Wedge: Splitting Applications into Reduced-Privilege Compartments

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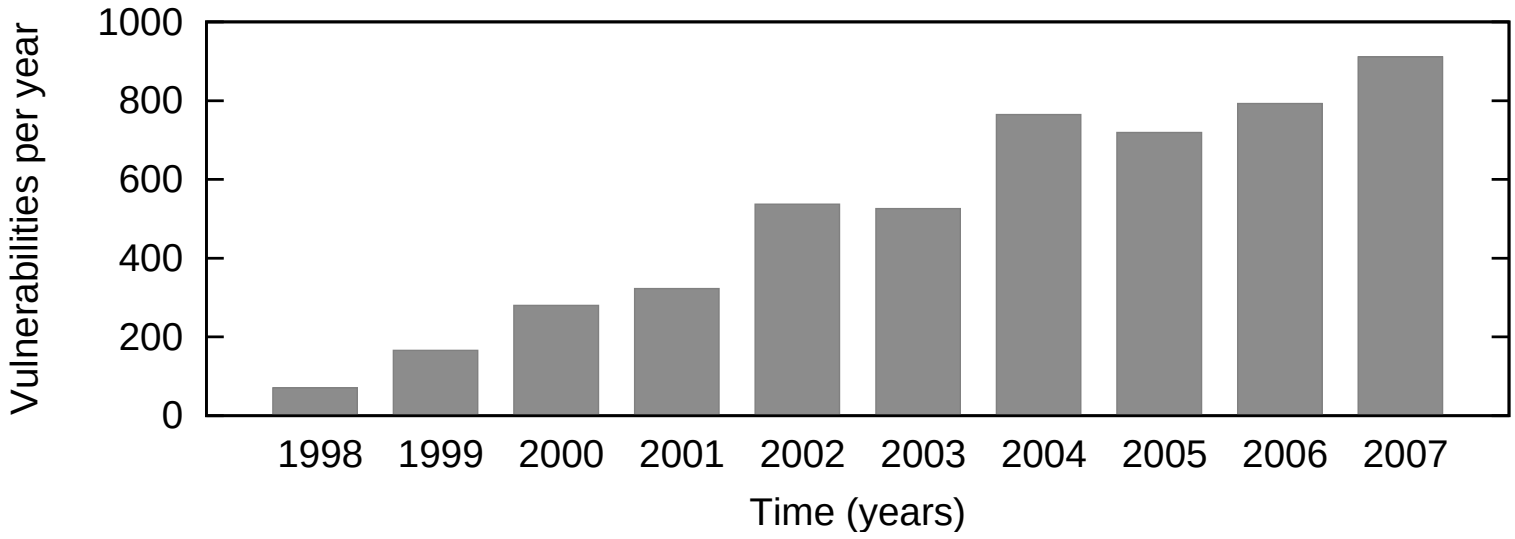
Vulnerabilities threaten sensitive data

- Exploits allow running arbitrary code on servers.
- An exploited web server can be used to leak sensitive information such as credit card numbers.

Have we managed to mitigate or prevent vulnerabilities?



Source: osvdb.org

Process-based privileges are too coarse-grained

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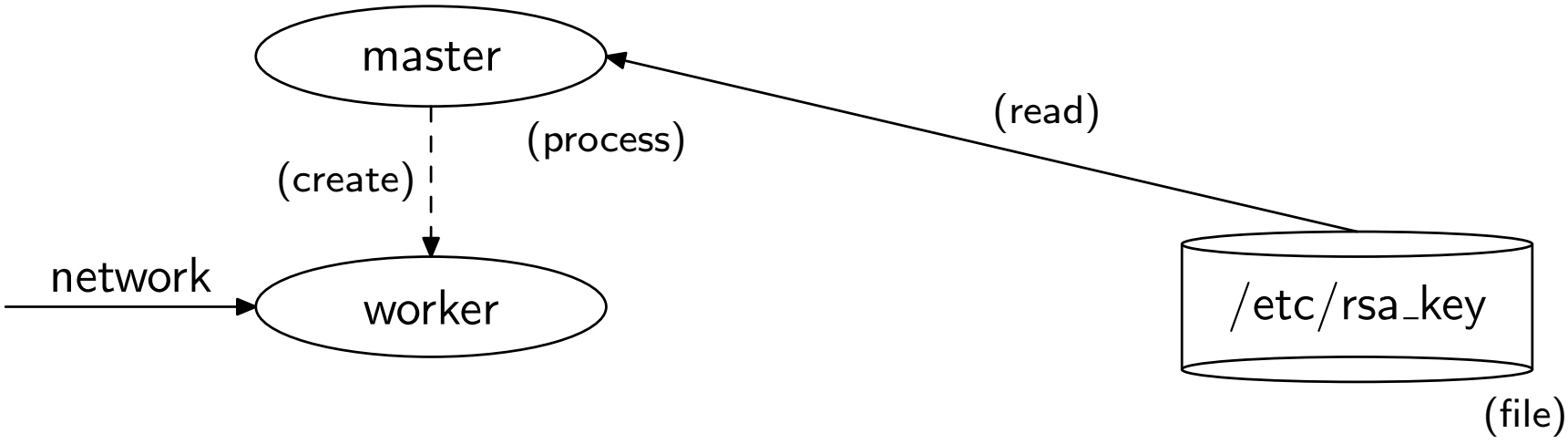

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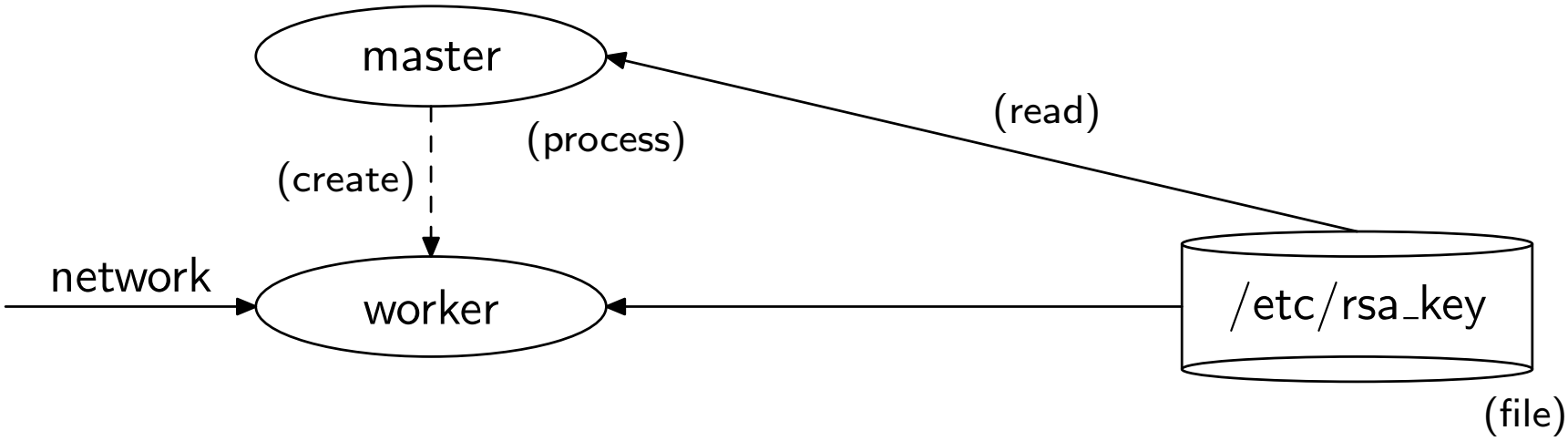

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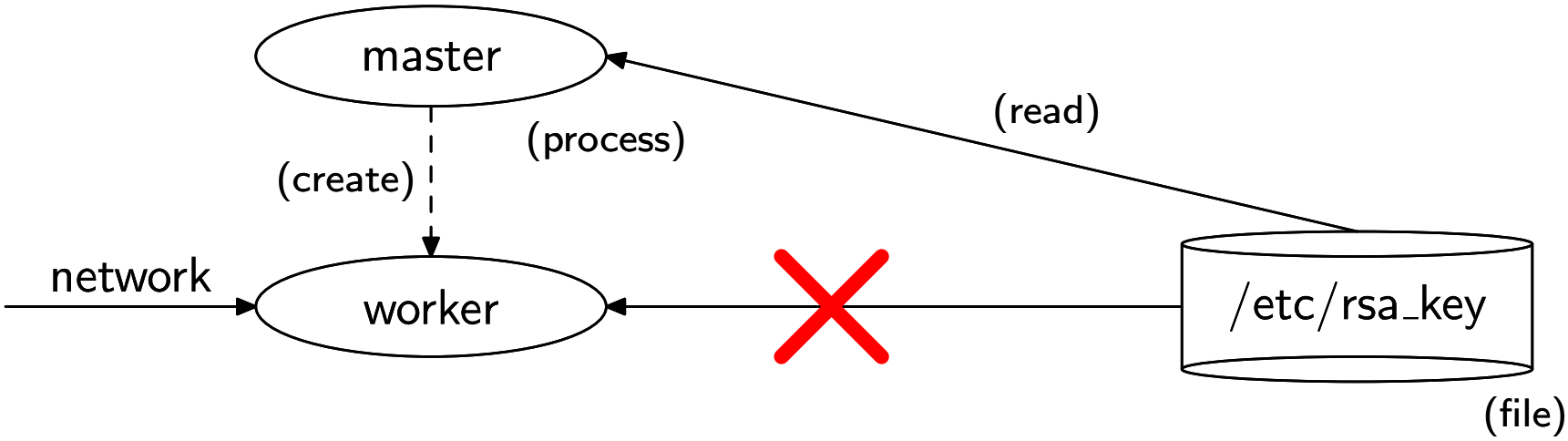

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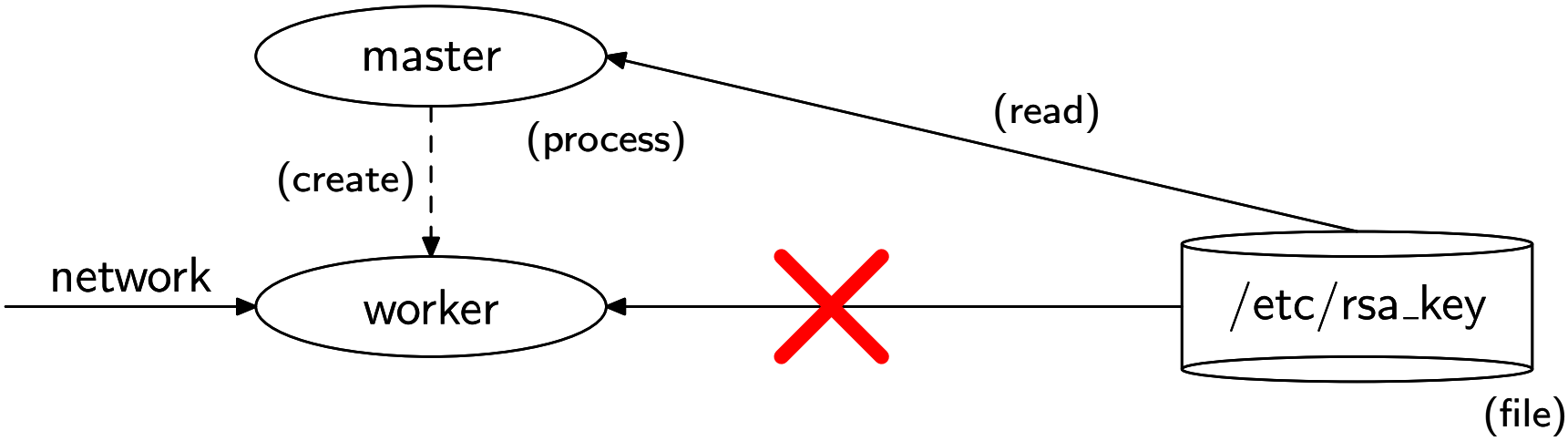

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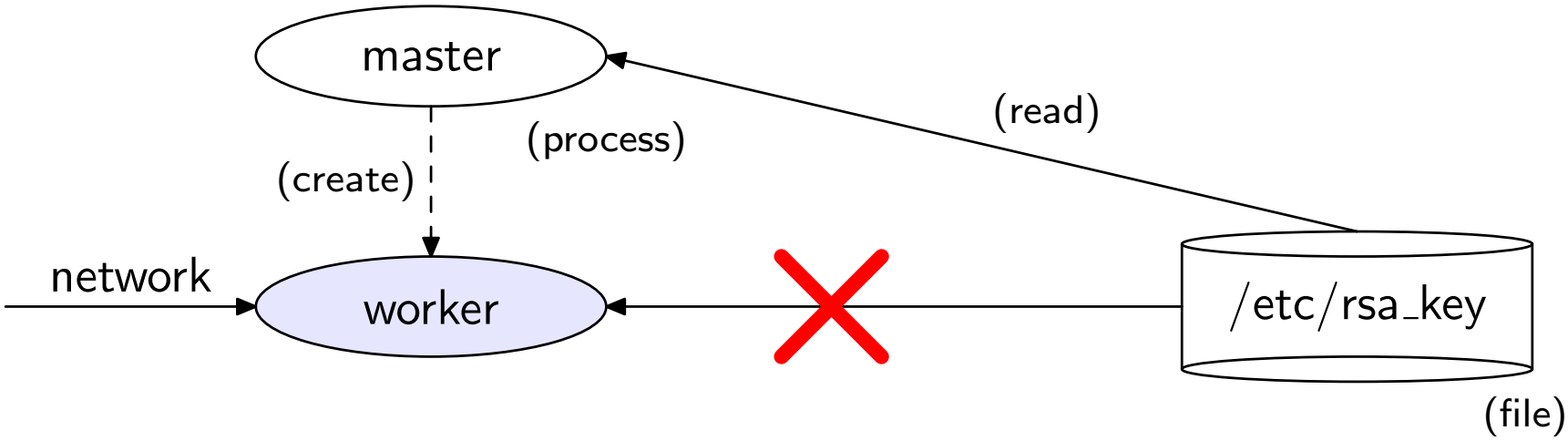

