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What is Linux Kernel keystore and why you should use it in your next application

Ignat Korchagin
@ignatkn

$ whoami

- Linux team at Cloudflare
- Systems security and performance
- Low-level programming

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- Linux team at Cloudflare
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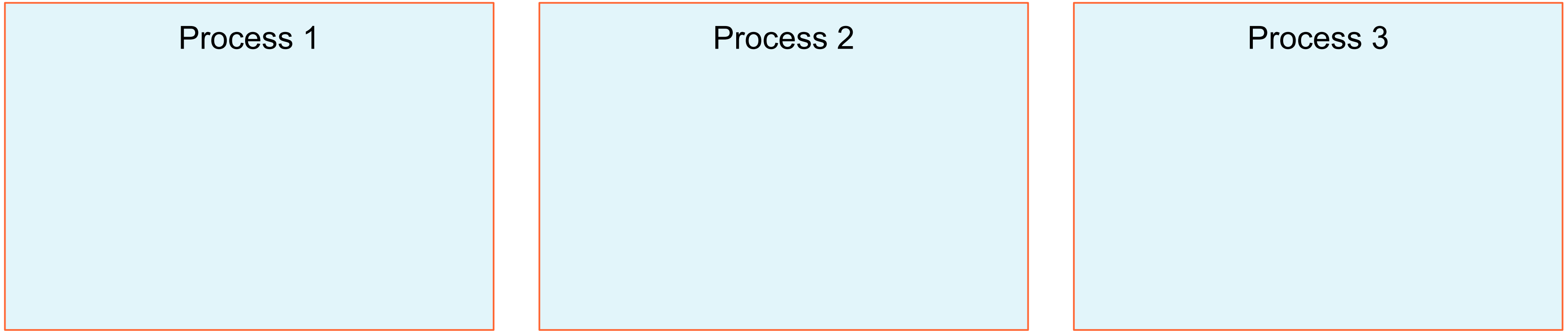
- *Fugitive programmer (US NSA banned C/C++)*

Application keys in memory

"NSA recommends that organizations use memory safe languages when possible and bolster protection through code-hardening defenses such as compiler options, tool options, and operating system configurations."

https://www.nsa.gov/Press-Room/News-Highlights/Article/Article/3215760/nsa-releases-guidance-on-how-to-protect-against-software-memory-safety-issues/

Linux address spaces



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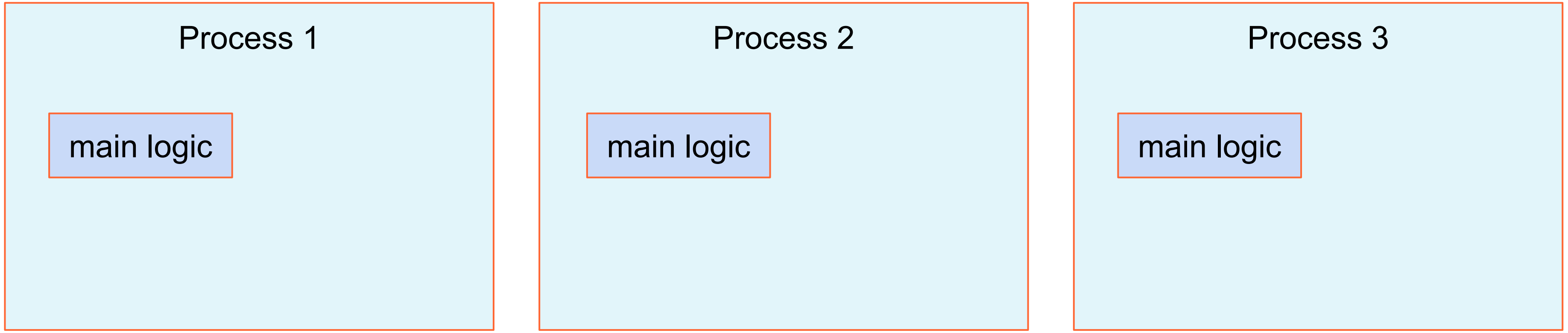

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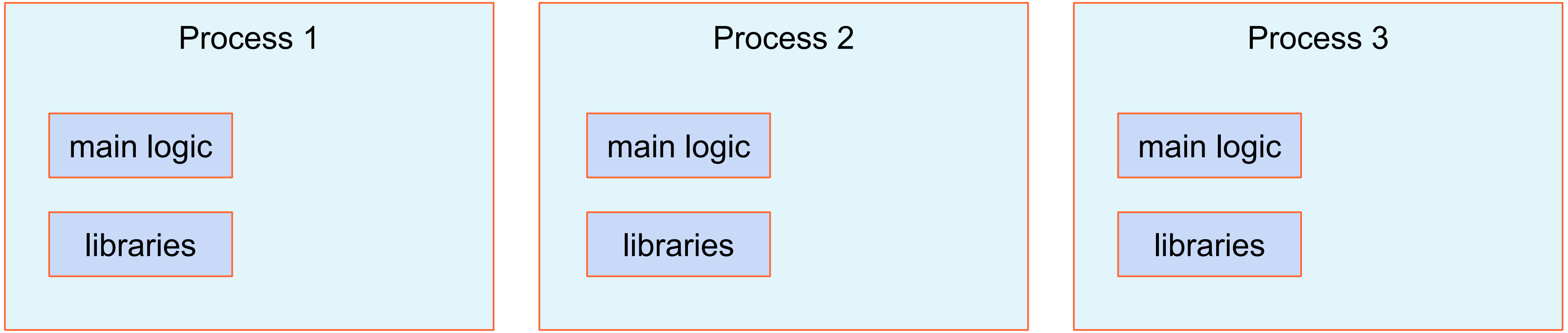

