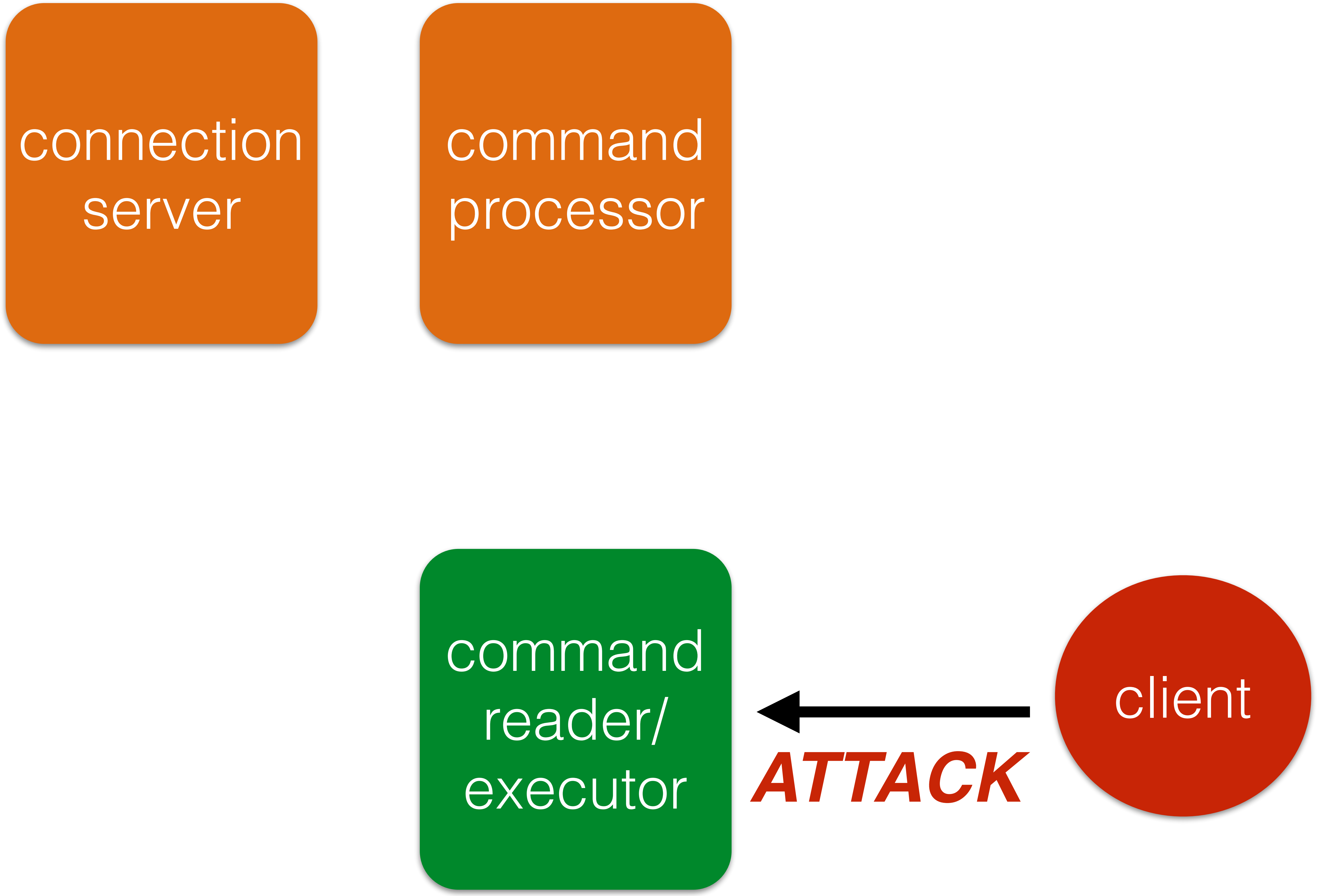

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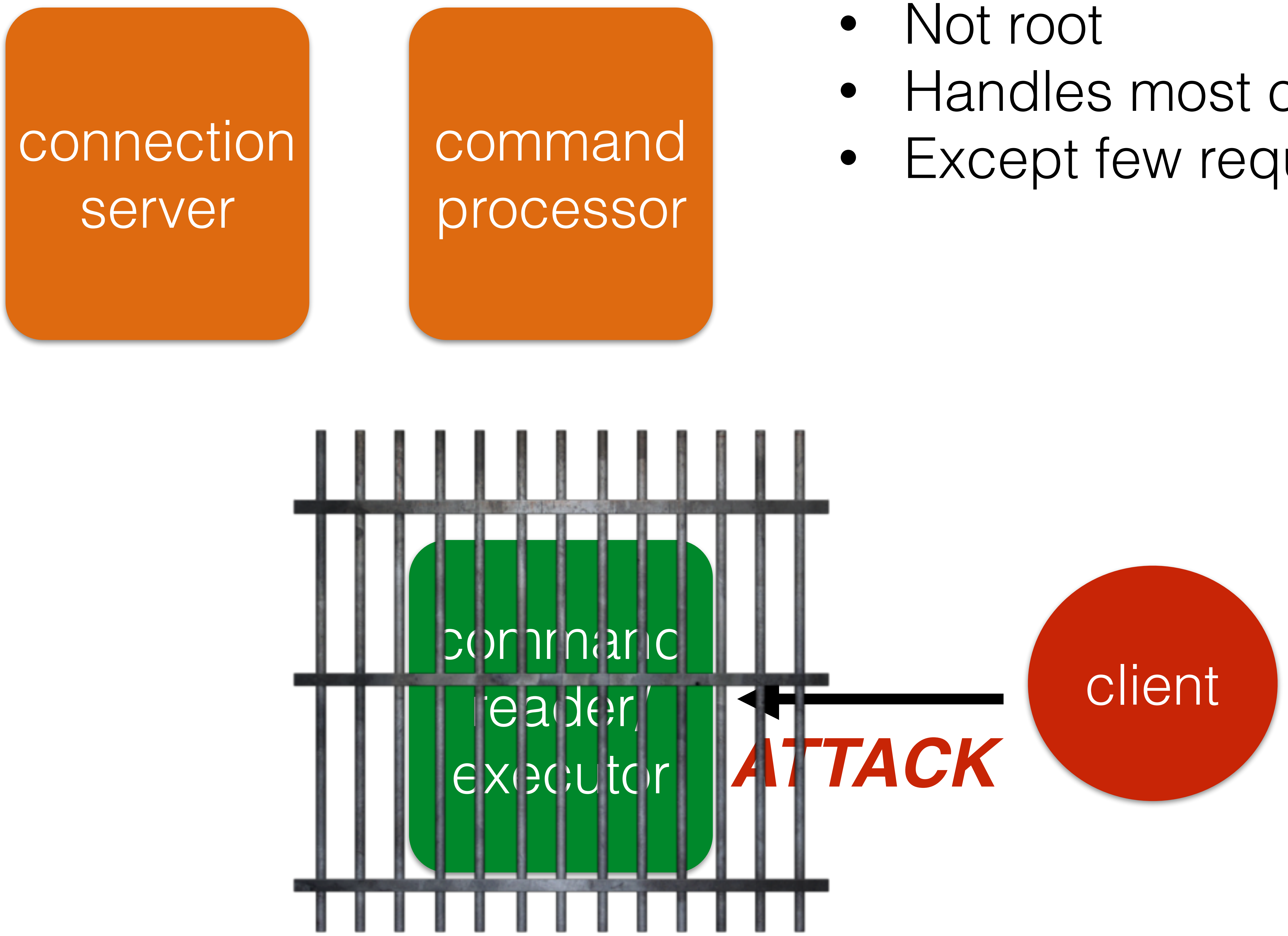