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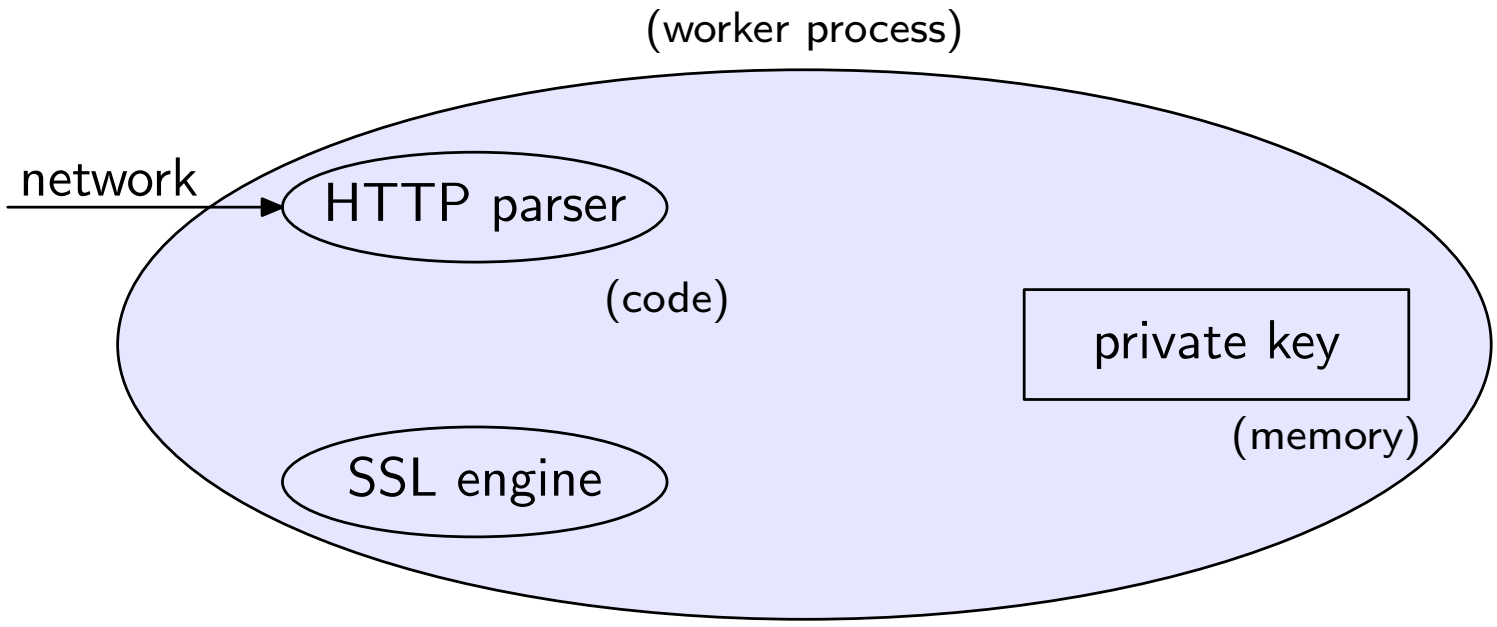

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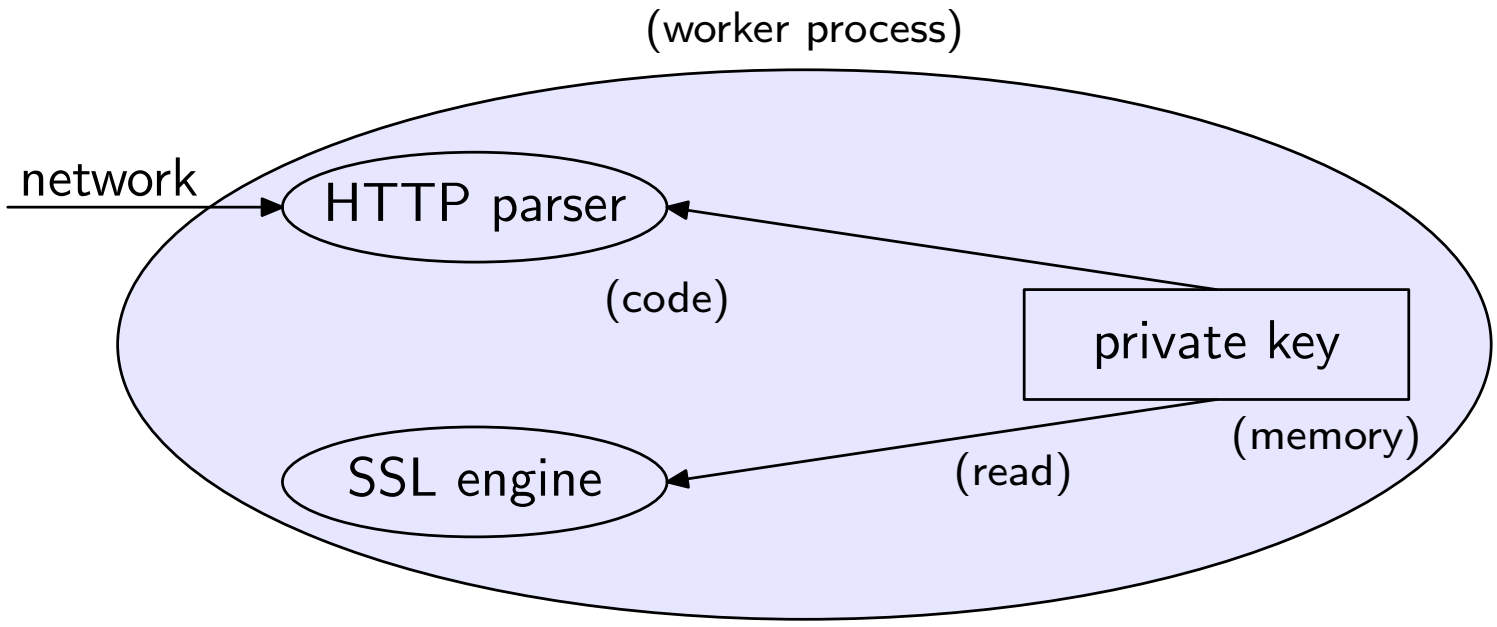

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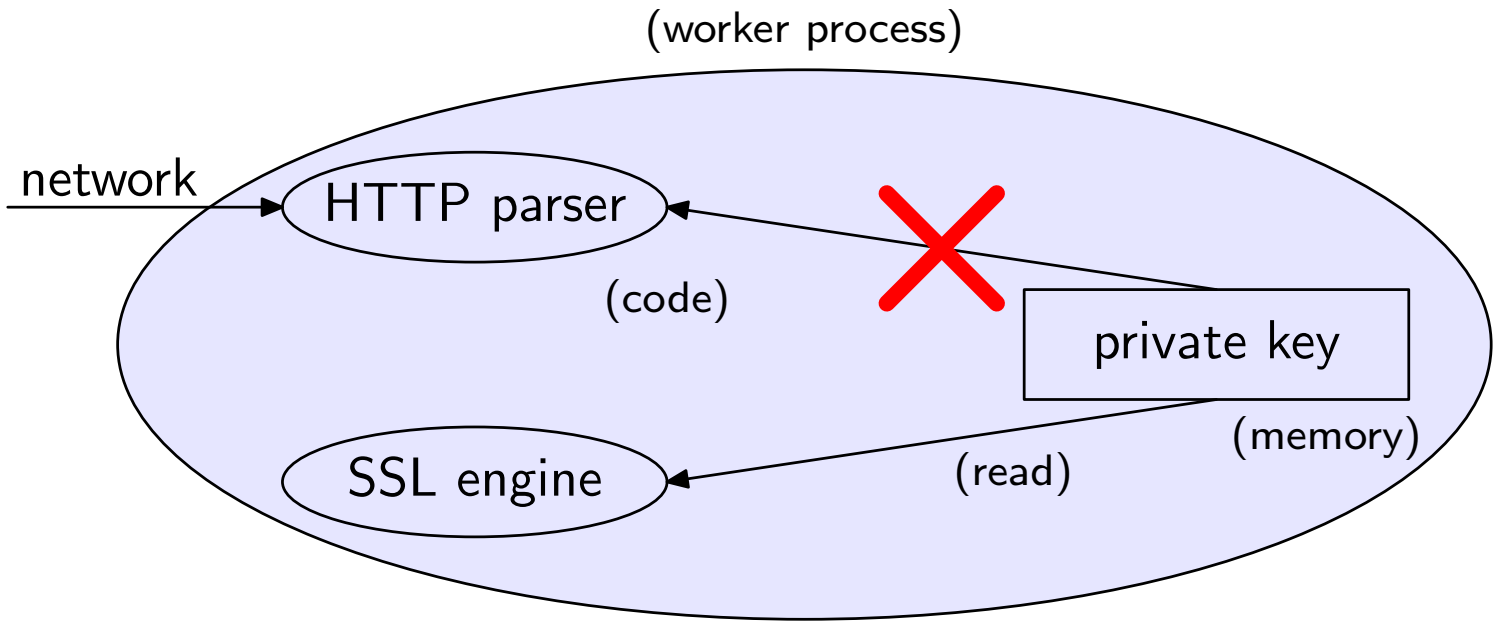

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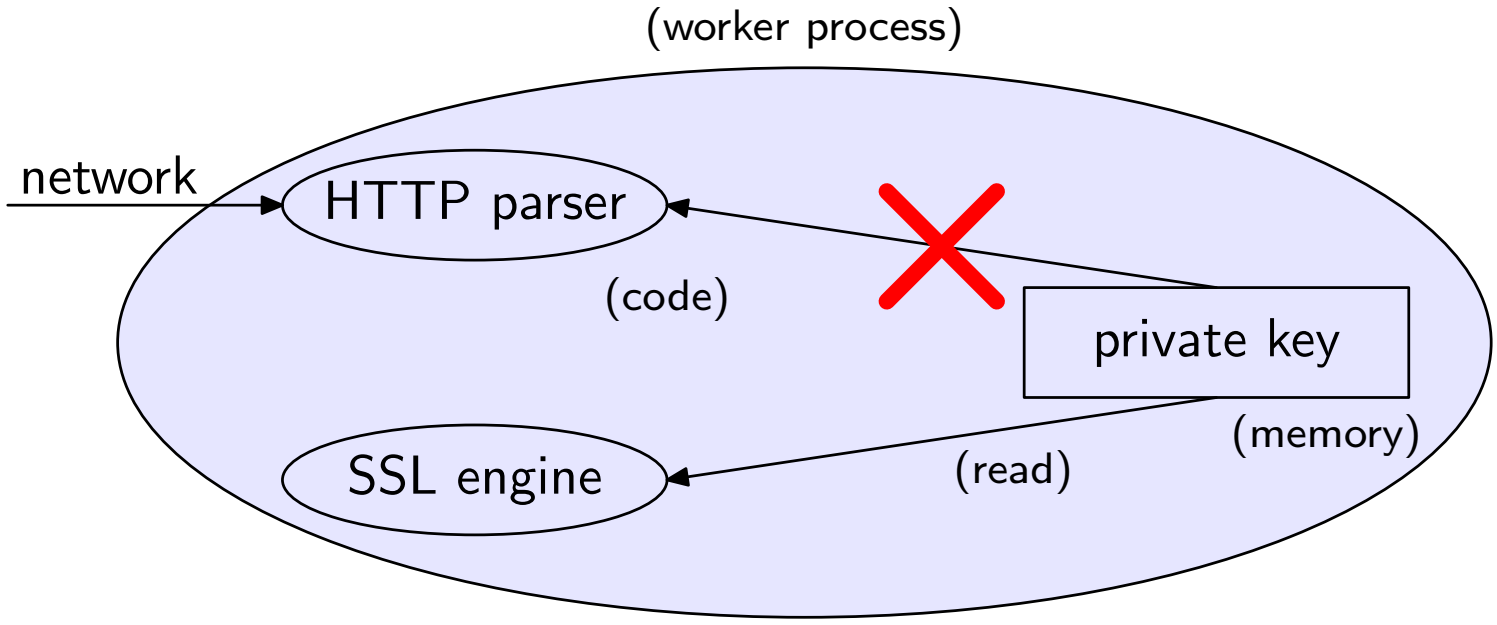
This talk: how to limit access of code to memory at fine granularity.



Old idea: principle of least privilege

Principle of least privilege:

- Partition code into *compartments*.
- Assign each compartment the minimal privileges it needs for its operation.
- Restrict interface and interactions between compartments.

How to implement compartments?

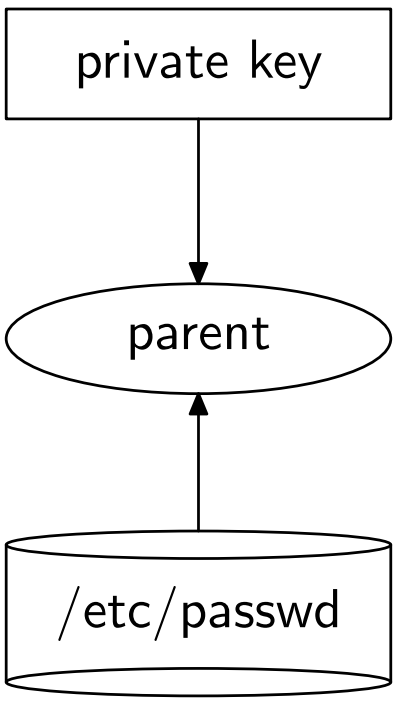
- Processes?

Why are traditional processes not sufficient?

Creating compartments with UNIX, *e.g.*, `fork`:

- Default grant. Child inherits memory map and file descriptors.

Operation of fork



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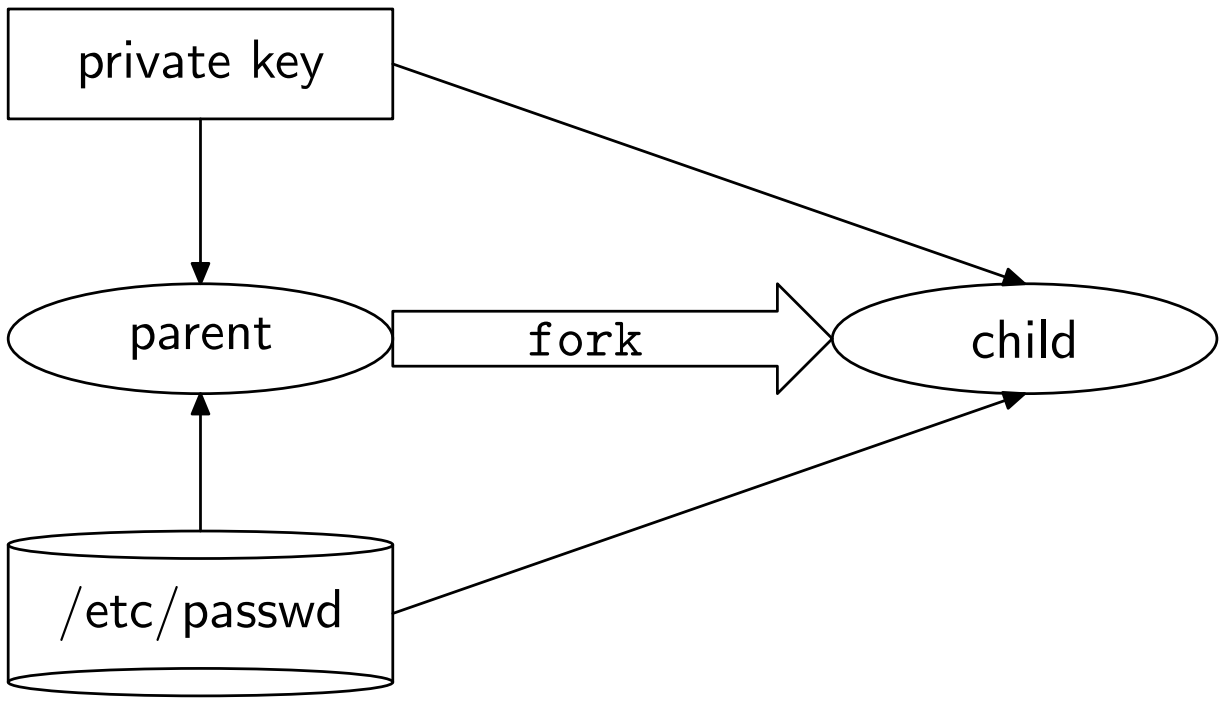