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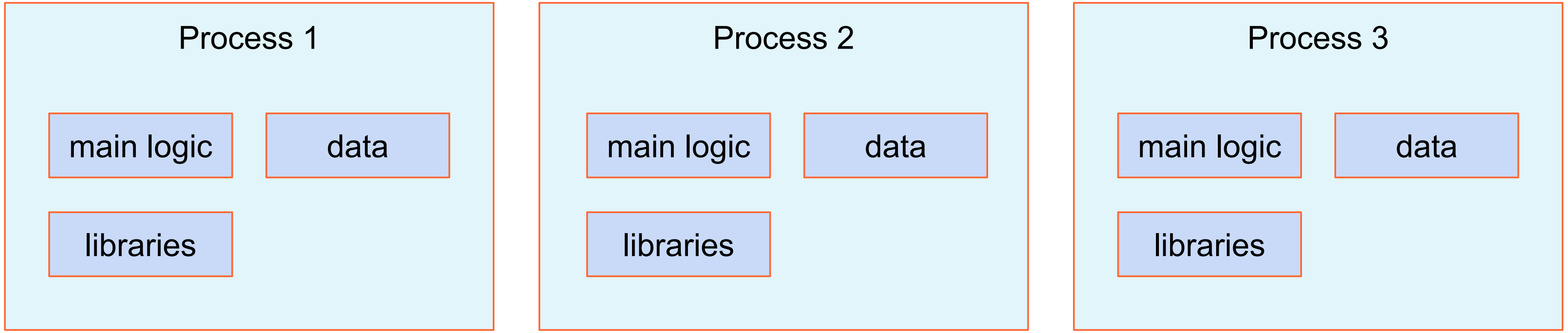

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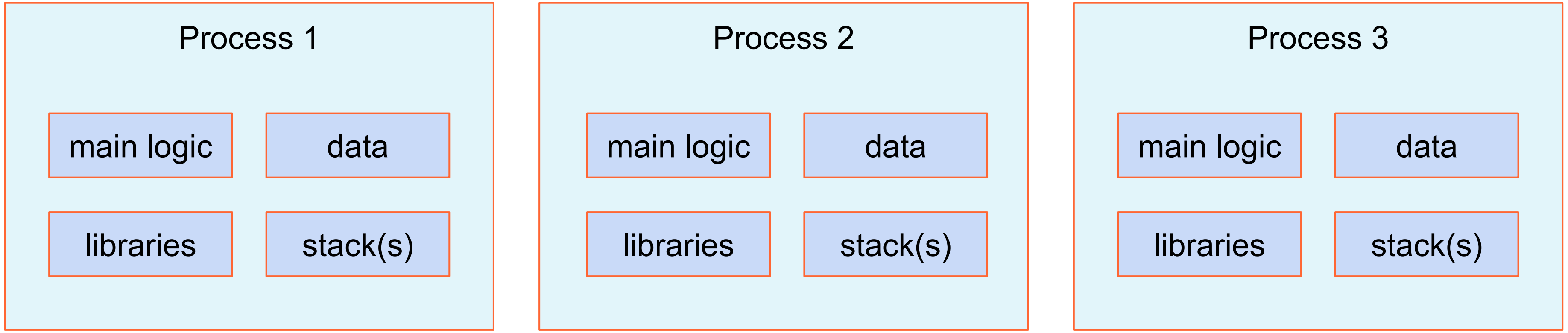

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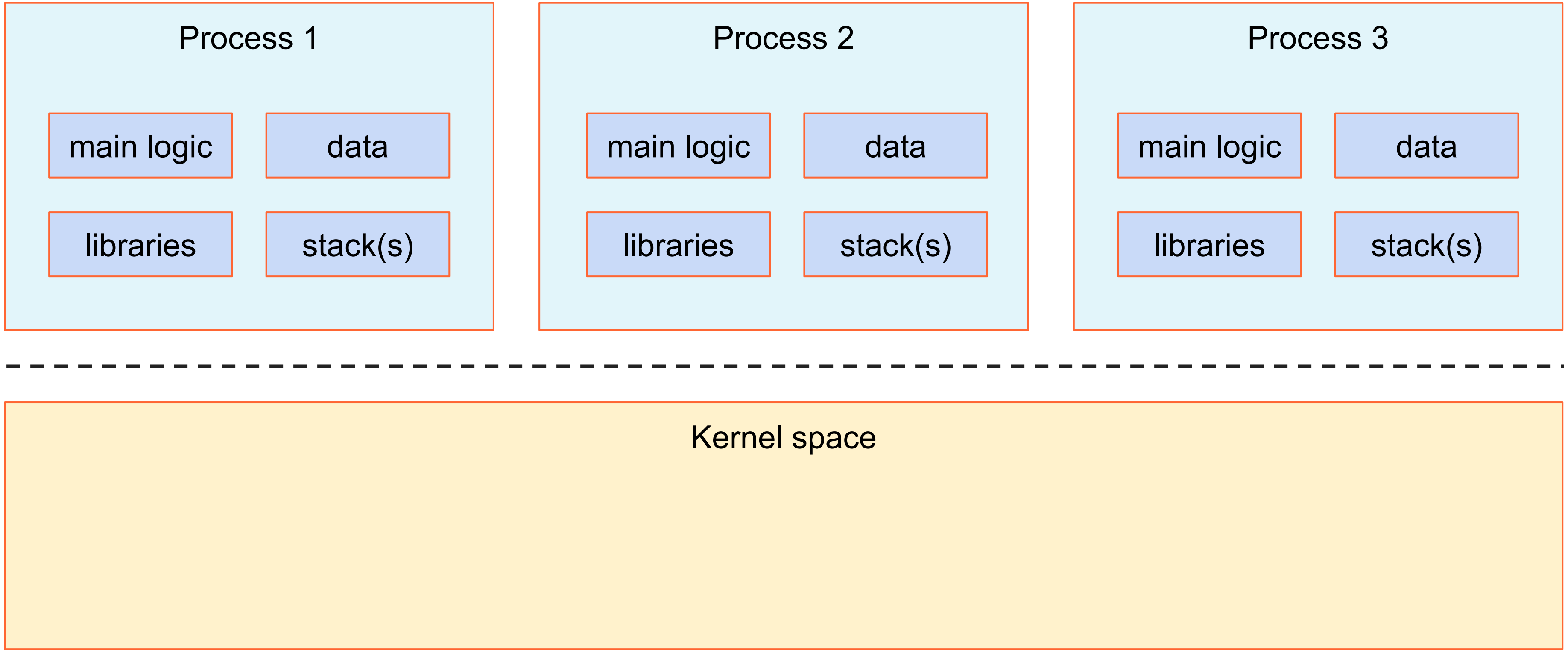