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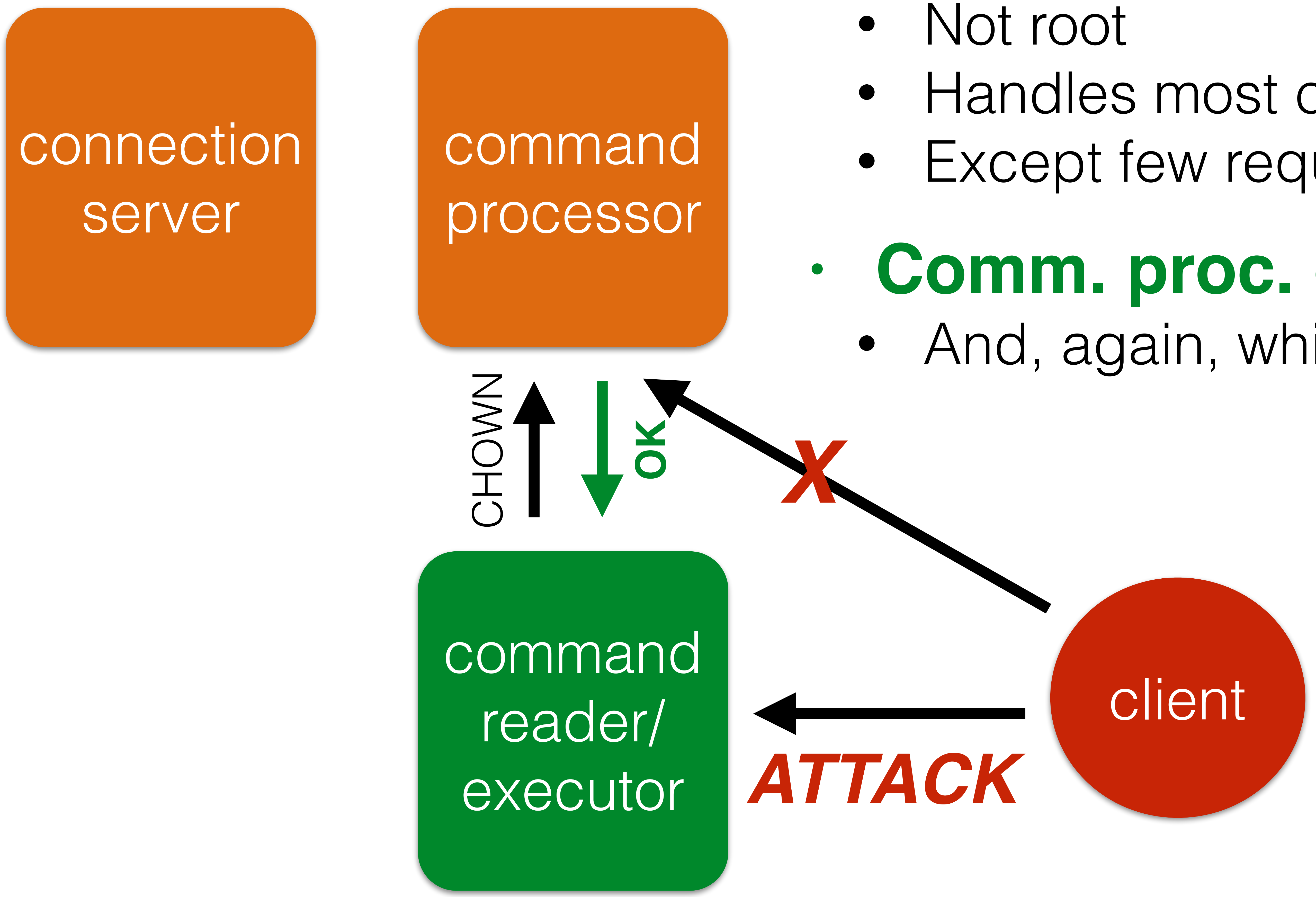