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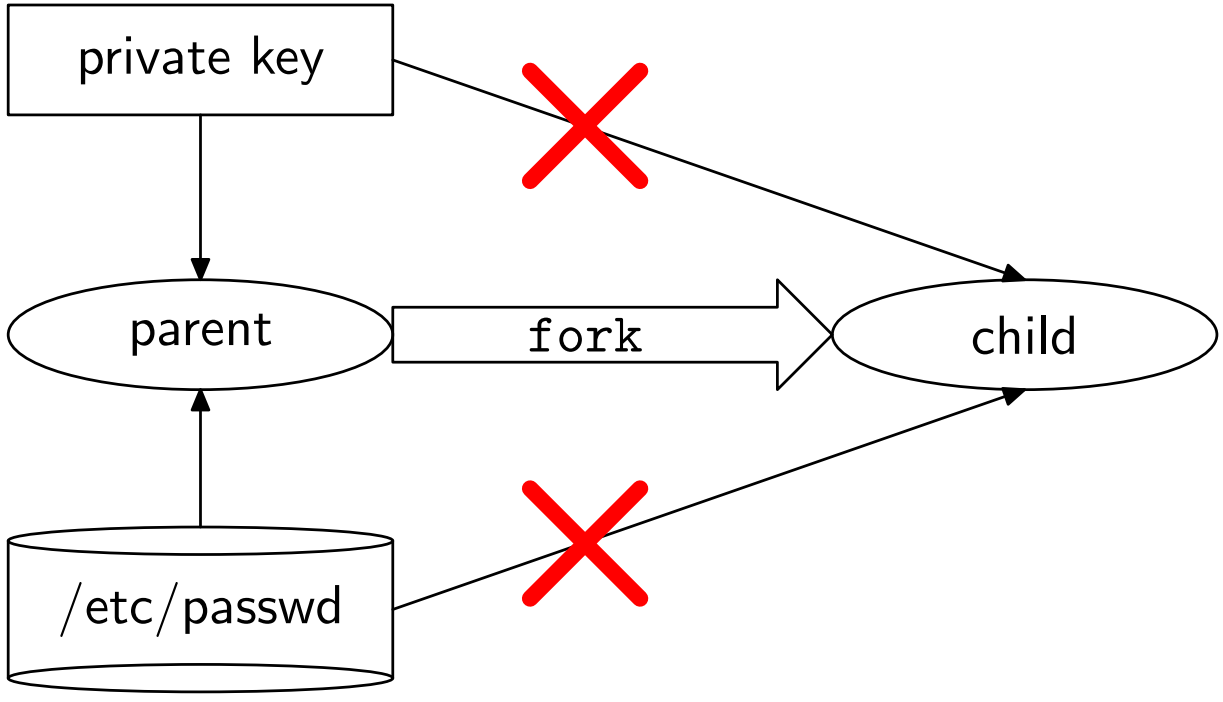
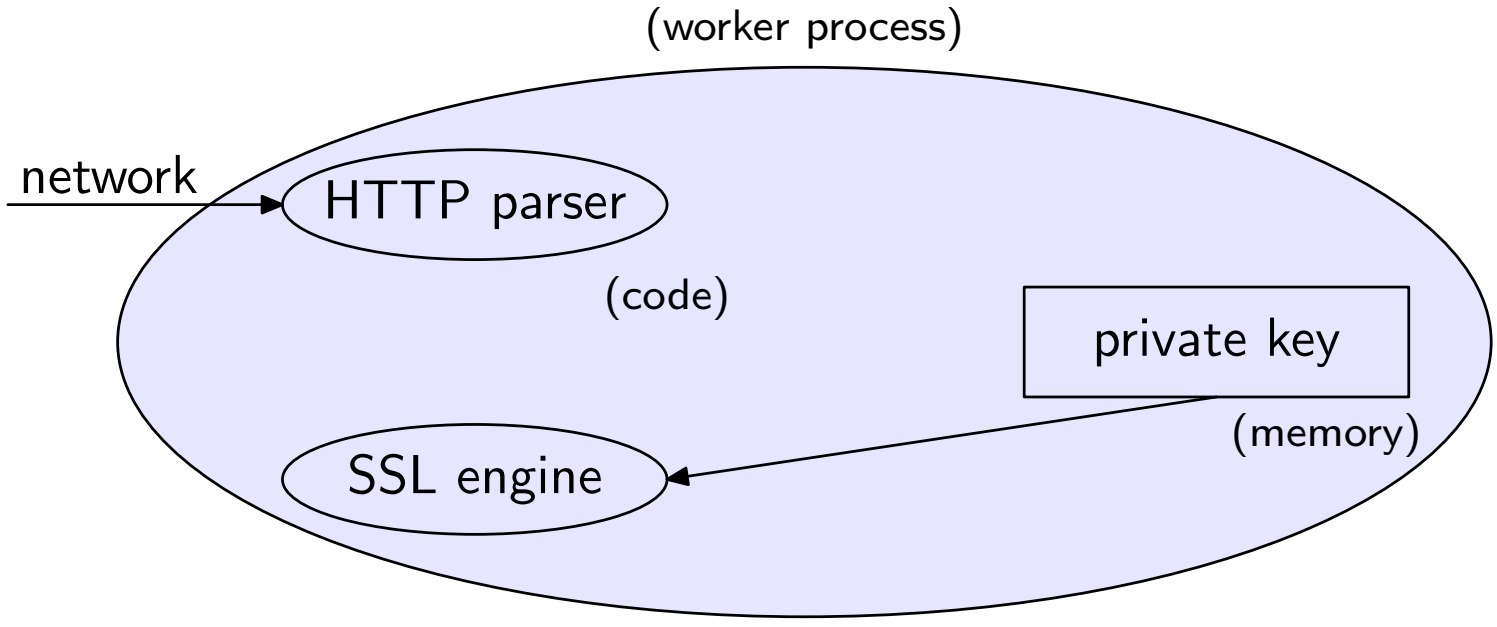


Default-deny: inherit nothing from parent. Closer to least-privilege.

But default-deny is difficult to use for legacy code

How many permissions do we need to explicitly grant?



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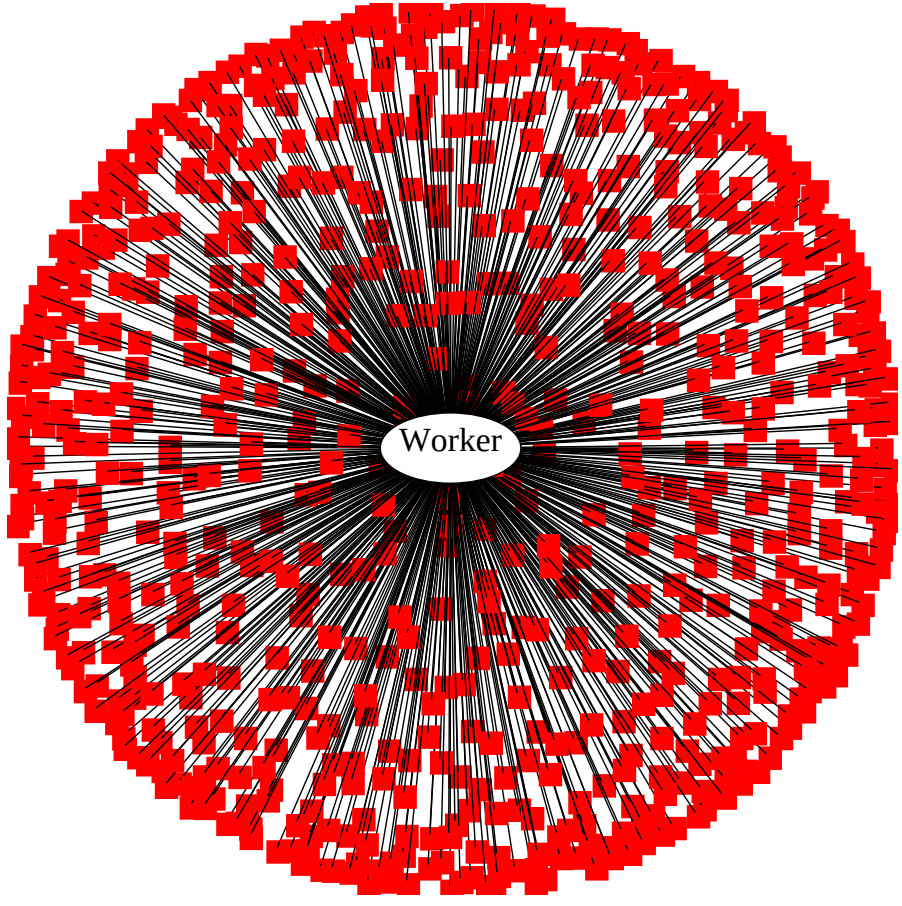


Apache's client handler uses over 600 memory objects.

Contributions

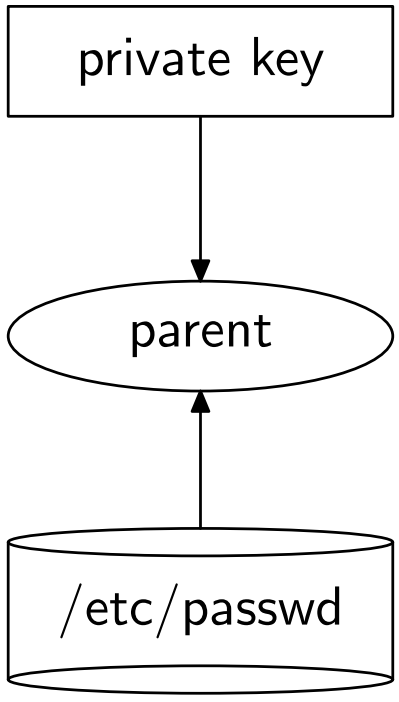
- New system calls for default-deny.
  - Creating compartments.
  - Specifying privileges.
- Tools to make default-deny usable when partitioning legacy code.
  - Identifying the privileges for compartments.

Outline

1. Wedge.
   - New system calls for default-deny.
   - Crowbar: tool for partitioning legacy code.

2. Wedge applied to Apache+OpenSSL.

sthreads: default-deny compartments



- Like processes, but default-deny.
- Like threads: can easily share pointers and file descriptors.
- Programmer must explicitly grant all permissions.

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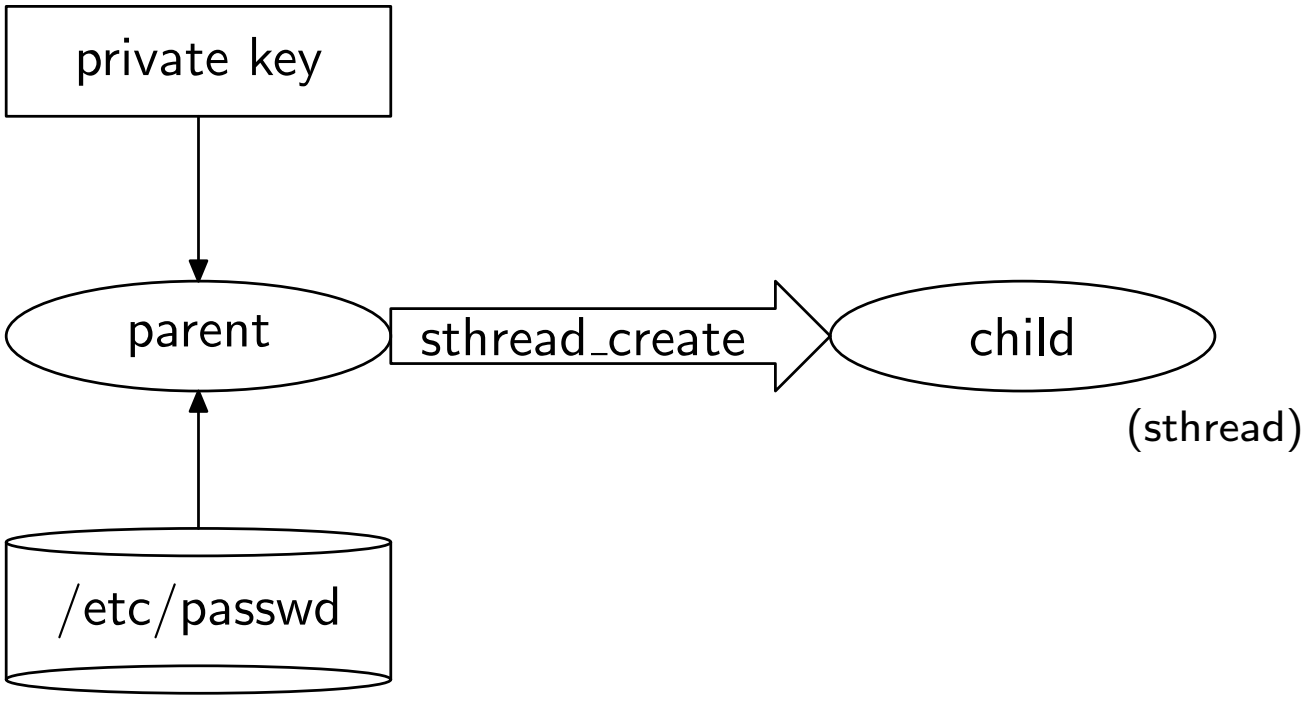