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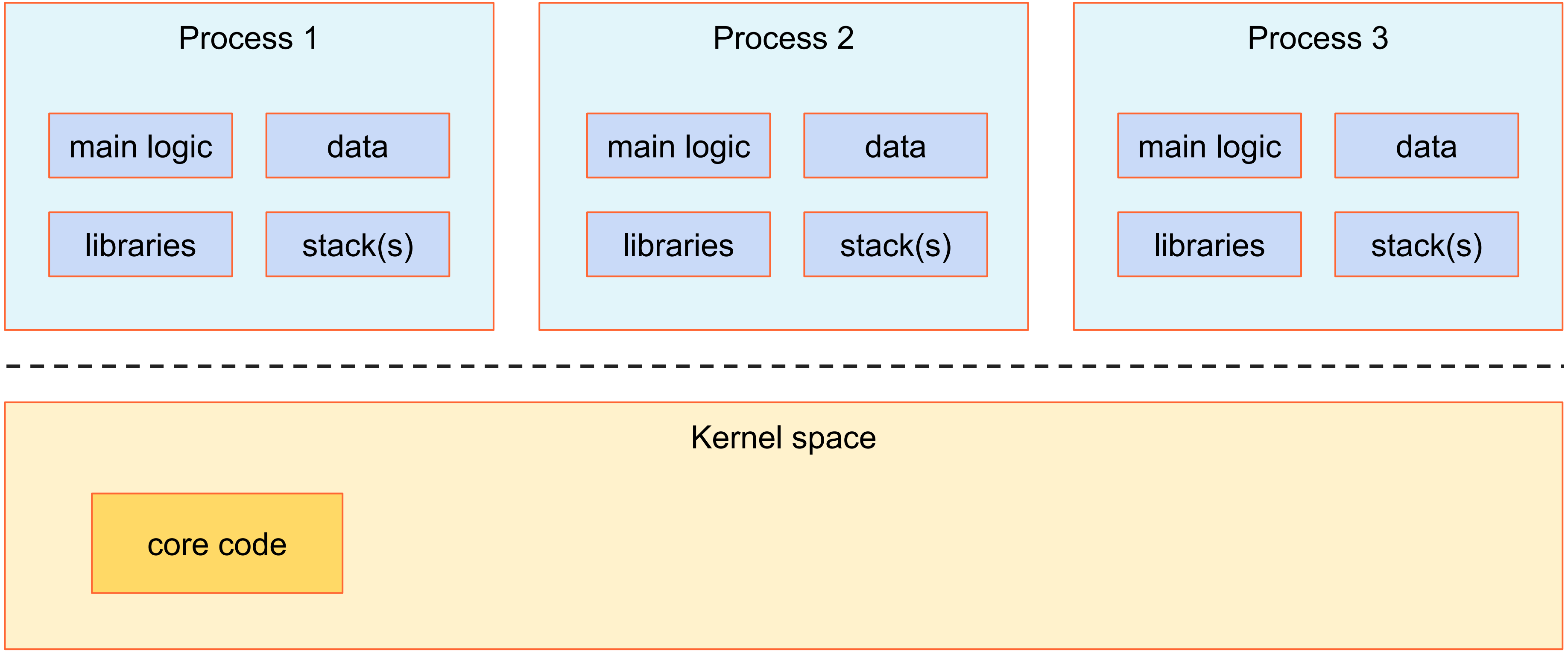

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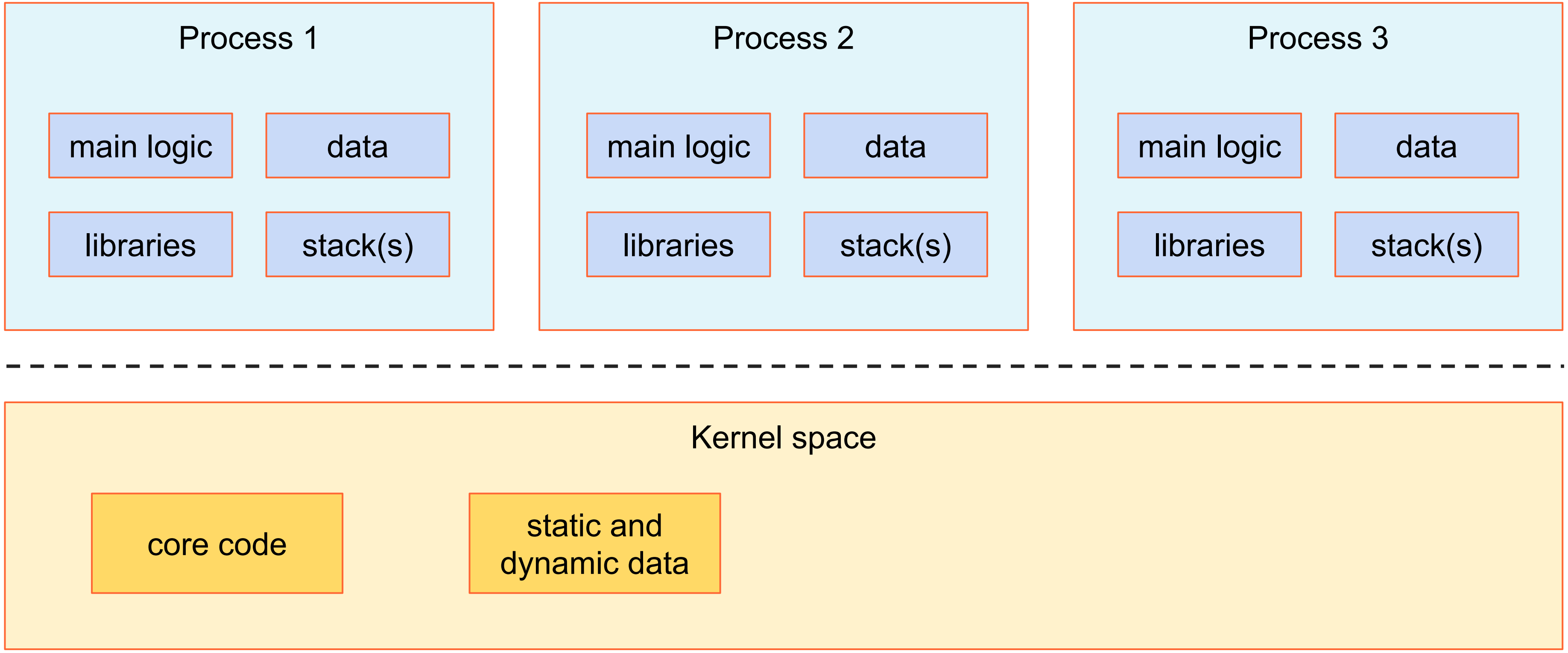