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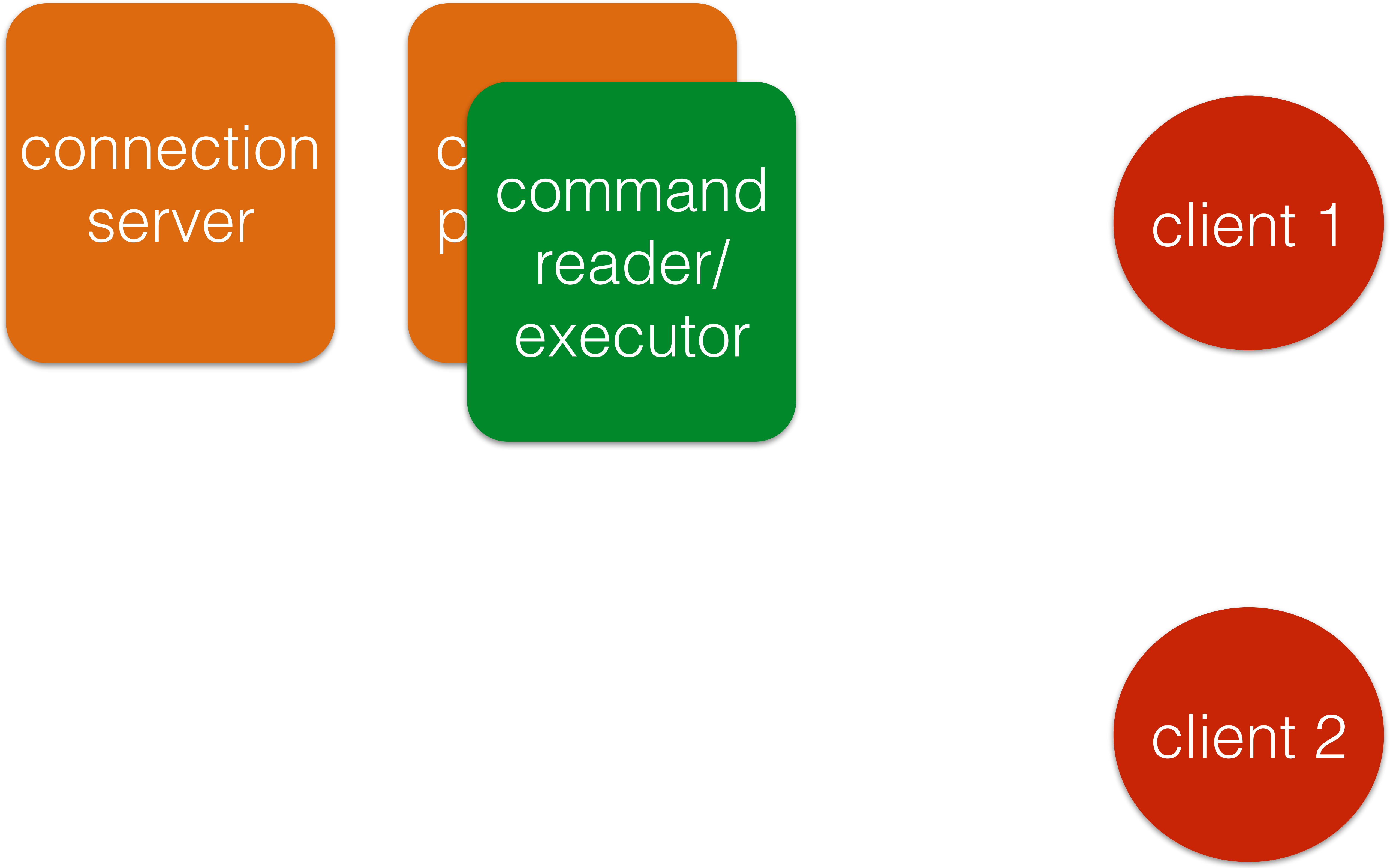