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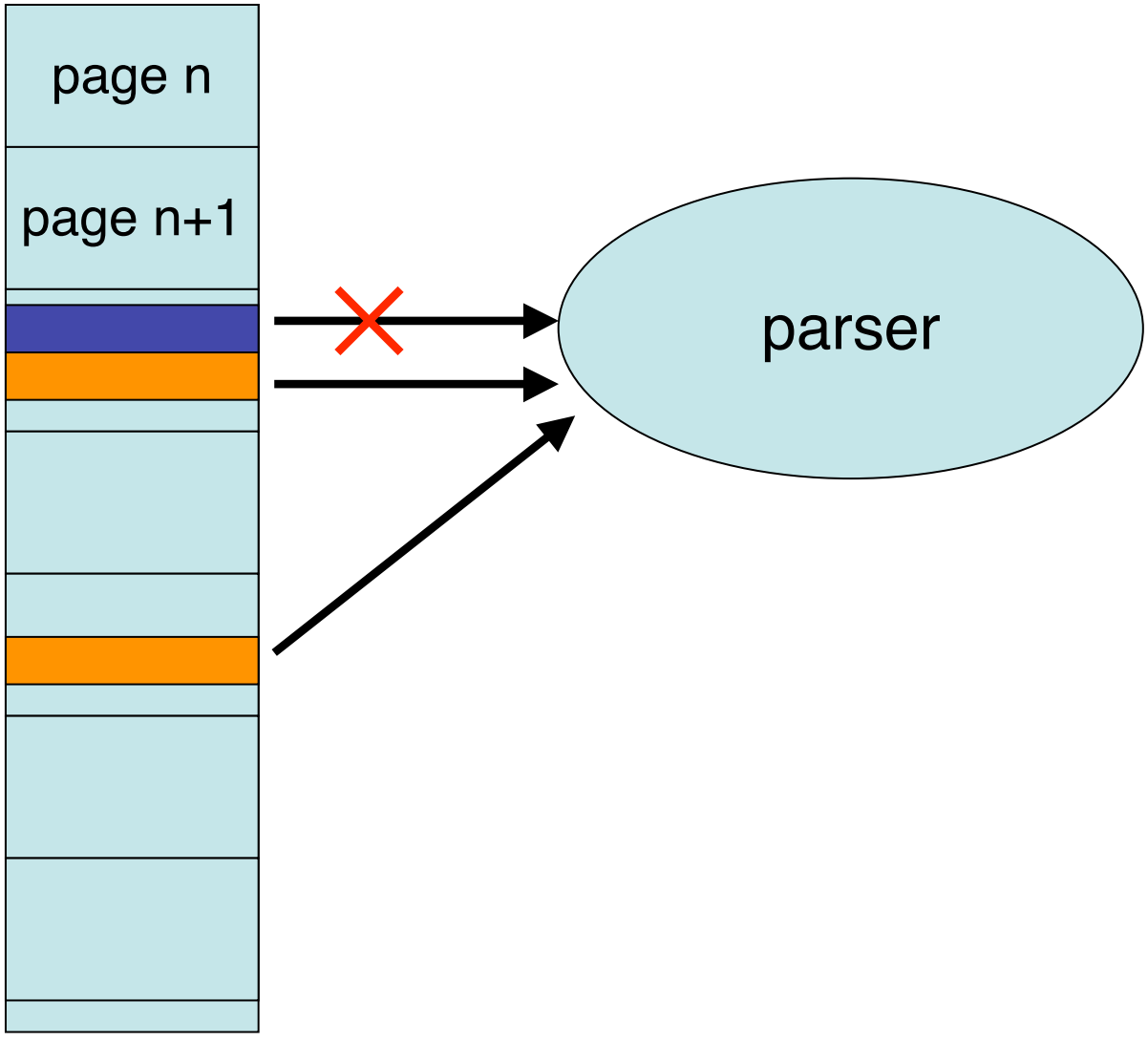
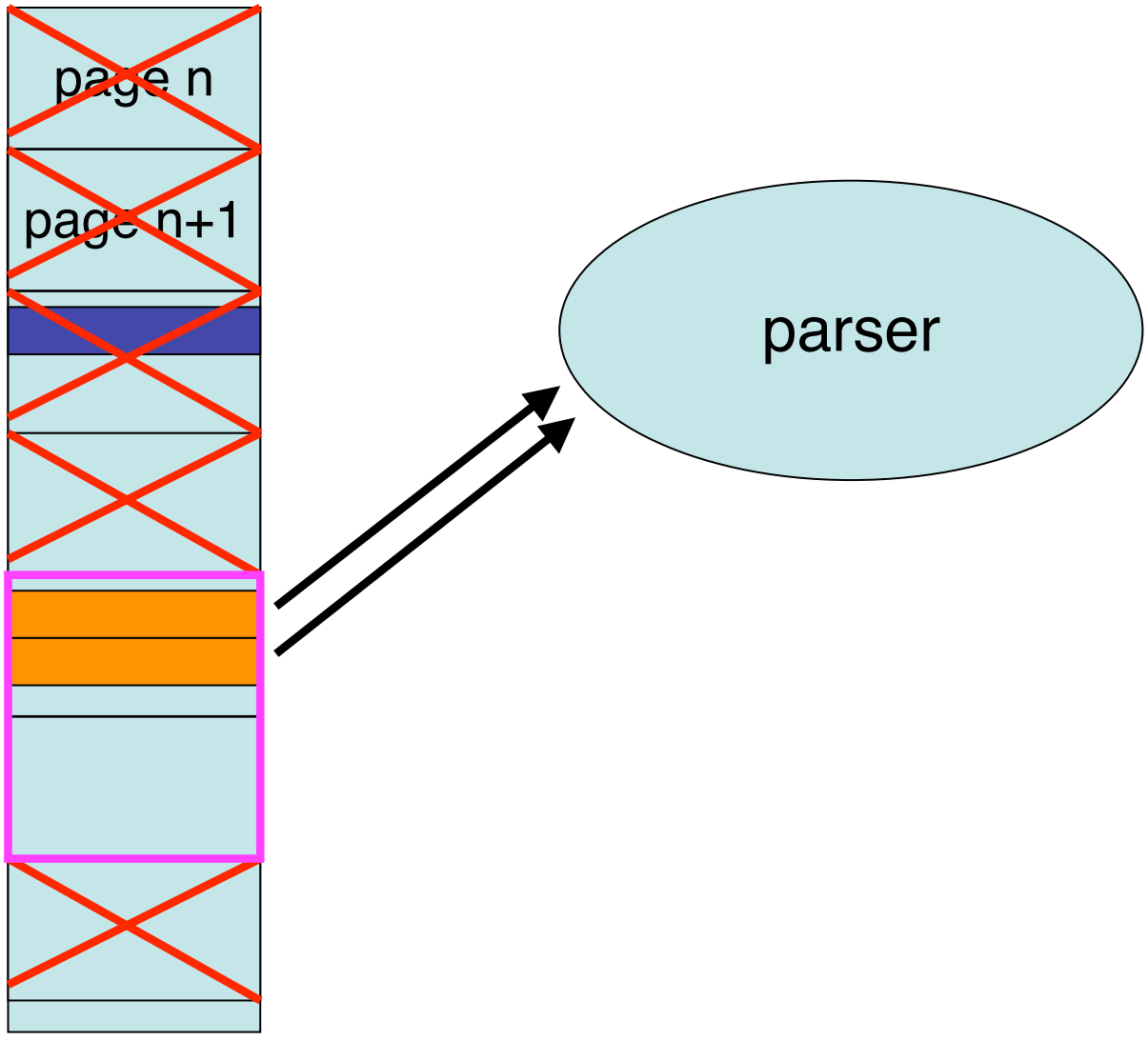
Virtual memory

```
{
    char *key, *buffer;
    char *config;
    key = malloc(16);
    buffer = malloc(80);
    ...

    config = malloc(128);
}
```



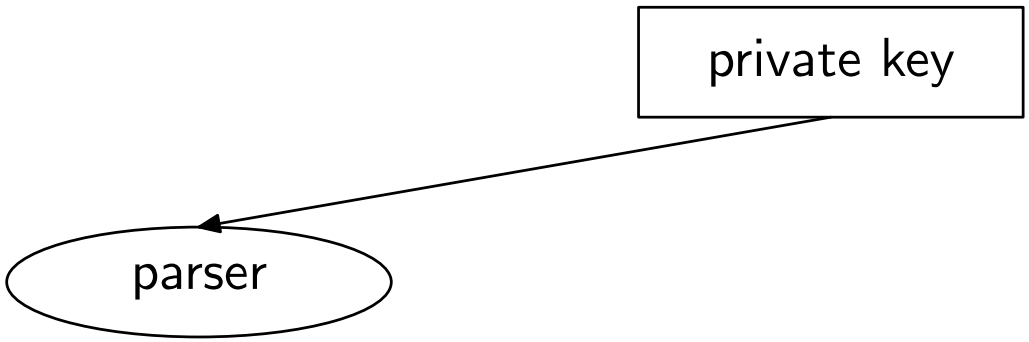
Tagged memory

```
{
    tag = tag_new();
    key = malloc(16);
    buffer =
       smalloc(80,tag);
    …

    config =
       smalloc(128,tag);
}
```



How can sthreads use sensitive data? Callgates.

Problem: unprivileged code cannot access sensitive data directly but must still use it.



Callgates: an entry-point with predefined privileges.

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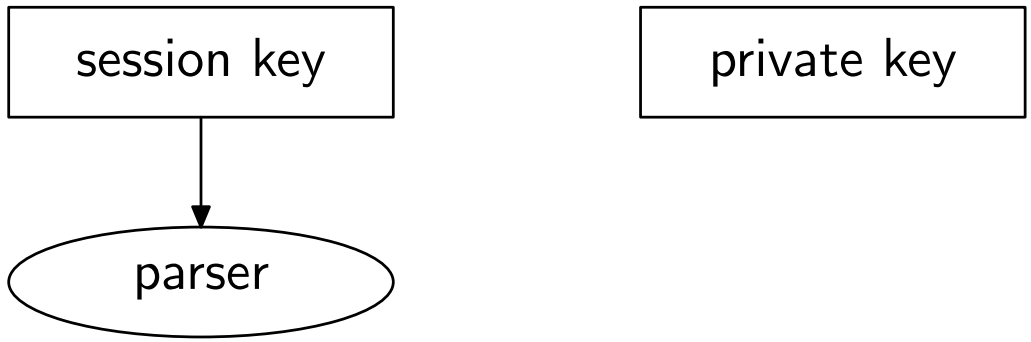

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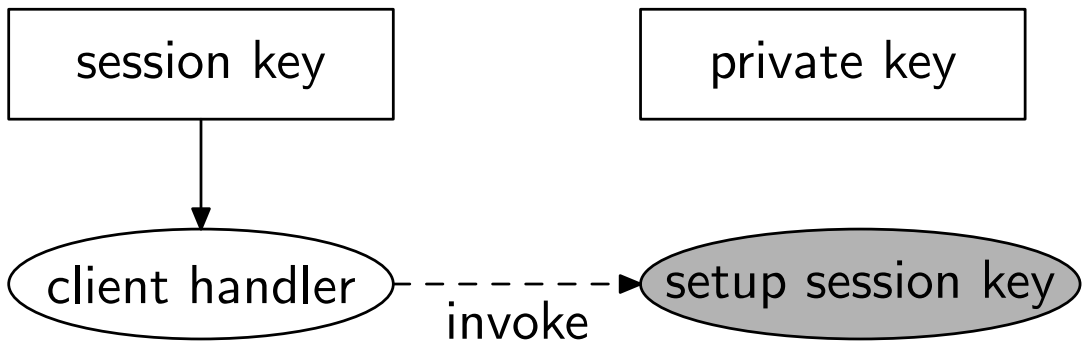

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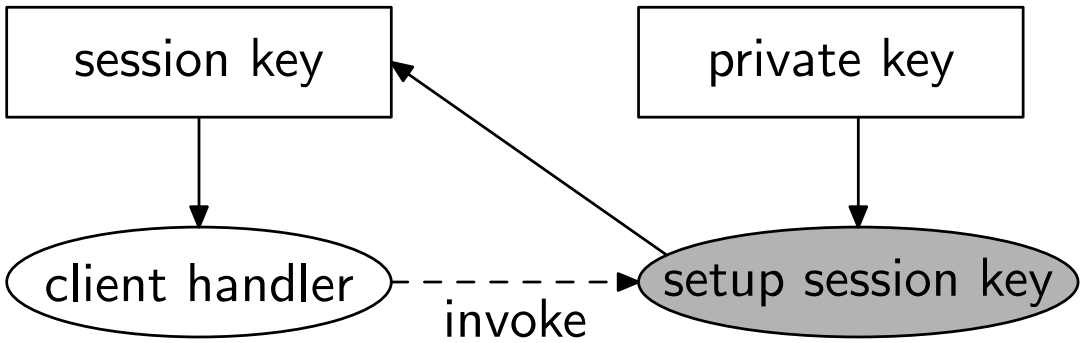

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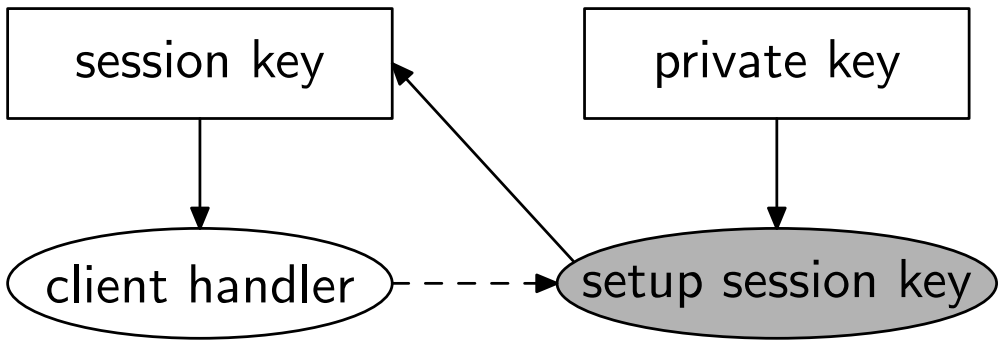
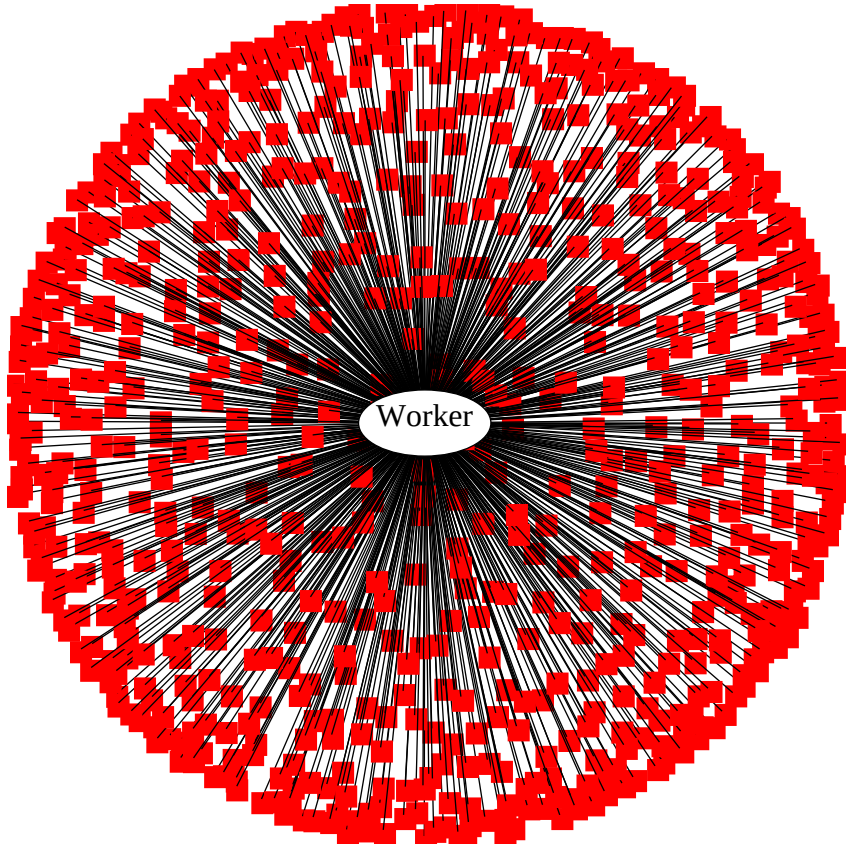
Summary: Wedge applied to Apache



- Sthreads: default-deny compartments—low privilege.
- Callgates: privilege elevation—high privilege.
- Tagged memory: naming memory for privilege specification.