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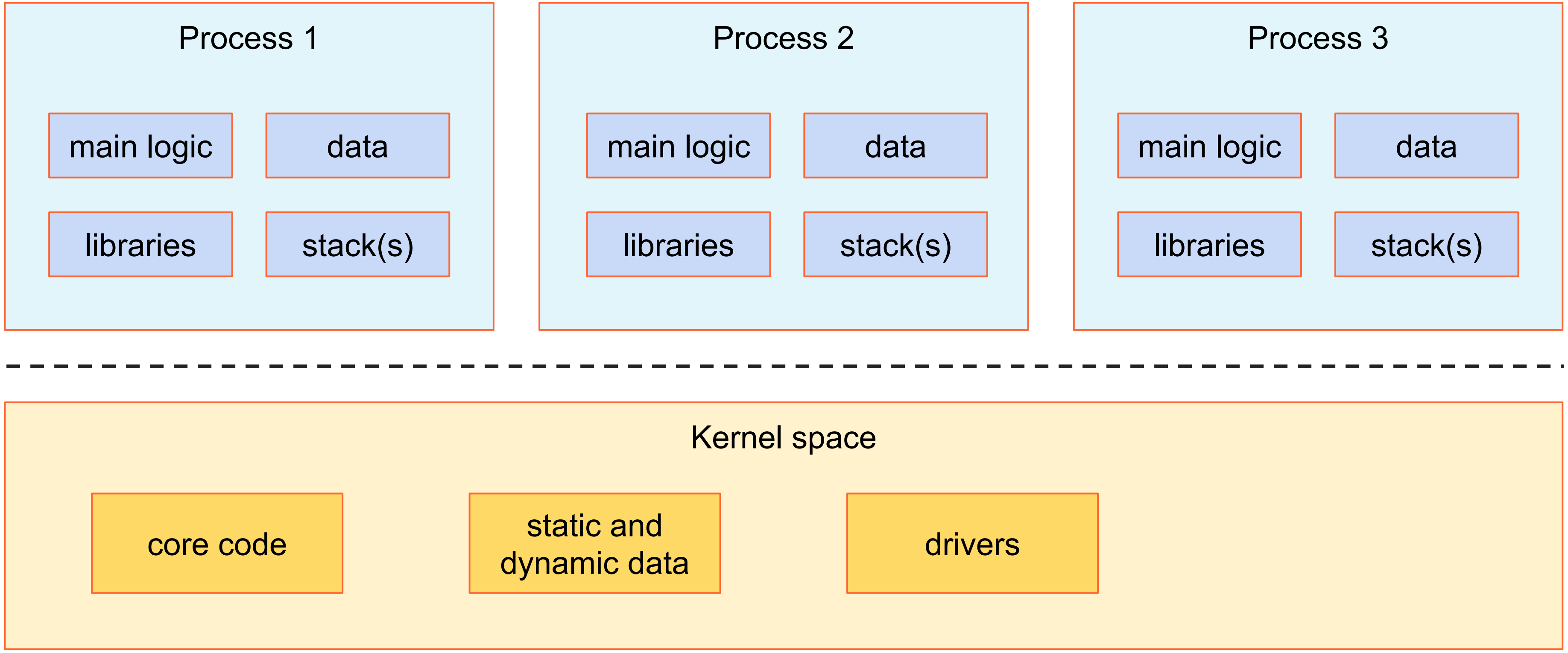

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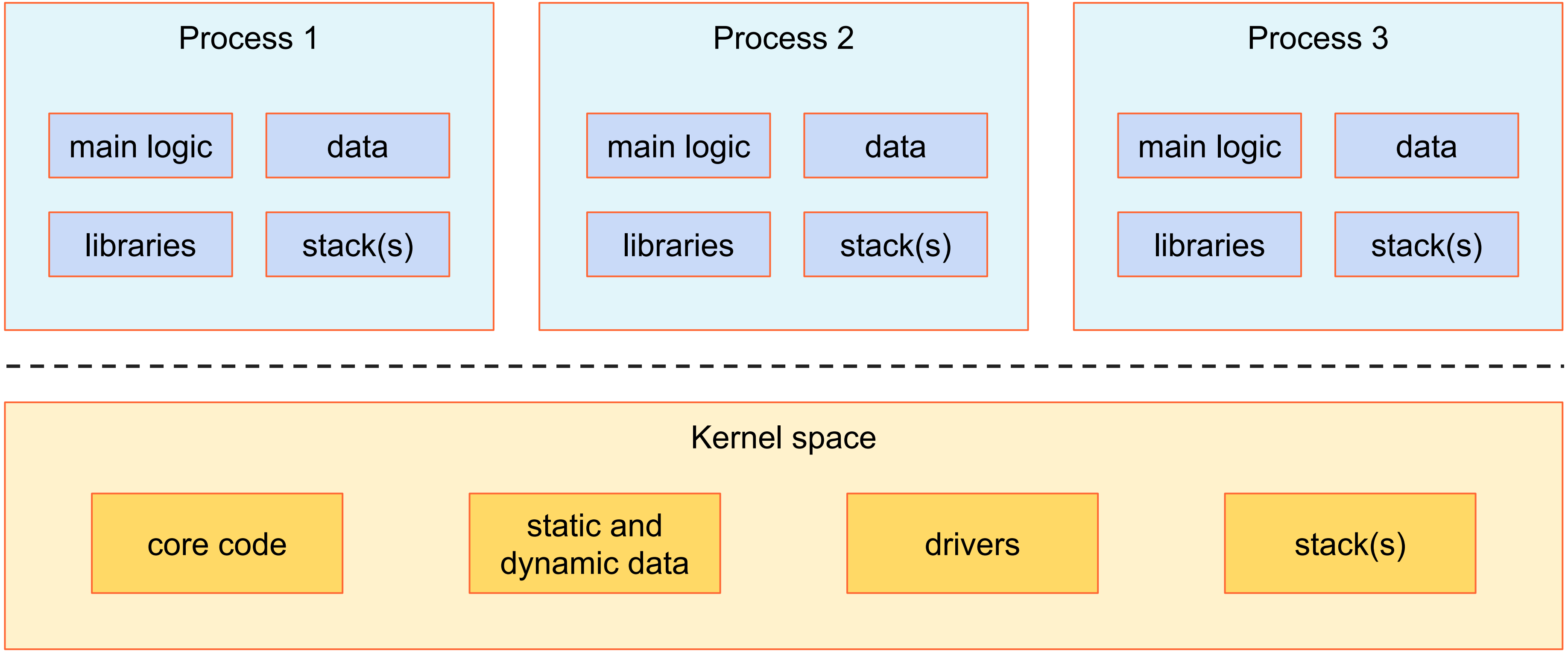