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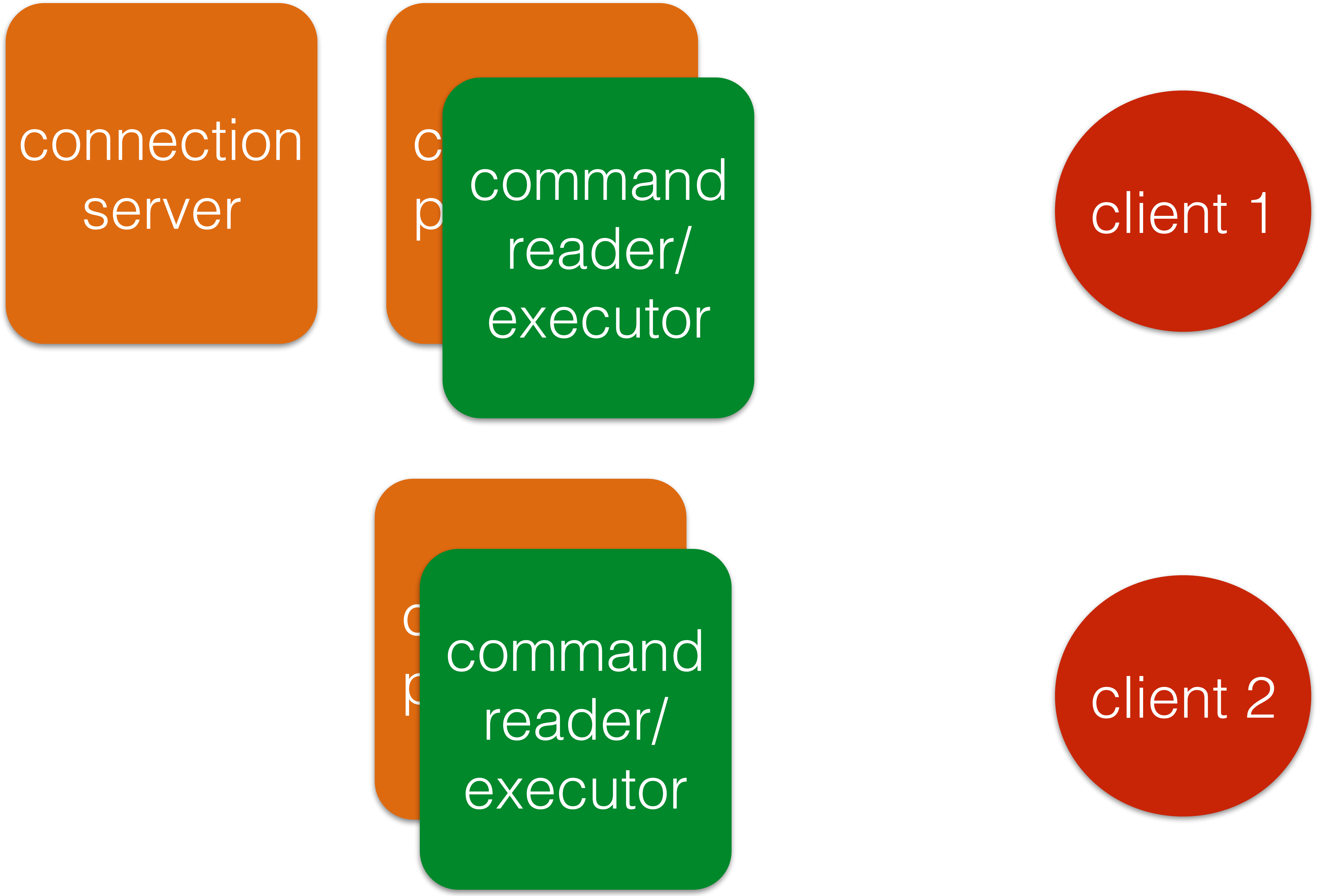

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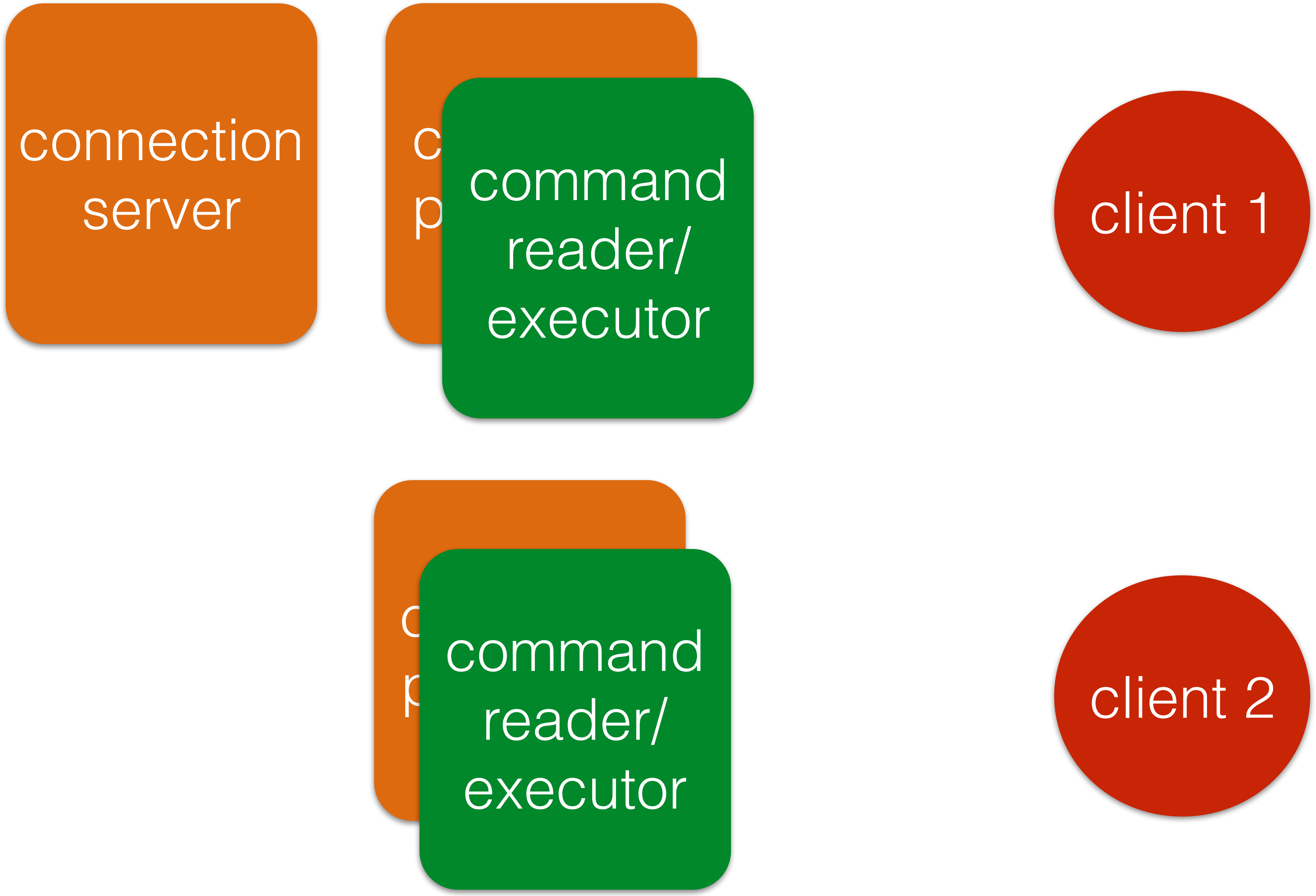