Ad-hoc code study?



Apache's client handler needs access to 222 heap objects and 389 globals. Need to read 72 source files (for heap only).

1. Which code is executed?
2. What objects do pointers point to?
3. Where were objects allocated?

Static analysis of memory accesses?

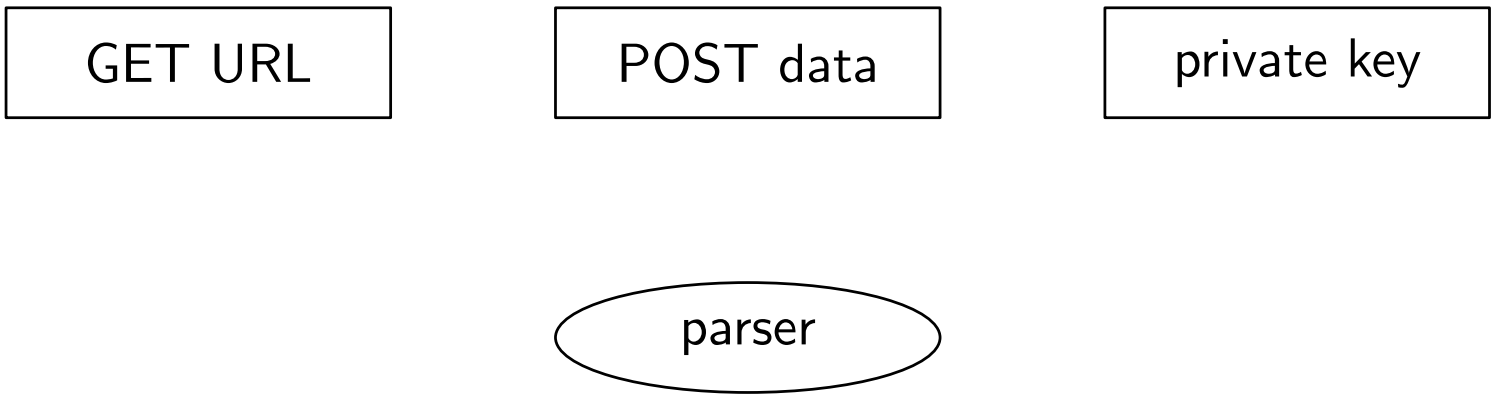
Static analysis for C code does not have runtime context (*e.g.*, format string for `printf`).

Consequences:

- May fail. *e.g.*, function pointers.
- If conservative, may give superset of privileges actually needed. *e.g.*, may follow code paths corresponding to exploits!

Crowbar: runtime analysis of memory accesses

Dynamic analysis yields least privilege:



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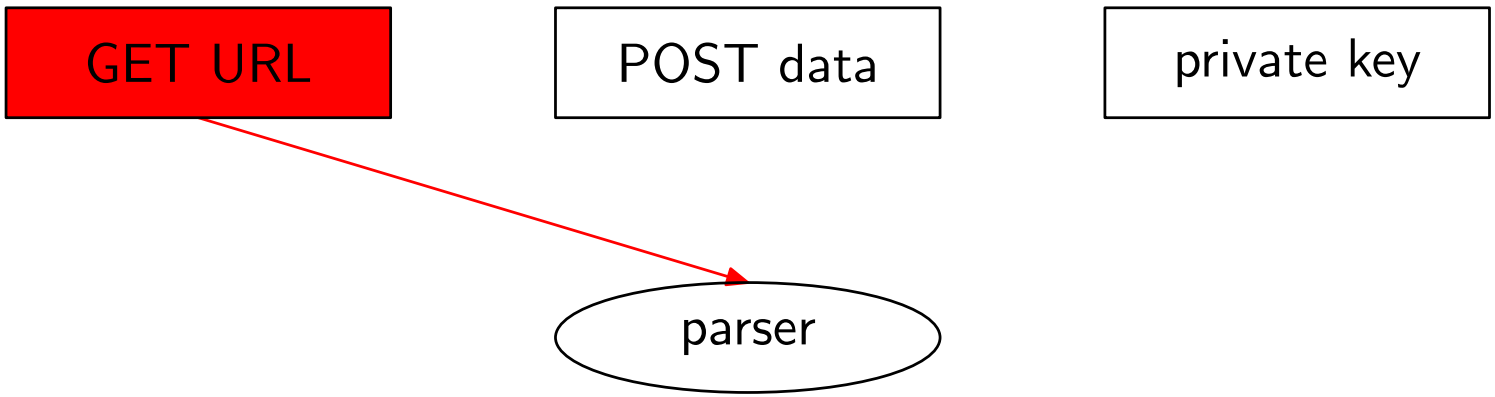

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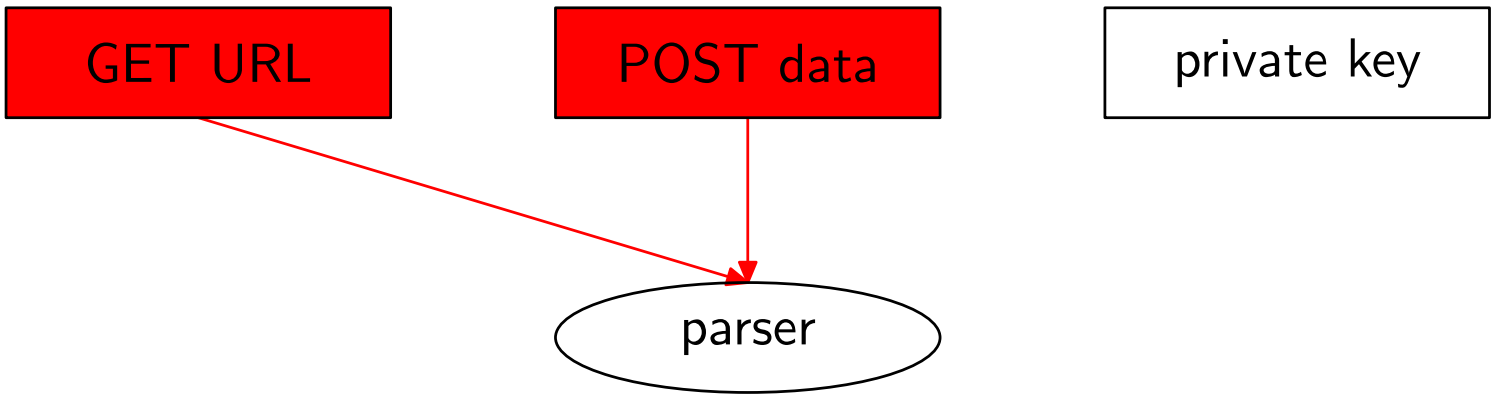

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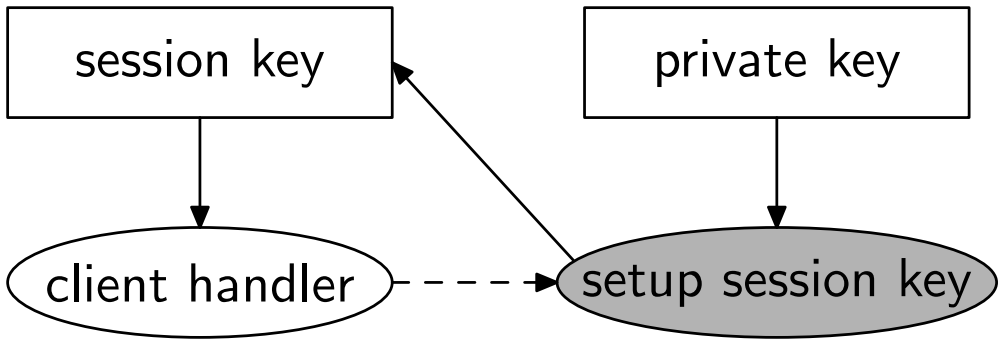
Goal: protect sensitive data (*e.g.*, credit card).



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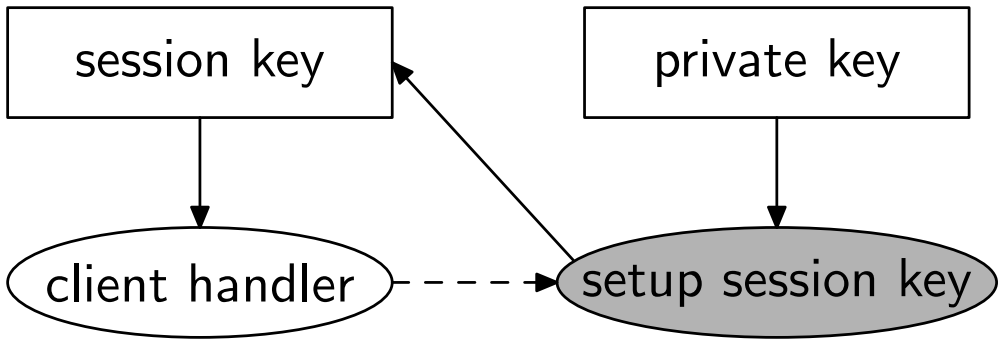

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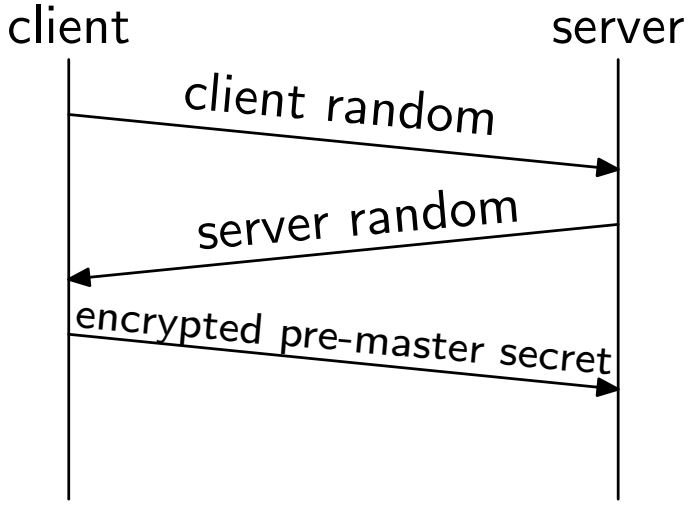
Threat models, with increasing complexity:

1. Passive eavesdropping and server exploit.
2. Active man-in-the-middle and server exploit.

Attacker can generate arbitrary session key

Session key components exchanged during SSL handshake



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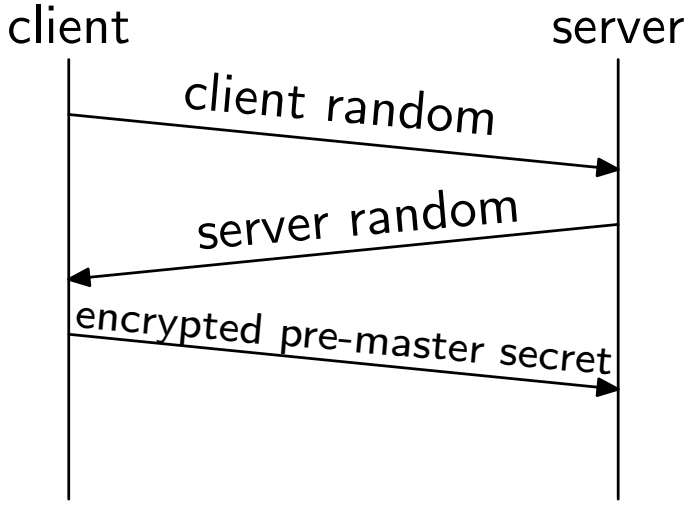

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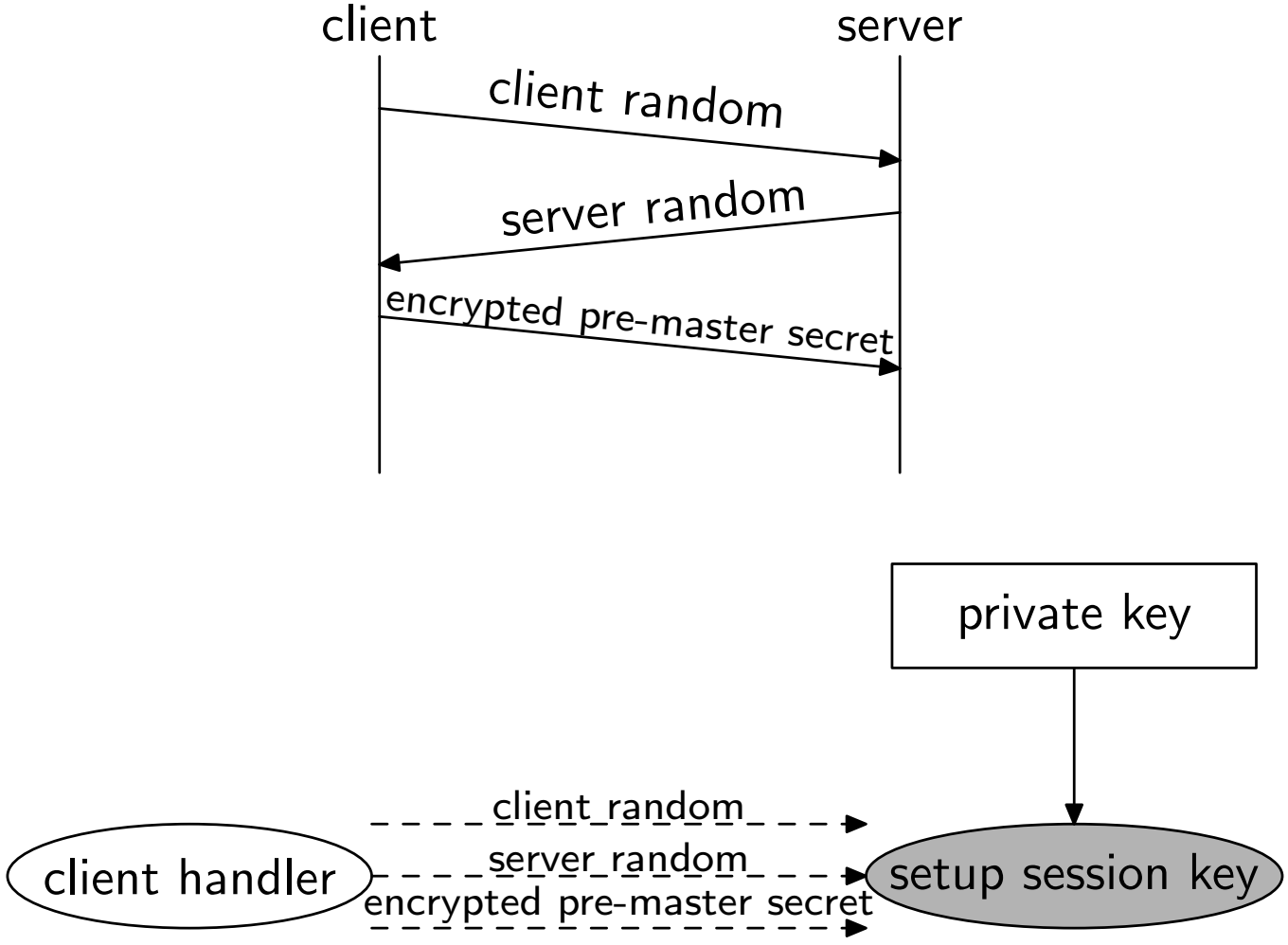