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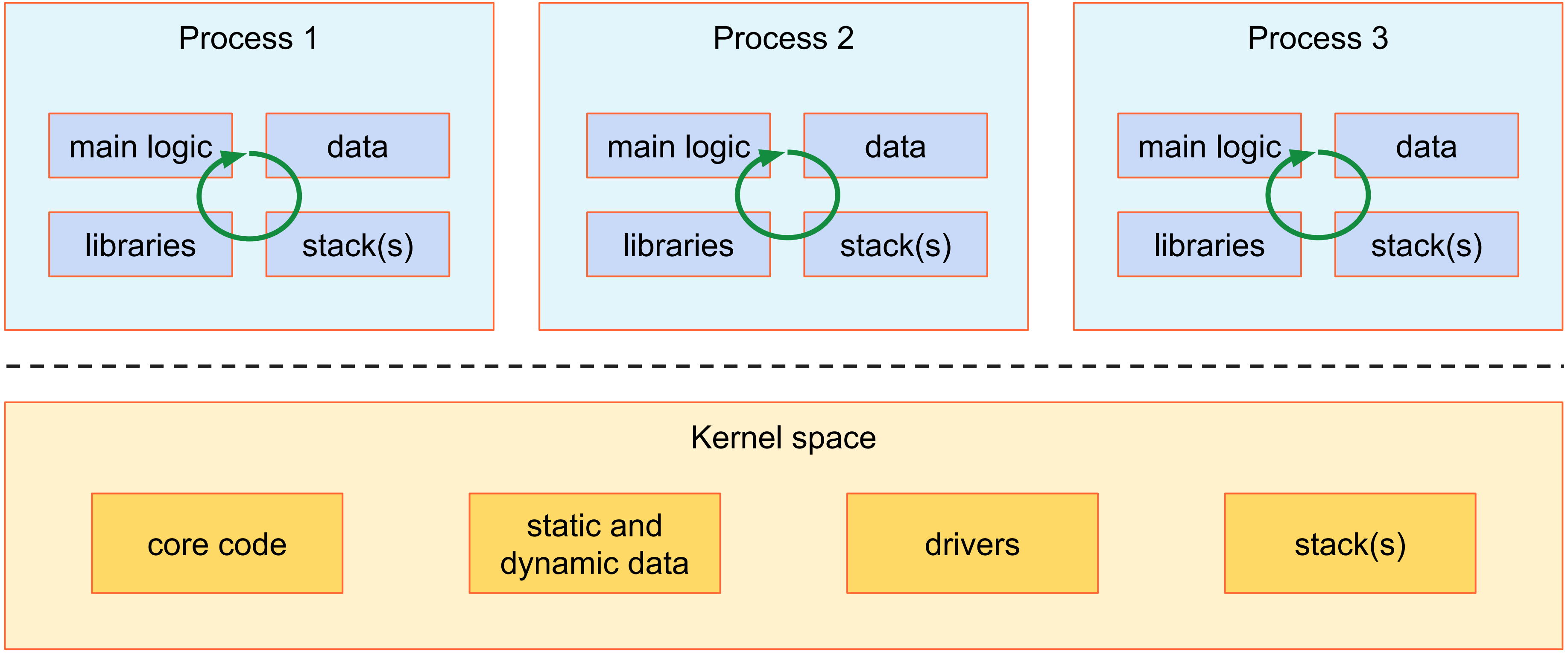

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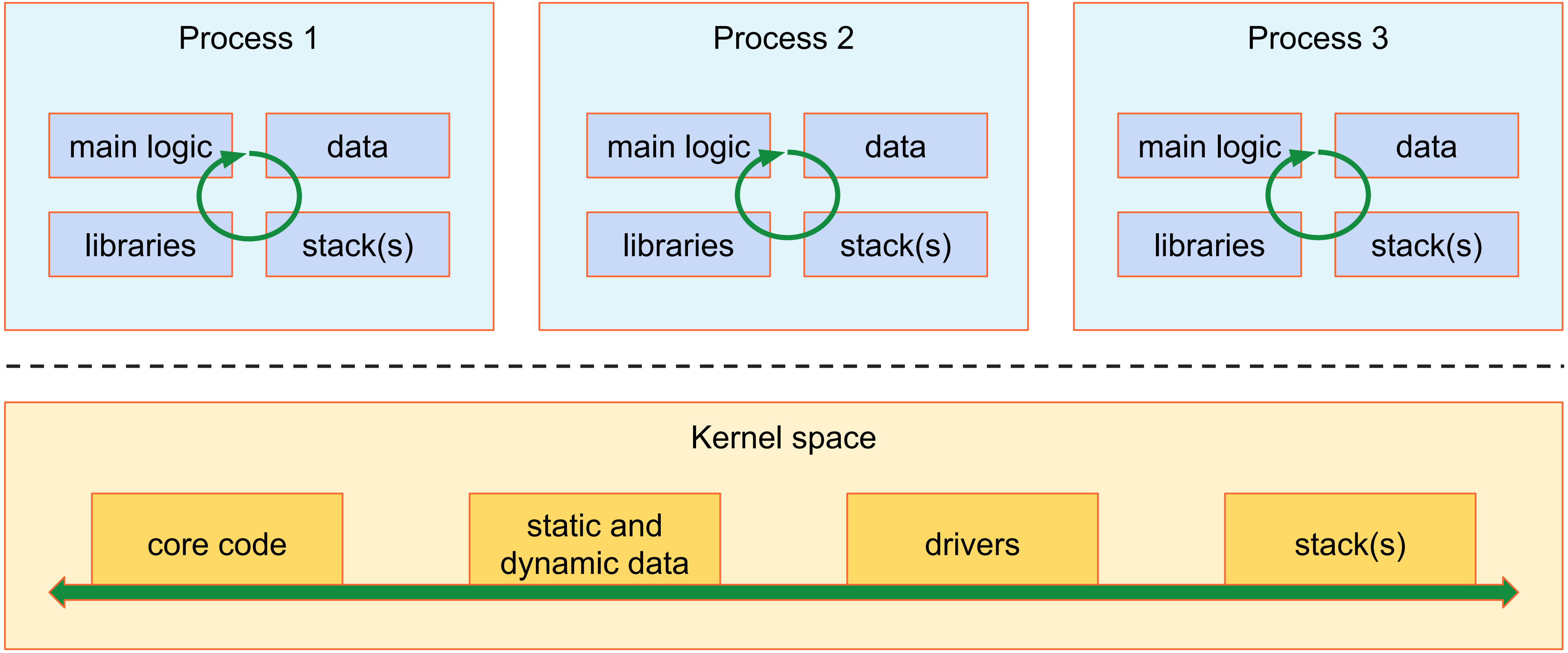