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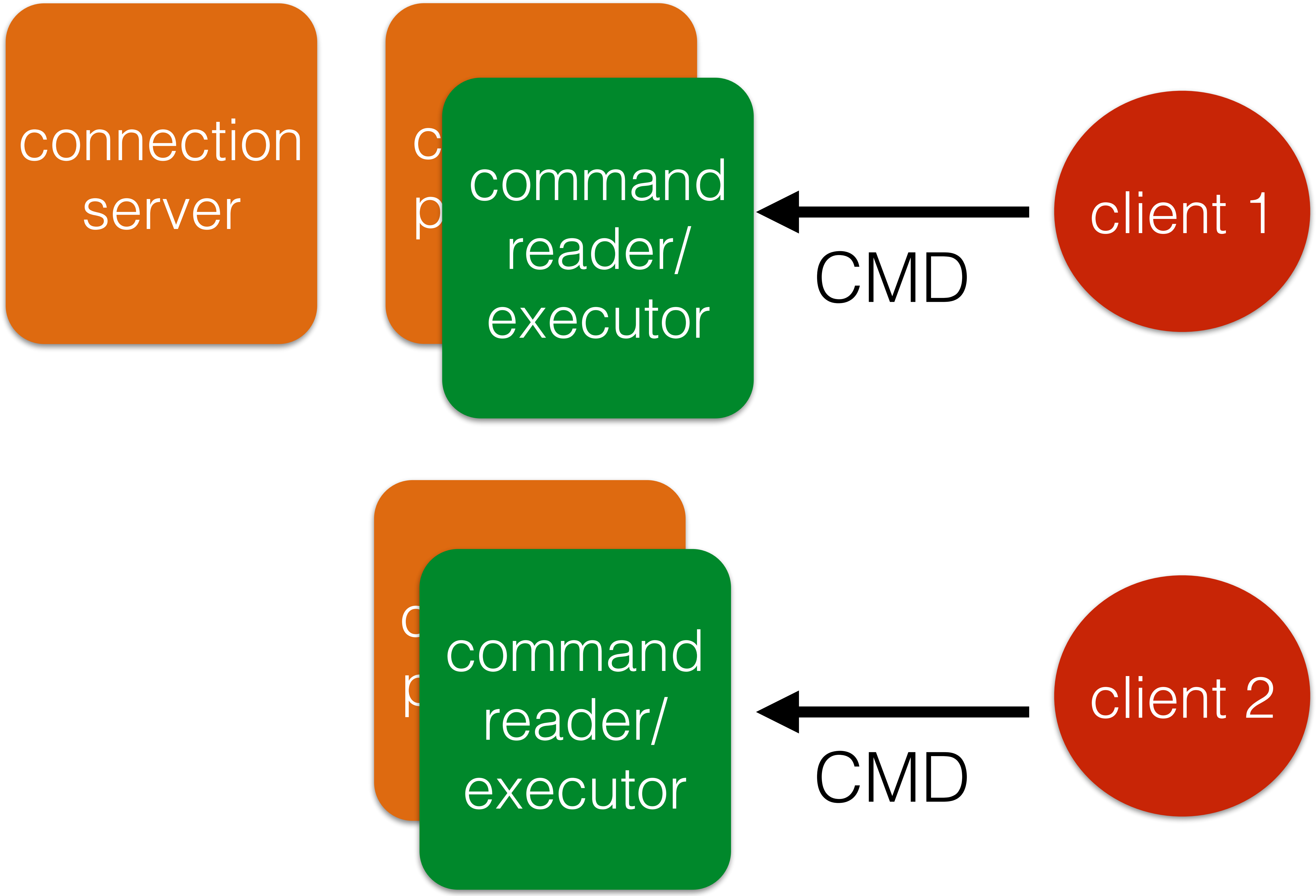