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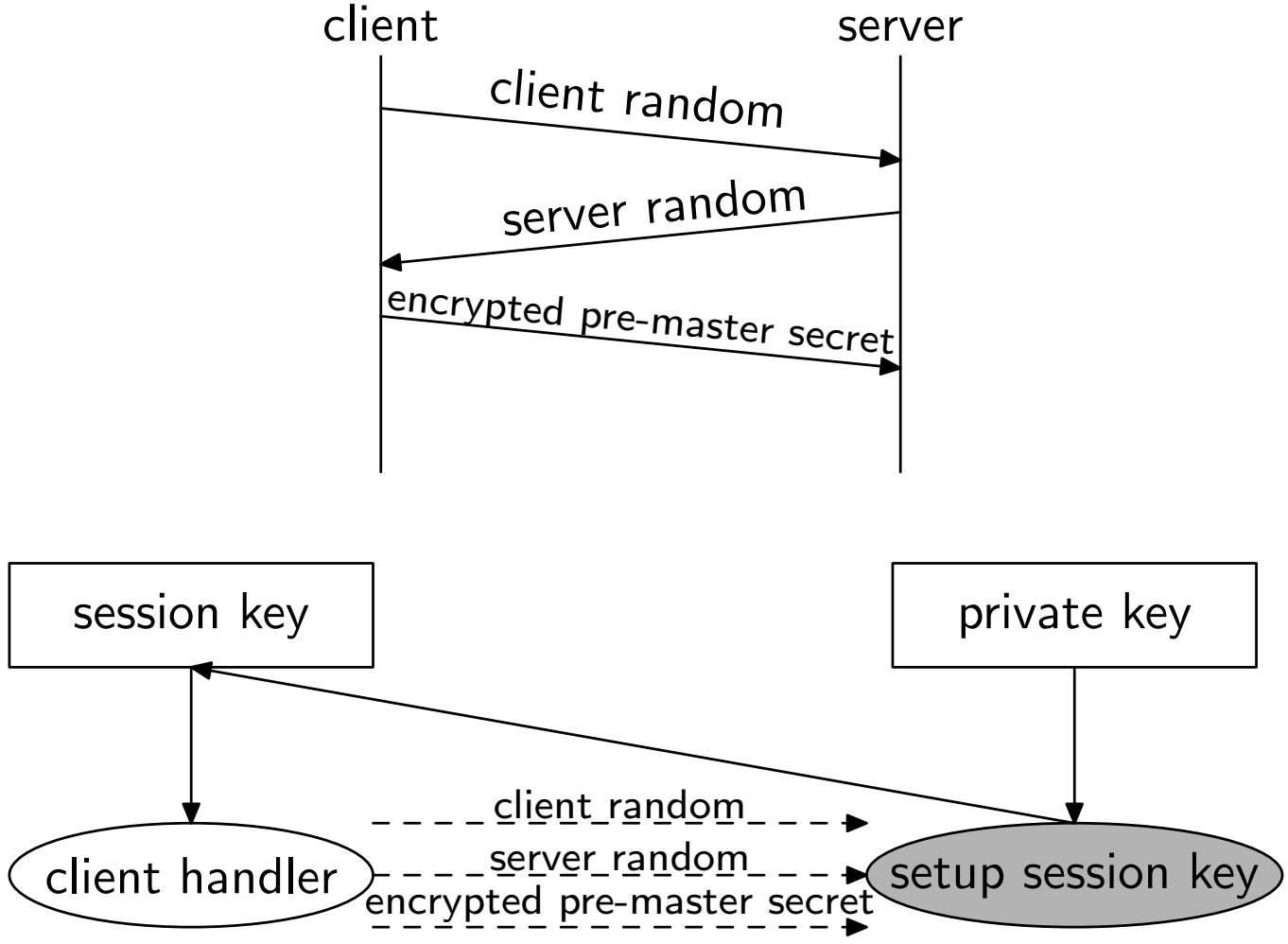

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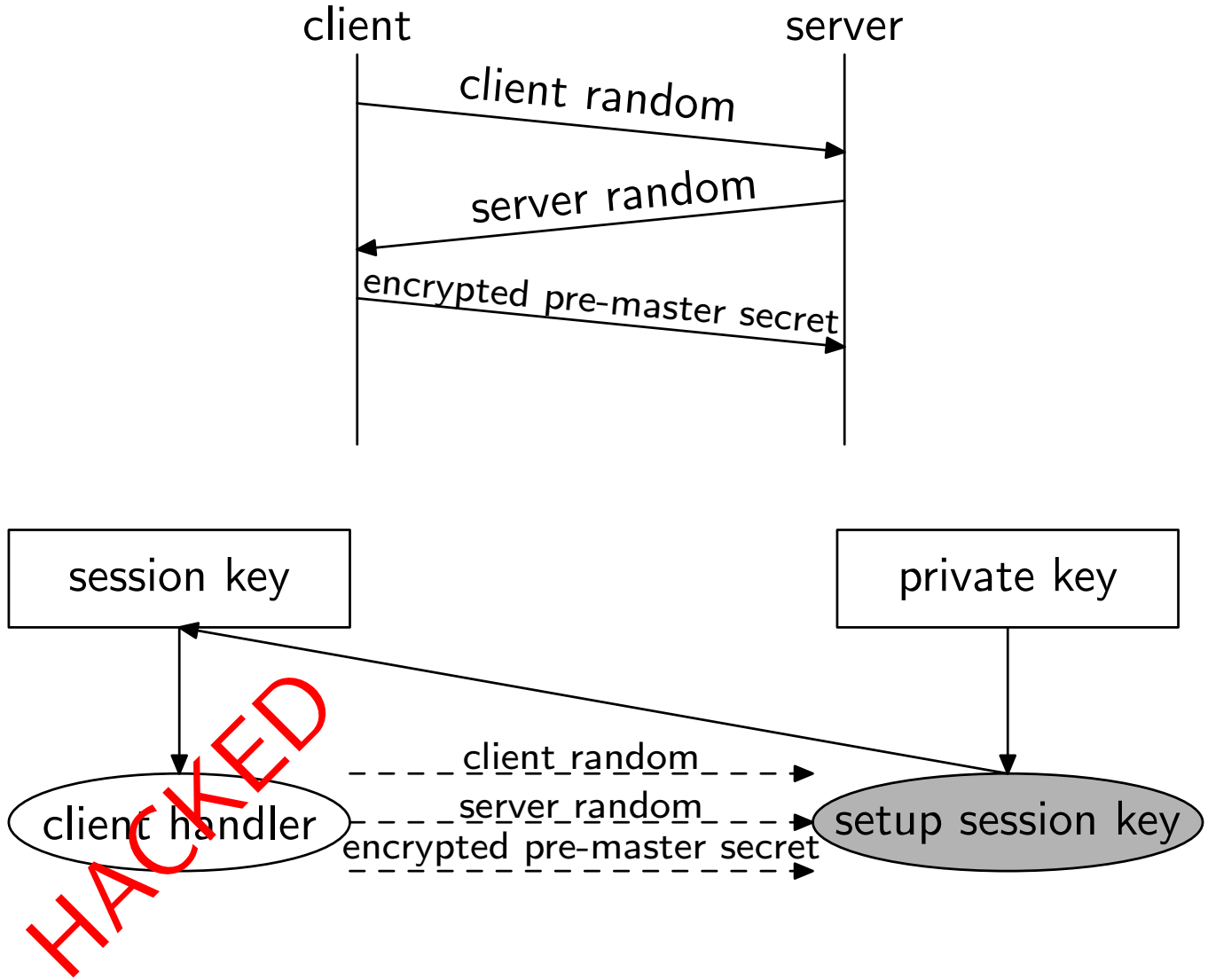

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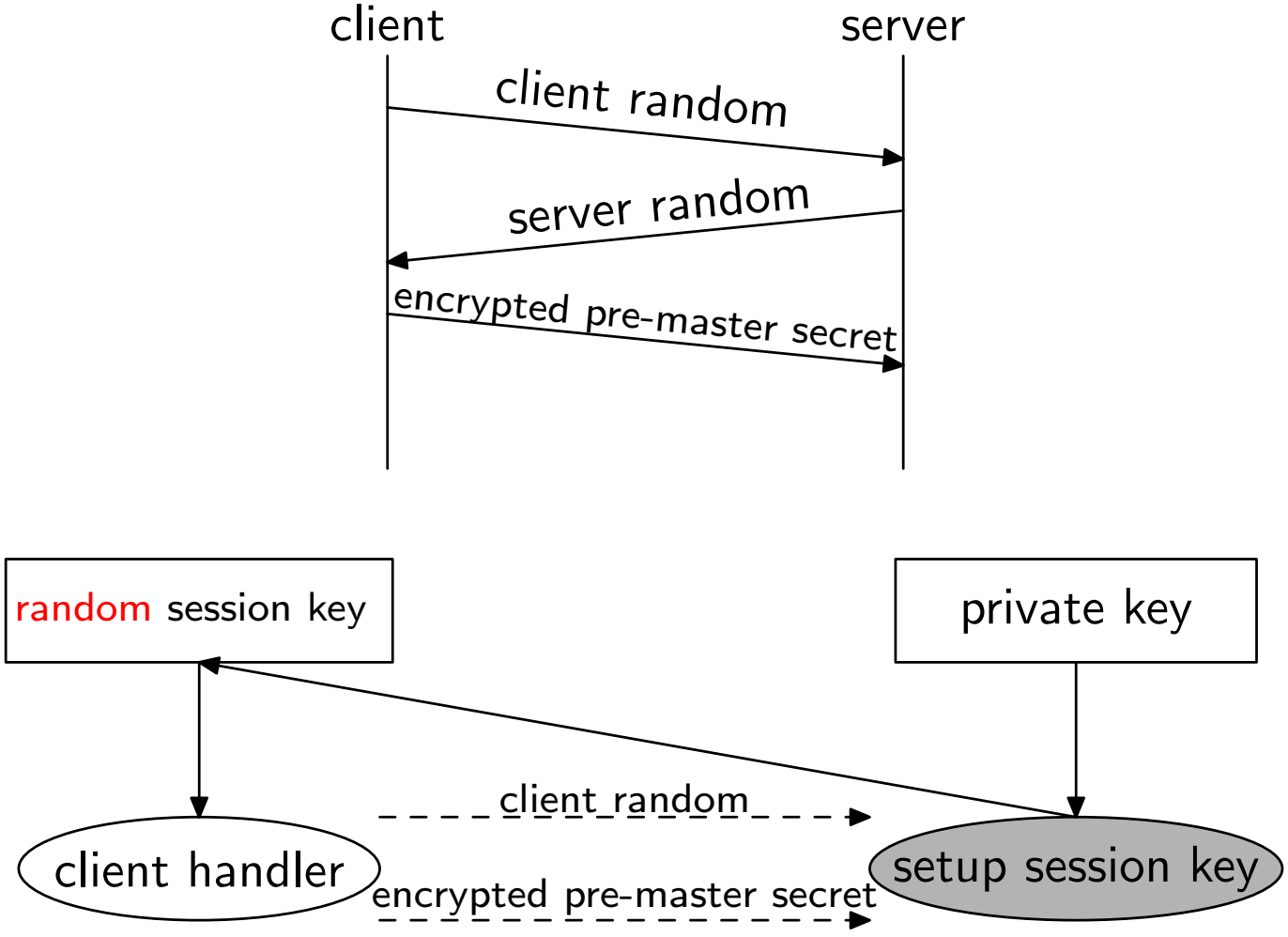
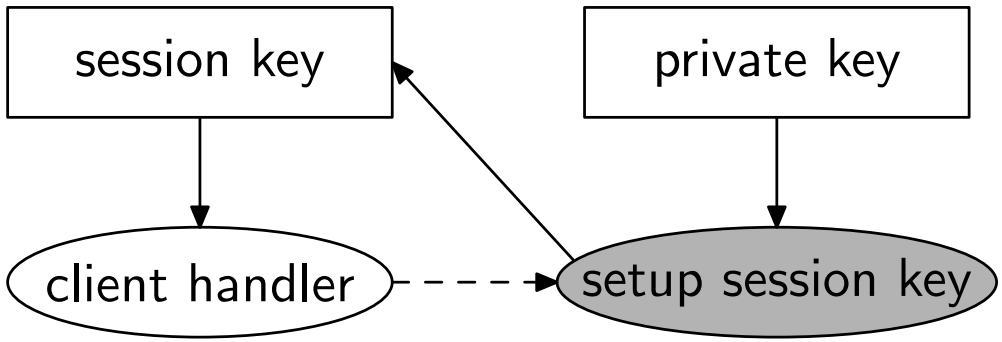