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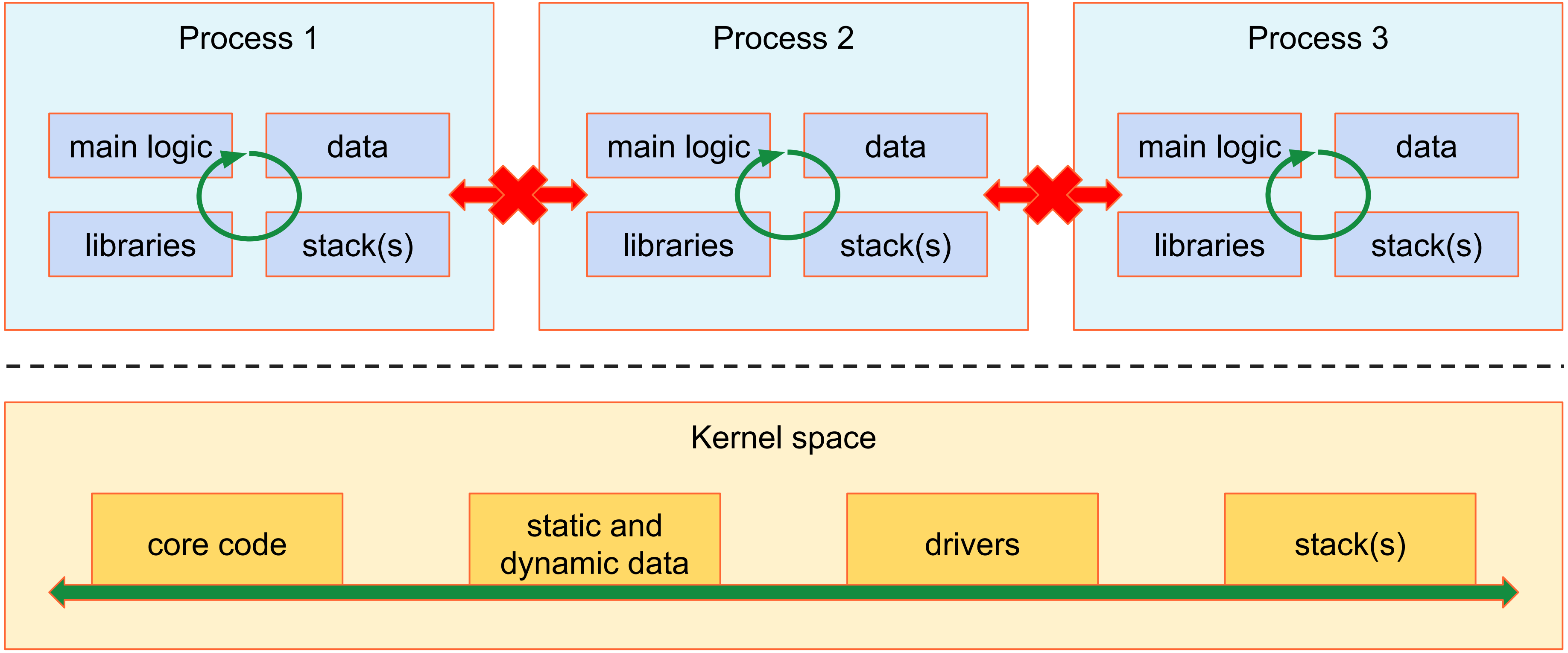

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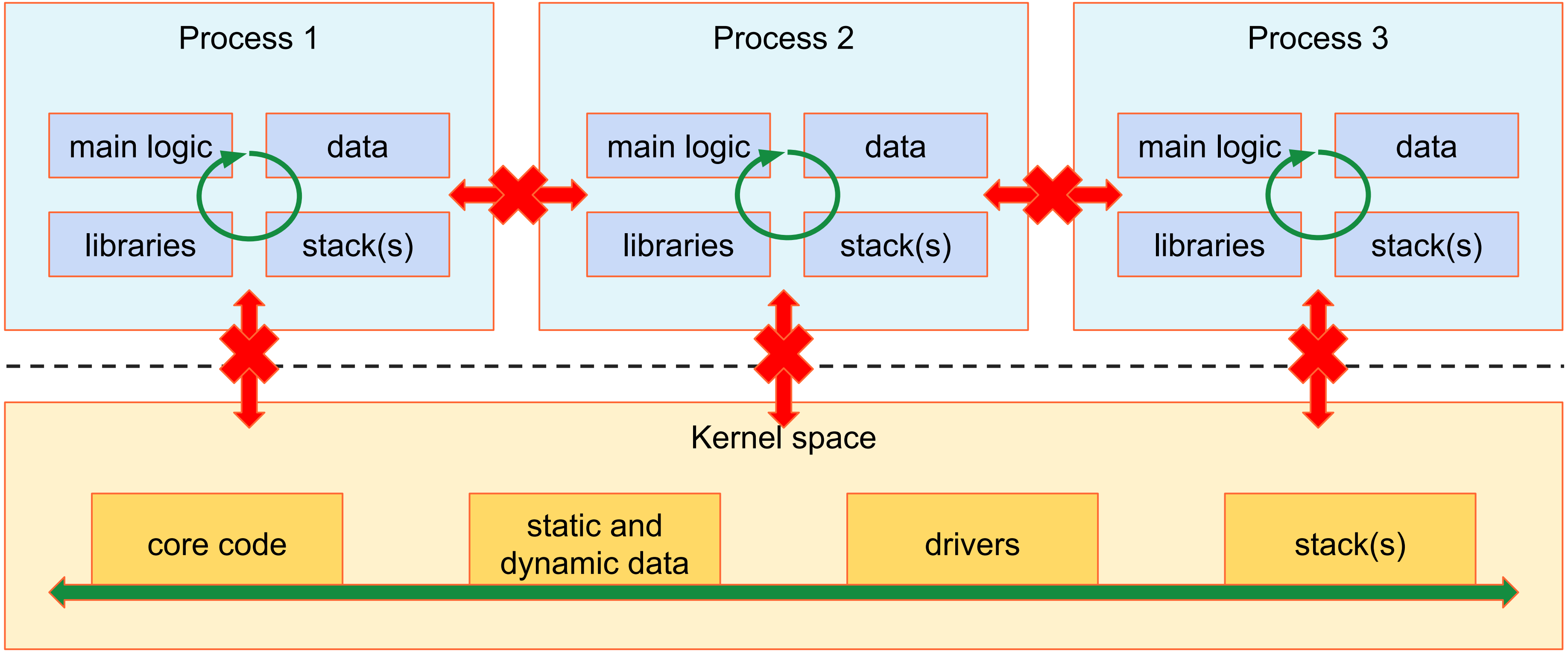