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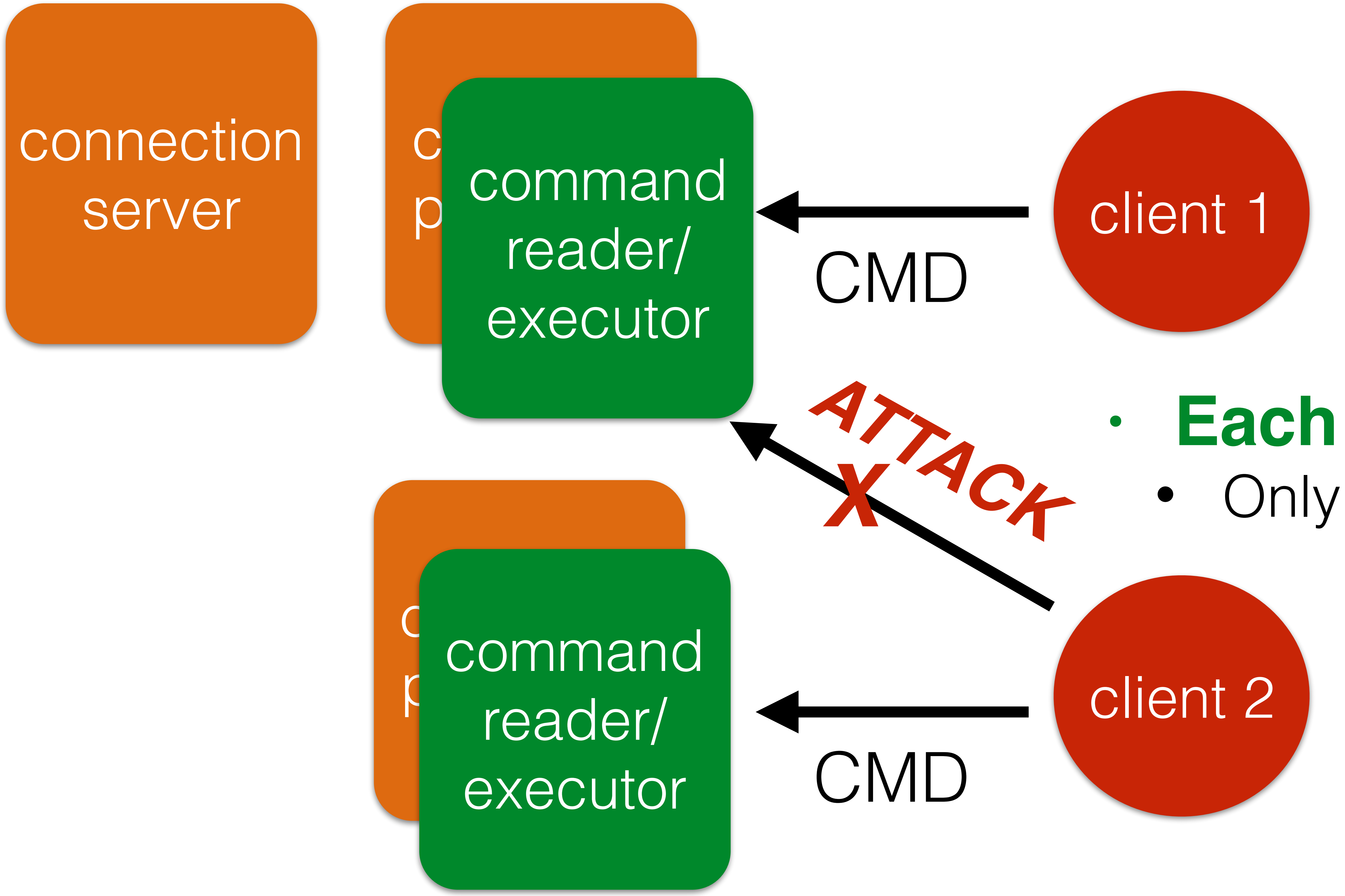

- **Each session isolated**
  - Only can talk to one client

Presenting vsftpd's secure design

vsftpd employs a secure design. The UNIX facilities outlined above are used to good effect. The design decisions taken are as follows:

1) All parsing and acting on potentially malicious remote network data is done in a process running as an unprivileged user. Furthermore, this process runs in a chroot() jail, ensuring only the ftp files area is accessible.

2) Any privileged operations are handled in a privileged parent process. The code for this privileged parent process is as small as possible for safety.

3) This same privileged parent process receives requests from the unprivileged child over a socket. All requests are distrusted. Here are example requests:
- Login request. The child sends username and password. Only if the details are correct does the privileged parent launch a new child with the appropriate user credentials.
- chown() request. The child may request a recently uploaded file gets chown'ed() to root for security purposes. The parent is careful to only allow chown() to root, and only from files owned by the ftp user.
- Get privileged socket request. The ftp protocol says we are supposed to emit data connections from port 20. This requires privilege. The privileged parent process creates the privileged socket and passes it to child over the socket.

4) This same privileged parent process makes use of capabilities and chroot(), to run with the least privilege required. After login, depending on what options have been selected, the privileged parent dynamically calculates what privileges it requires. In some cases, this amounts to no privilege, and the privileged parent just exits, leaving no part of vsftpd running with privilege.

5) vsftpd-2.0.0 introduces SSL / TLS support using OpenSSL. ALL OpenSSL protocol parsing is performed in a chroot() jail, running under an unprivileged user. This means both pre-authenticated and post-authenticated OpenSSL protocol parsing; it's actually quite hard to do, but vsftpd manages it in the name of being secure. I'm unaware of any other FTP server which supports both SSL / TLS and privilege separatation, and gets this right.

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Separation of responsibilities

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Kerkhoff's principle!