Preventing arbitrary session key leak



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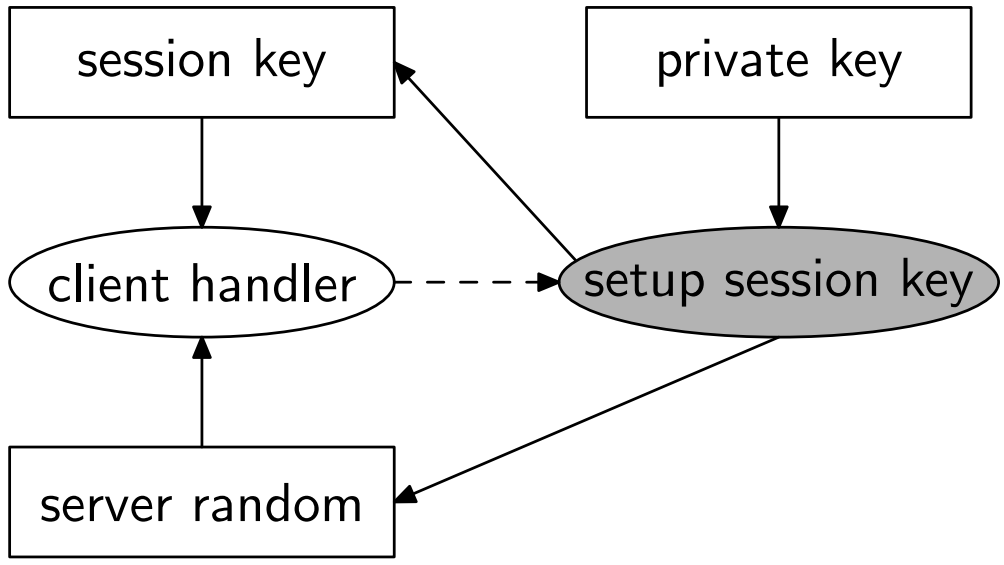
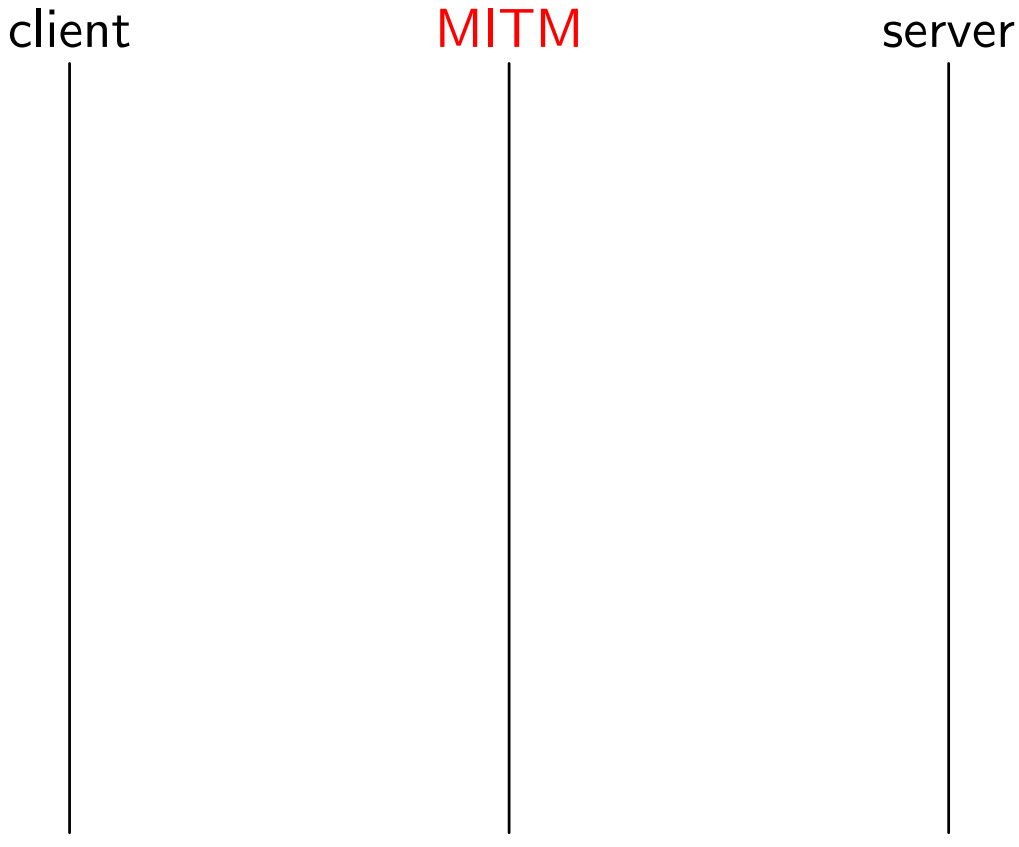


Attacker exploiting client handler:

- Has no control over server random and session key generation.
- Cannot generate session key of eavesdropped sessions.
- Can only obtain a new, personal session key.

Vulnerable to man-in-the-middle

Disclosing session key causes a security breach with man-in-the-middle (MITM) attacks:



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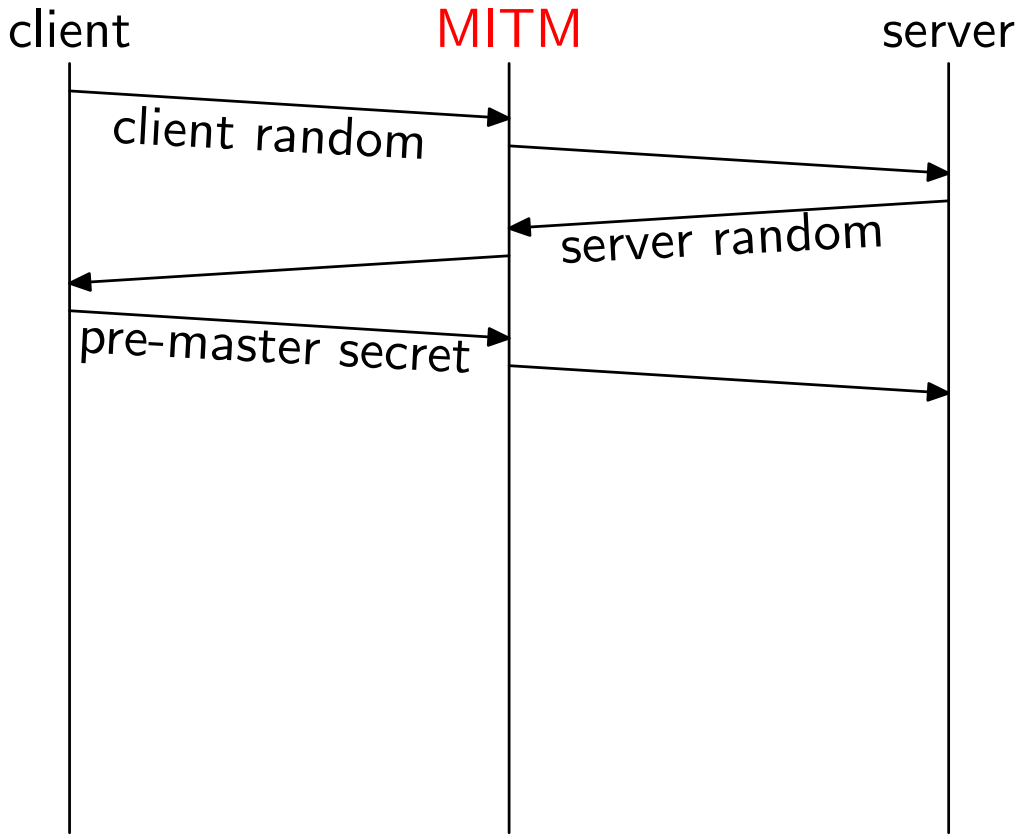

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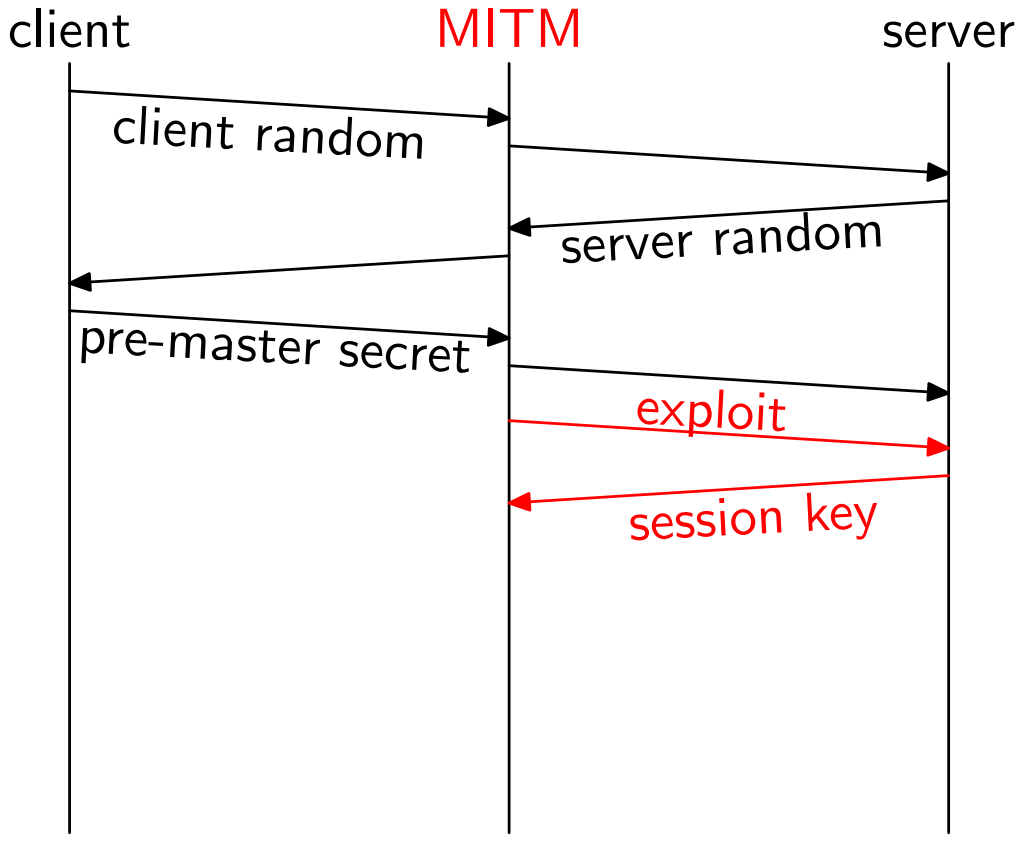

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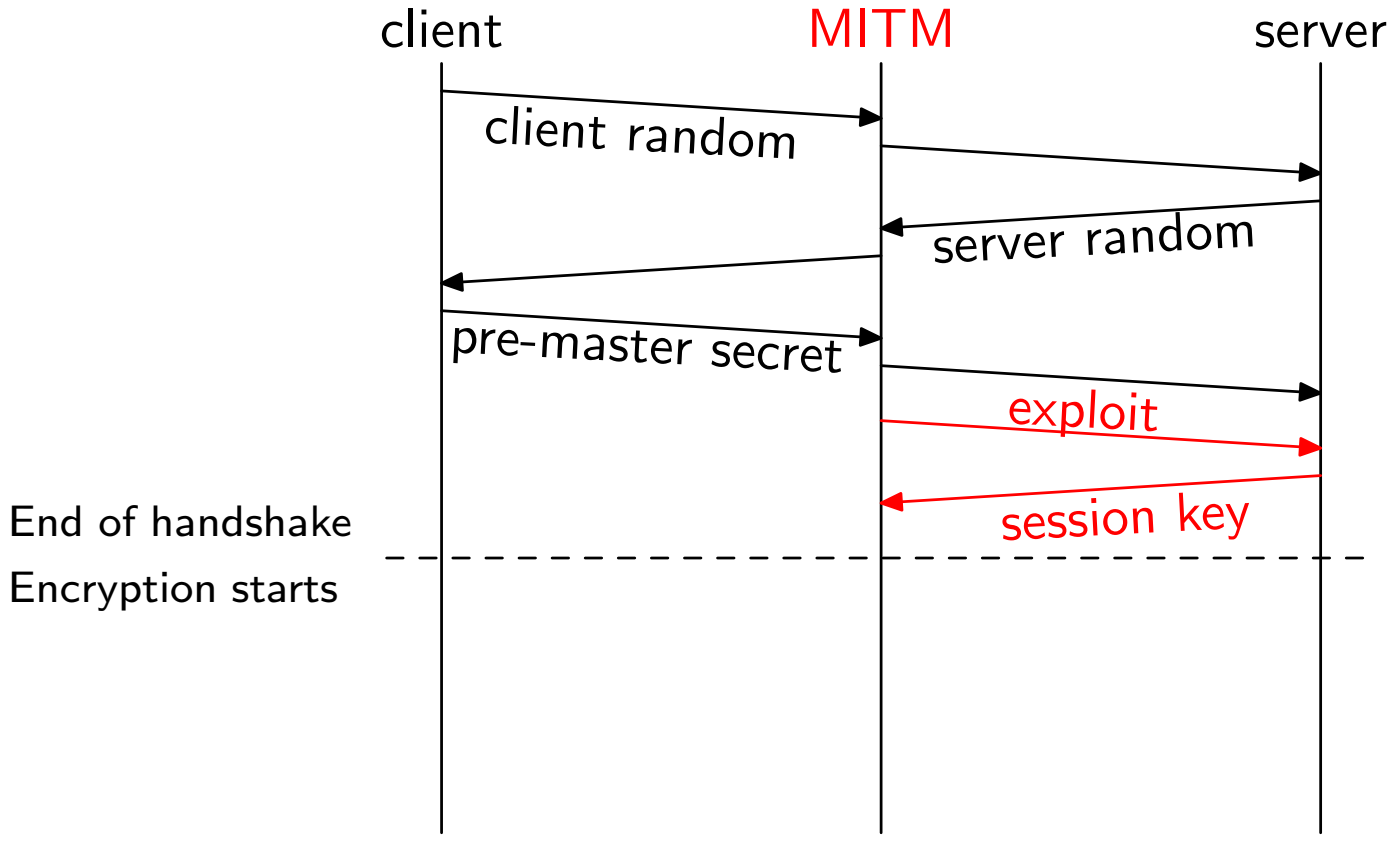