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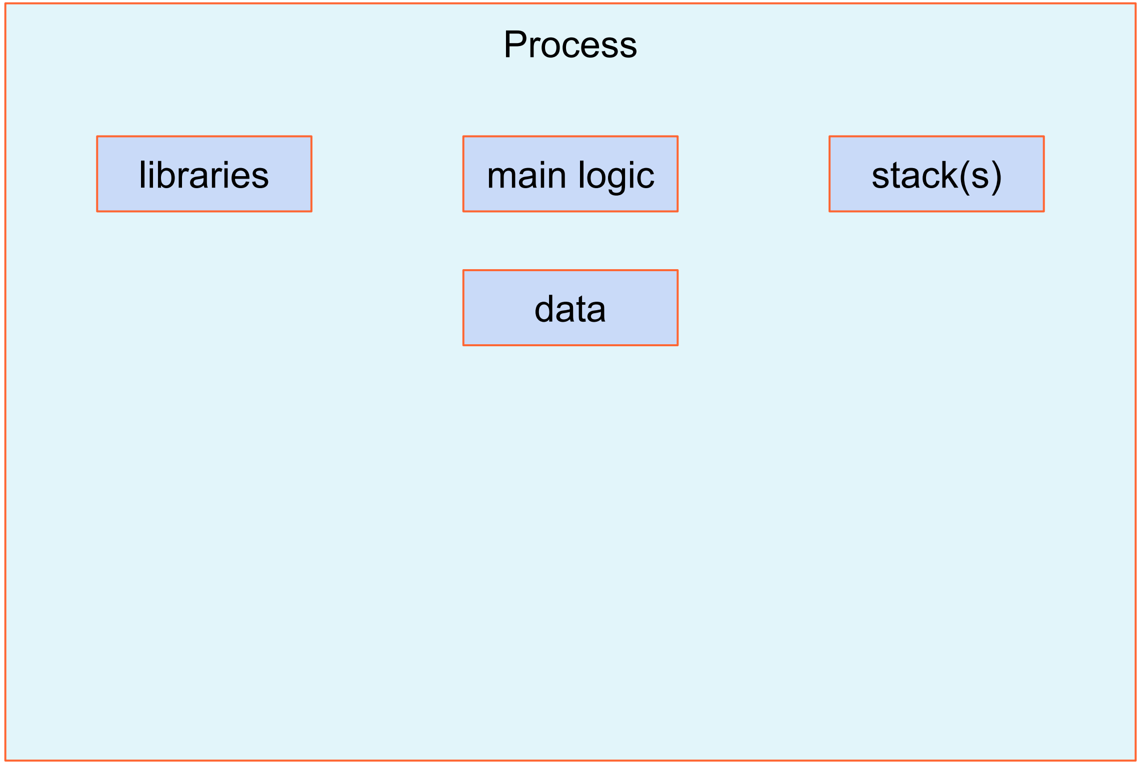

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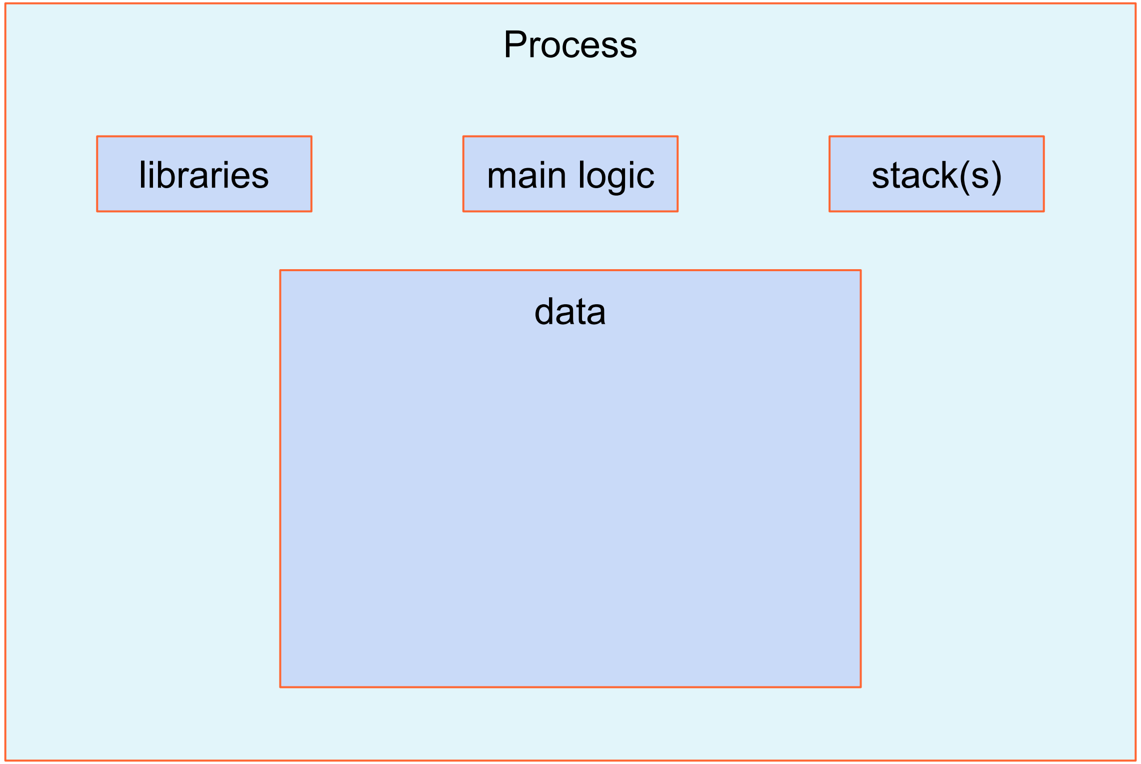