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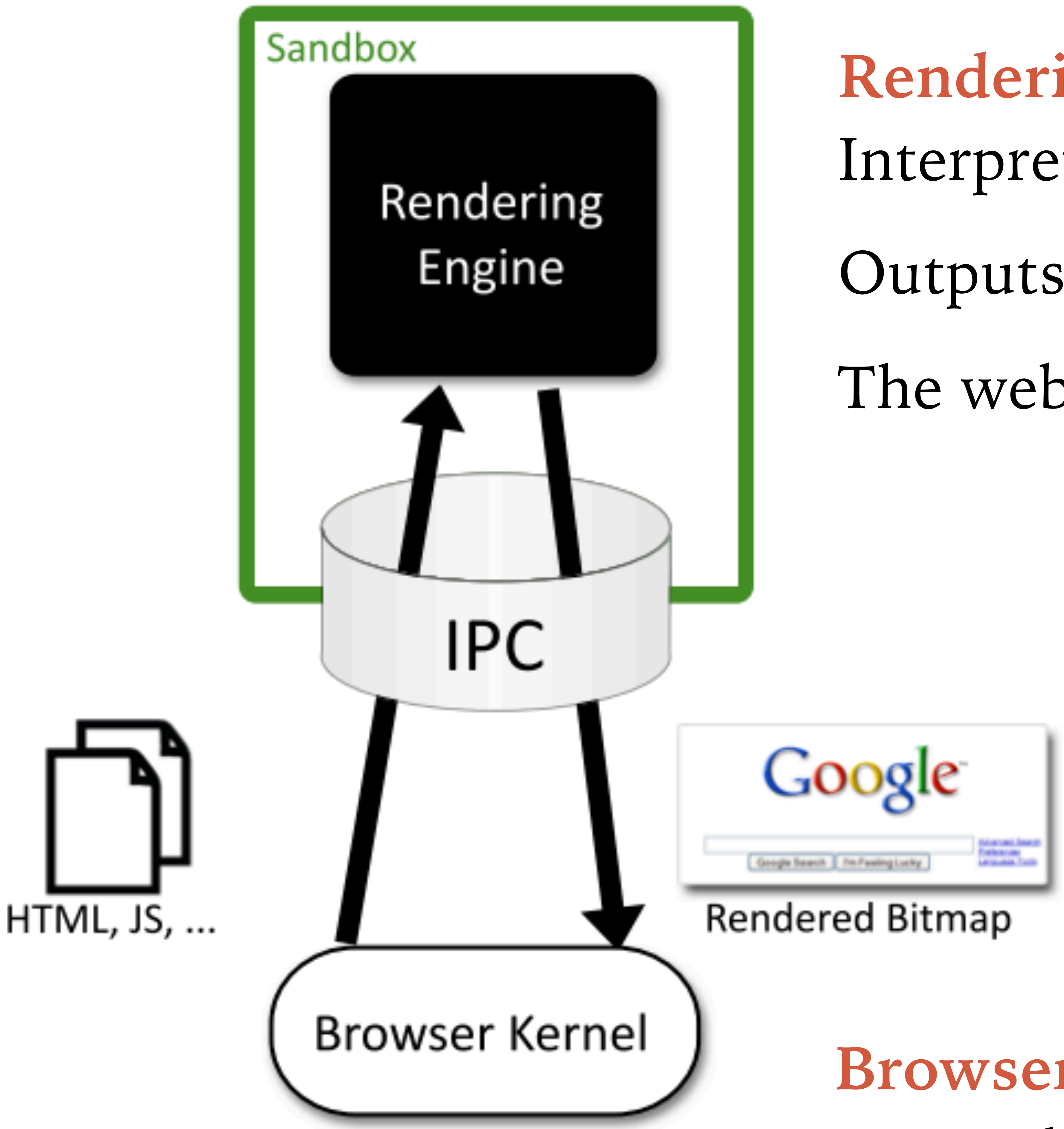
CHROMIUM ARCHITECTURE



Rendering Engine:

Interprets and executes web content

Outputs rendered bitmaps

The website is the “untrusted code”

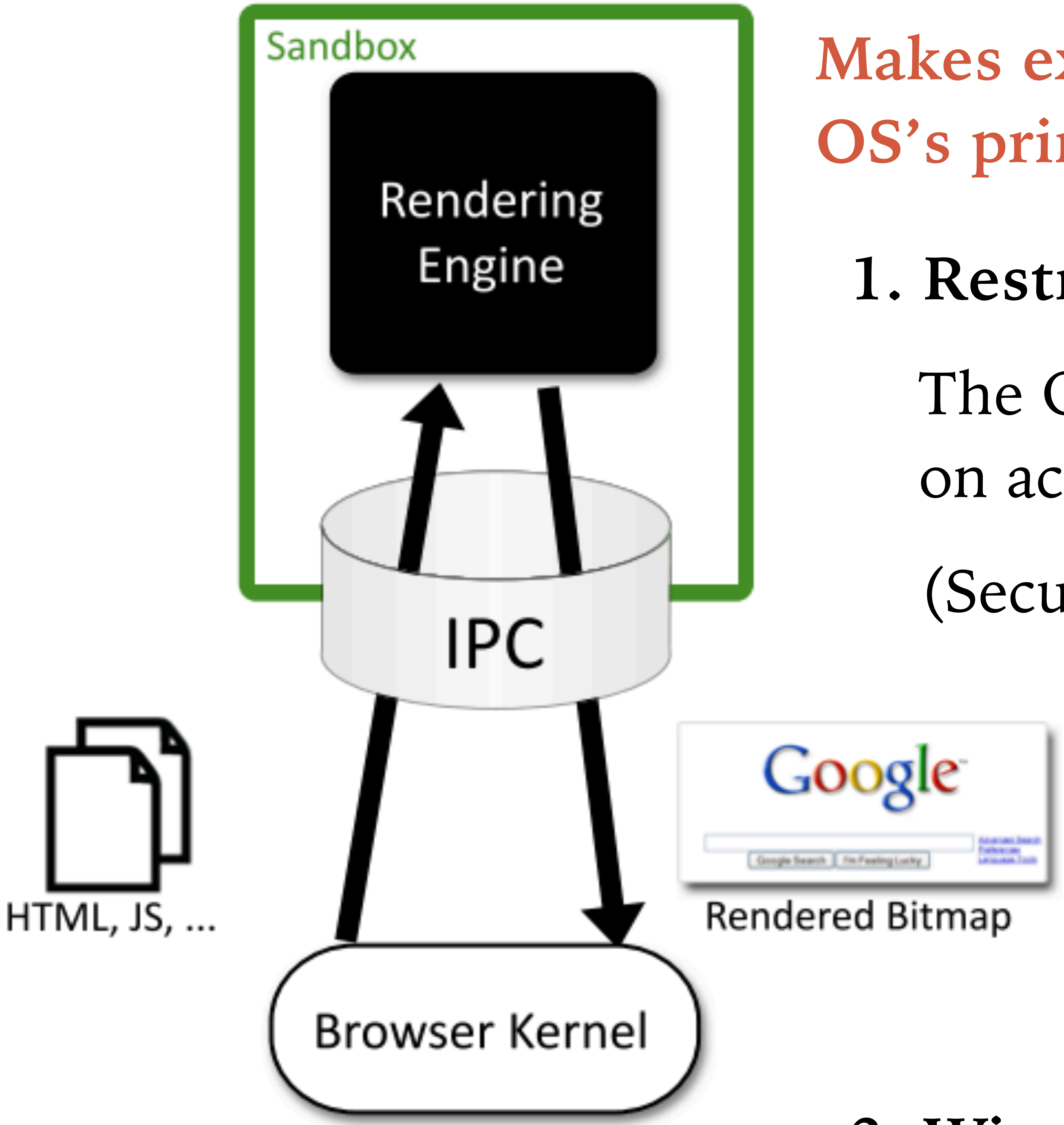
Goal: Enforce a narrow interface between the two