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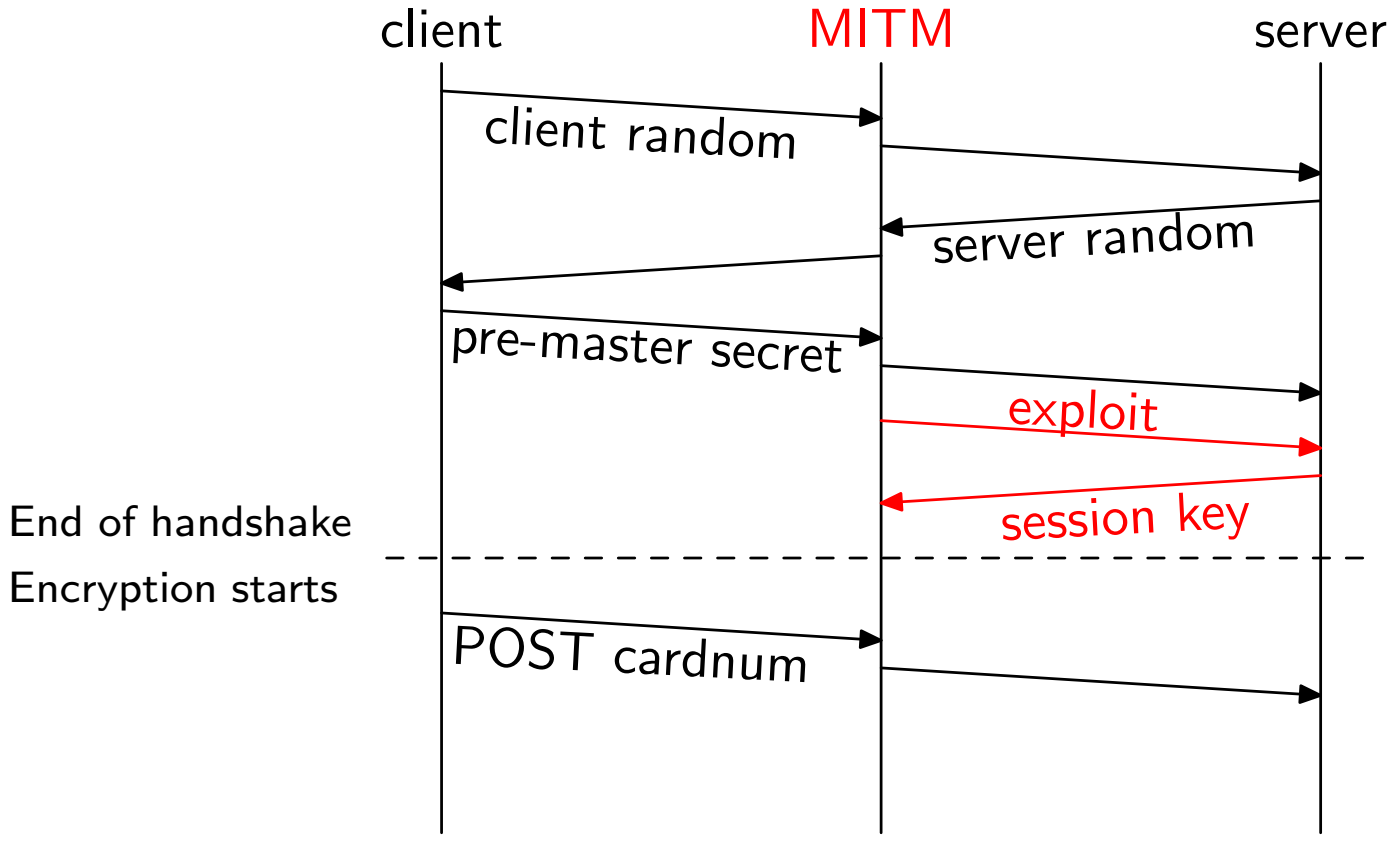
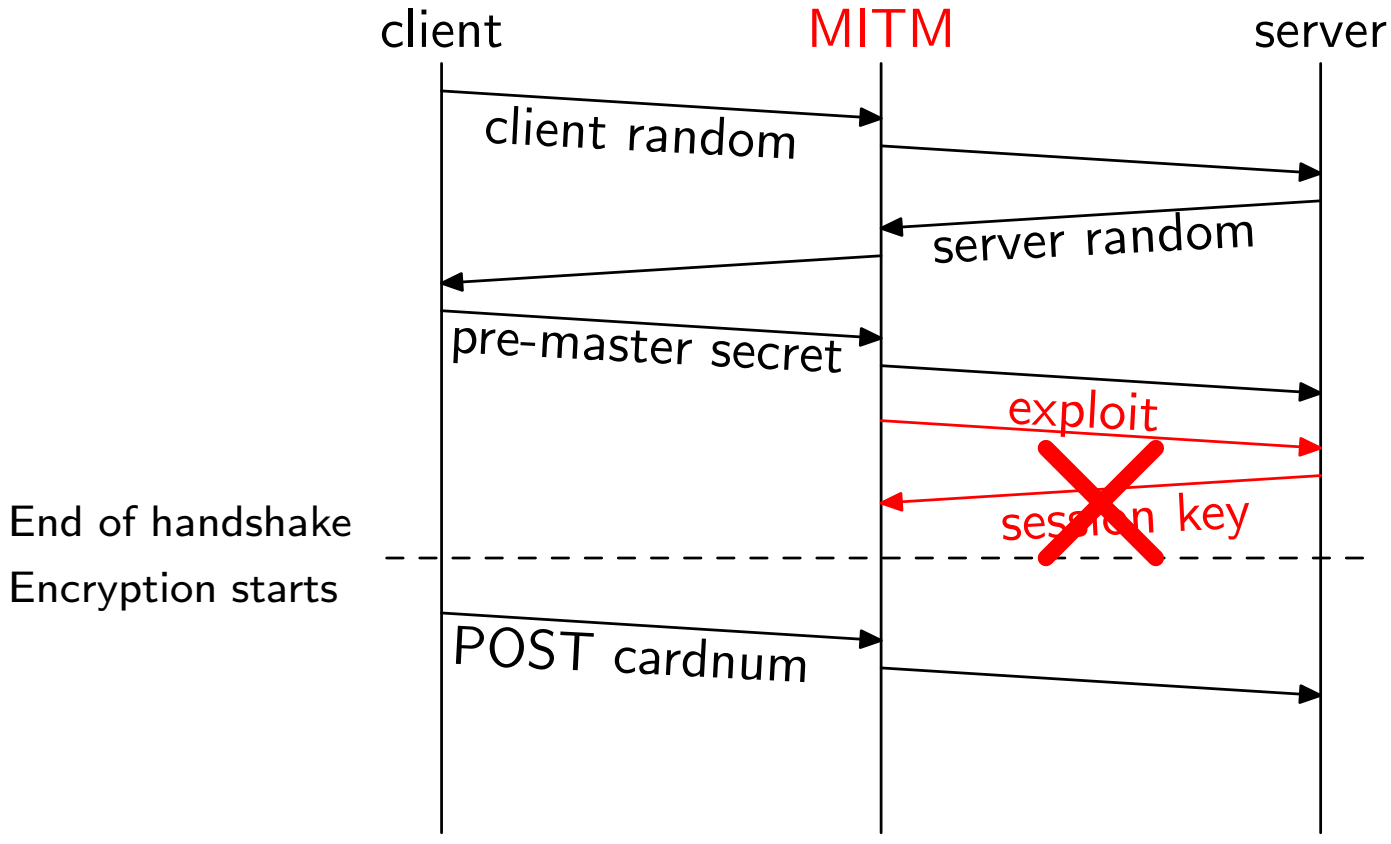


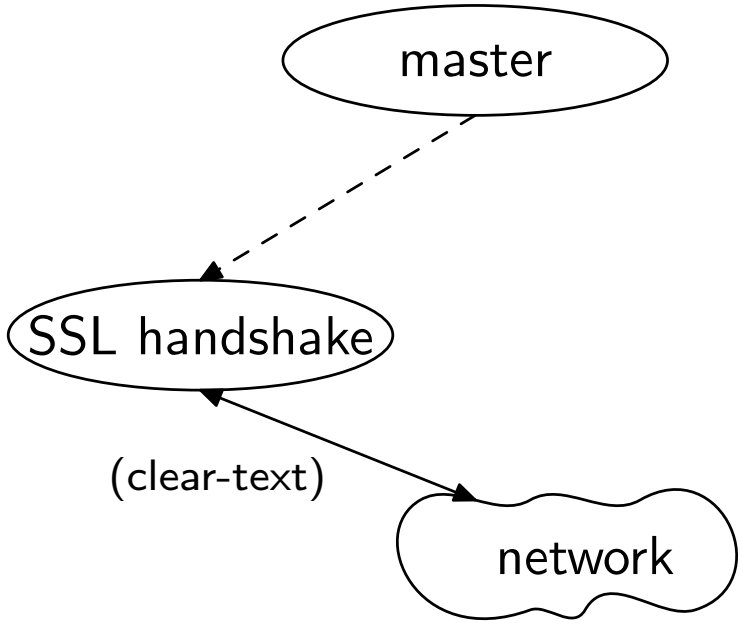
Vulnerable to man-in-the-middle

Disclosing session key causes a security breach with man-in-the-middle (MITM) attacks:



Man-in-the-middle defense overview

Can we protect against a MITM that has also exploited the server?



Strategy:

1. Prevent session key disclosure during handshake.

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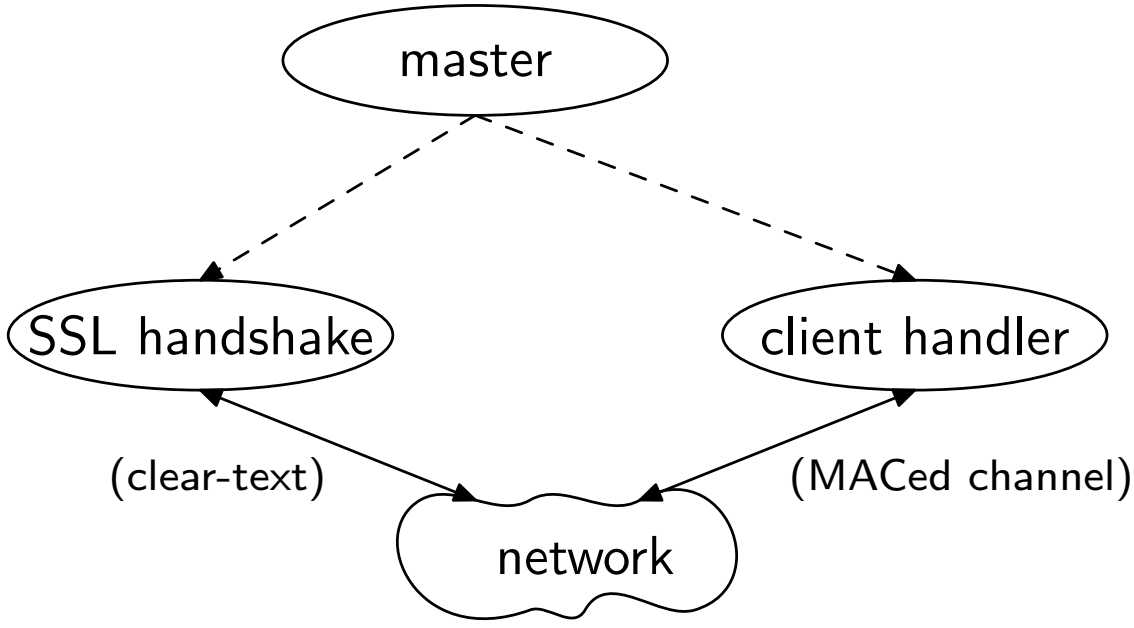

Strategy:

1. Prevent session key disclosure during handshake.
2. MITM cannot exploit client handler without session key: packets with invalid MAC will be dropped.

Implementation

Sthreads:

- Linux v2.6.19. 496 line diff, 1485 line module.
- Userland library: 1154 lines.

Crowbar:

- Binary instrumentation tool (using Pin): 2391 lines.
- Post processor: 959 lines.

Applications we partitioned using Wedge:

- Apache+OpenSSL.
- OpenSSH (prior to privilege separation).

Wedge reduces size of privileged code

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Line counts in Wedge's Apache+SSL

Component	Line count	Percentage
Apache+OpenSSL total	252,030	100%
Default config after accept	60,844	
Callgates total (privileged)	15,769	6%

Lines changed when partitioning: 1,700 (0.7%).

Crowbar performs acceptably for developers

Crowbar is used by developers for partitioning. It is not an overhead seen during production run-time.

Does Crowbar perform acceptably for developers?

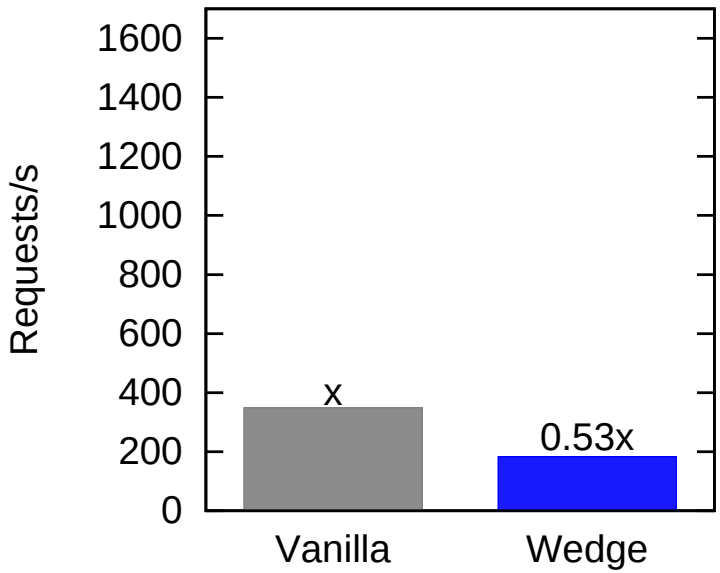
- A trace for Apache was obtained in 15s.
- Traces for SPEC applications: 82s on average.

Anecdotally, one trace was enough for our Apache (and OpenSSH) partitioning.

Enhanced privacy at acceptable cost

Throughput of many clients retrieving small static page:

No sessions cached



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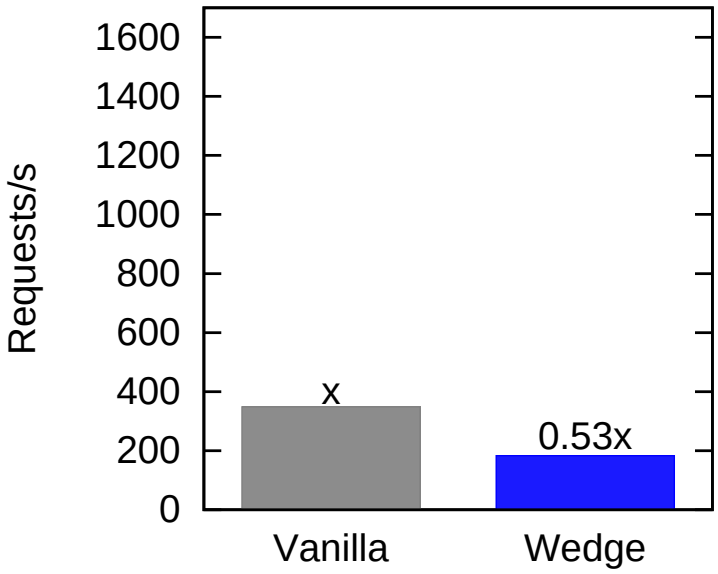
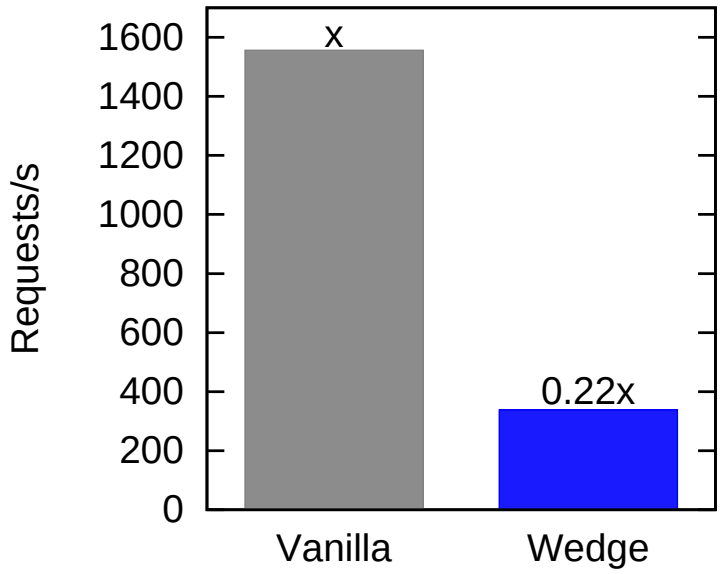


All sessions cached



- Vanilla reuses workers—we create new sthreads.
- We create many compartments & callgates per session.

Related work

We build on privilege separation: OpenSSH, OKWS, Privtrans

- Wedge allows finer-grained partitioning, and with default-deny, encourages tighter privileges for each compartment.

DIFC: JIF, Asbestos, HiStar, Flume, DStar

- Crowbar is complementary: could help partitioning legacy code in DIFC systems.
- Wedge does not allow unprivileged code to compute over sensitive data.

Conclusion

Wedge:

- Generalizes privilege separation and provides primitives for fine-grained default-deny partitioning of applications.
- Crowbar: tool to aid in partitioning legacy code.

Wedge enables fine-grained partitioning of legacy code:

- Programmers can defend applications against stronger adversaries and more complex threat models than those addressed to date.

`http://nrg.cs.ucl.ac.uk/wedge/`