Browser Kernel:

Stores data (cookies, history, clipboard)

Performs all network operations

CHROMIUM'S SANDBOX



Makes extensive use of the underlying OS's primitives

1. **Restricted security token**

   The OS then provides complete mediation on access to "securable objects"

   (Security token set s.t. it fails almost always)

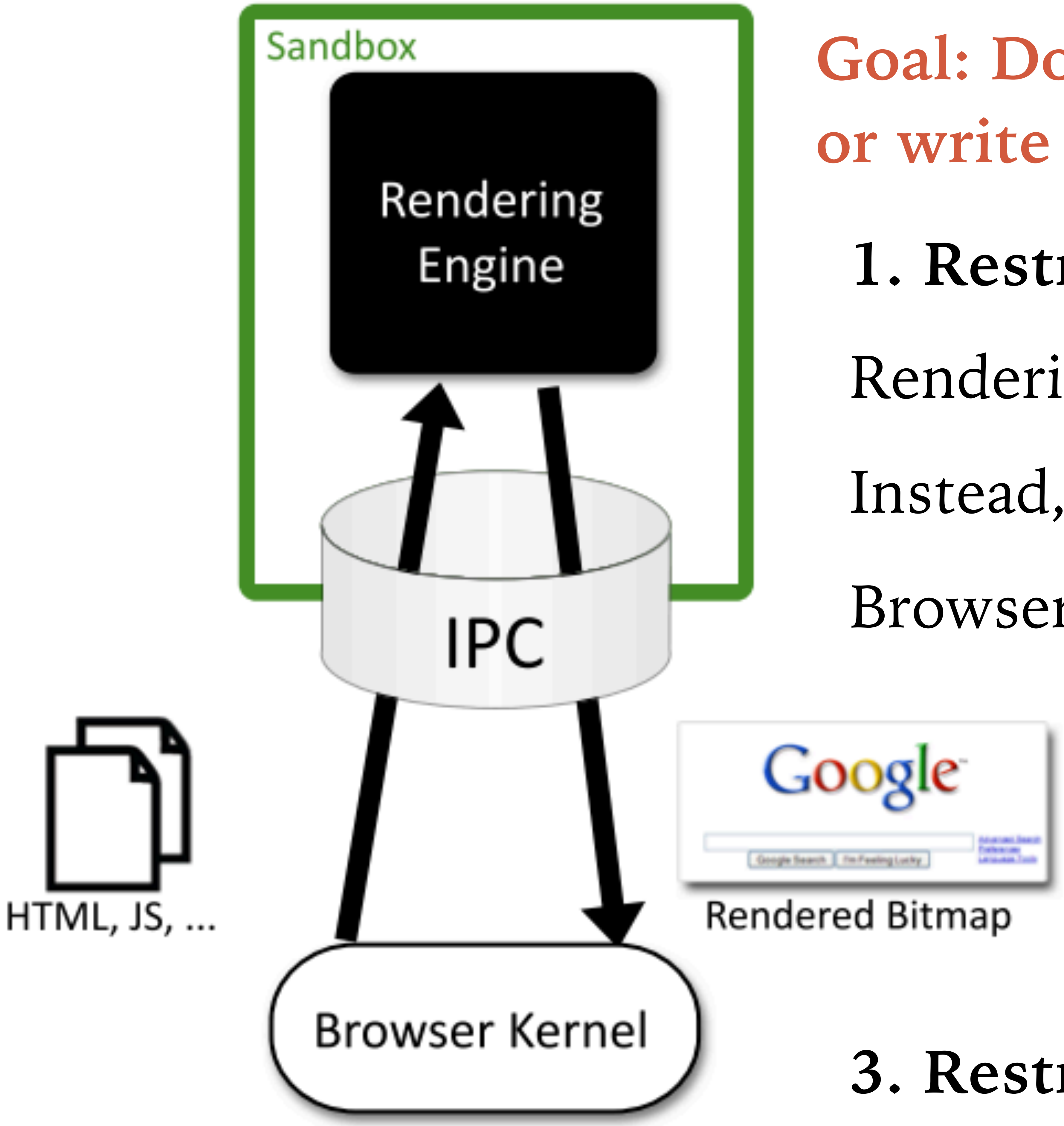
2. **Separate desktop**

   Avoid Windows API's lax security checks

3. **Windows Job Object**

   Can't fork processes; can't access clipboard

CHROMIUM'S BROWSER KERNEL INTERFACE



Goal: Do not leak the ability to read or write the user's file system

1. **Restrict rendering**

Rendering engine doesn't get a window handle

Instead, draws to an off-screen bitmap

Browser kernel copies this bitmap to the screen

2. **Network & I/O**

Rendering engine requests uploads, downloads, and file access thru BKI

3. **Restrict user input**

Rendering engine doesn't get user input directly

Instead, browser kernel delivers it via BKI