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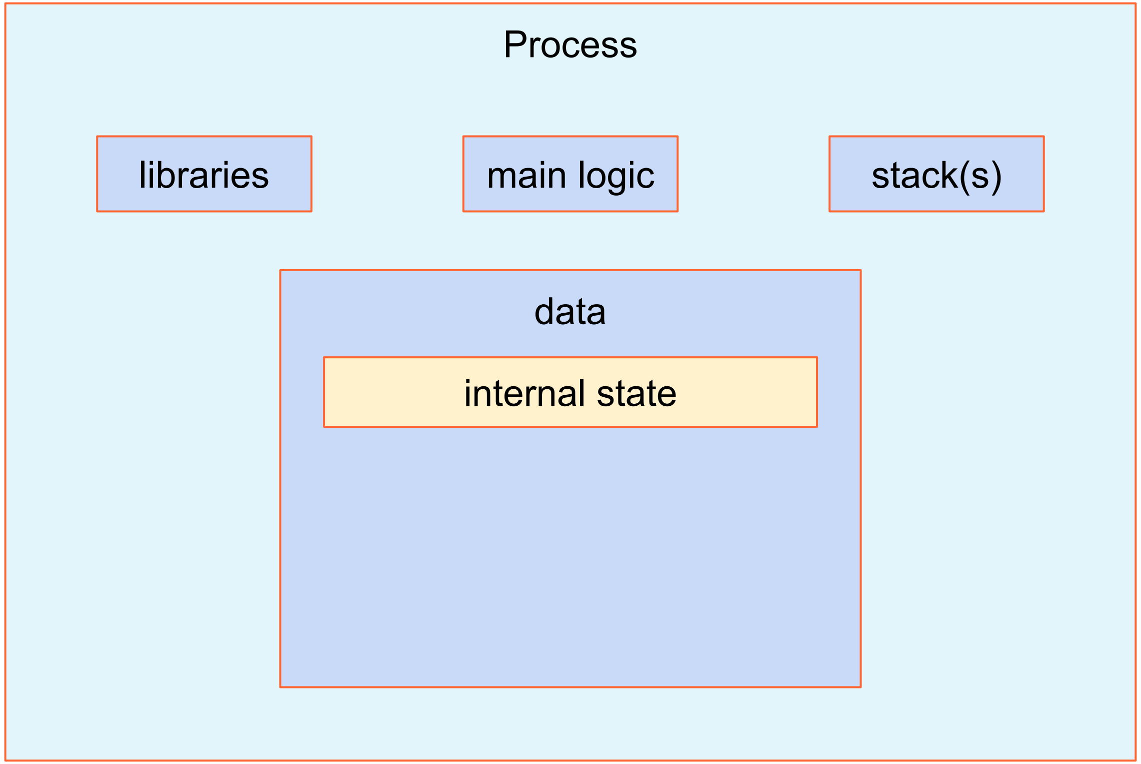

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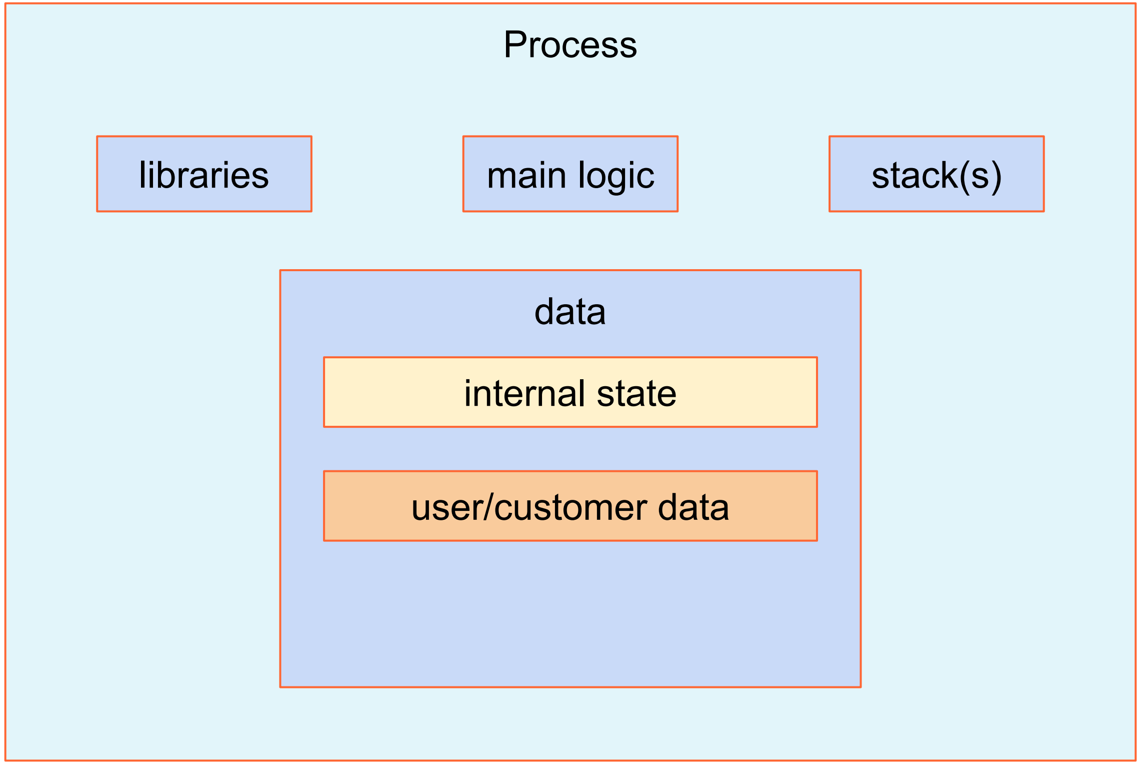

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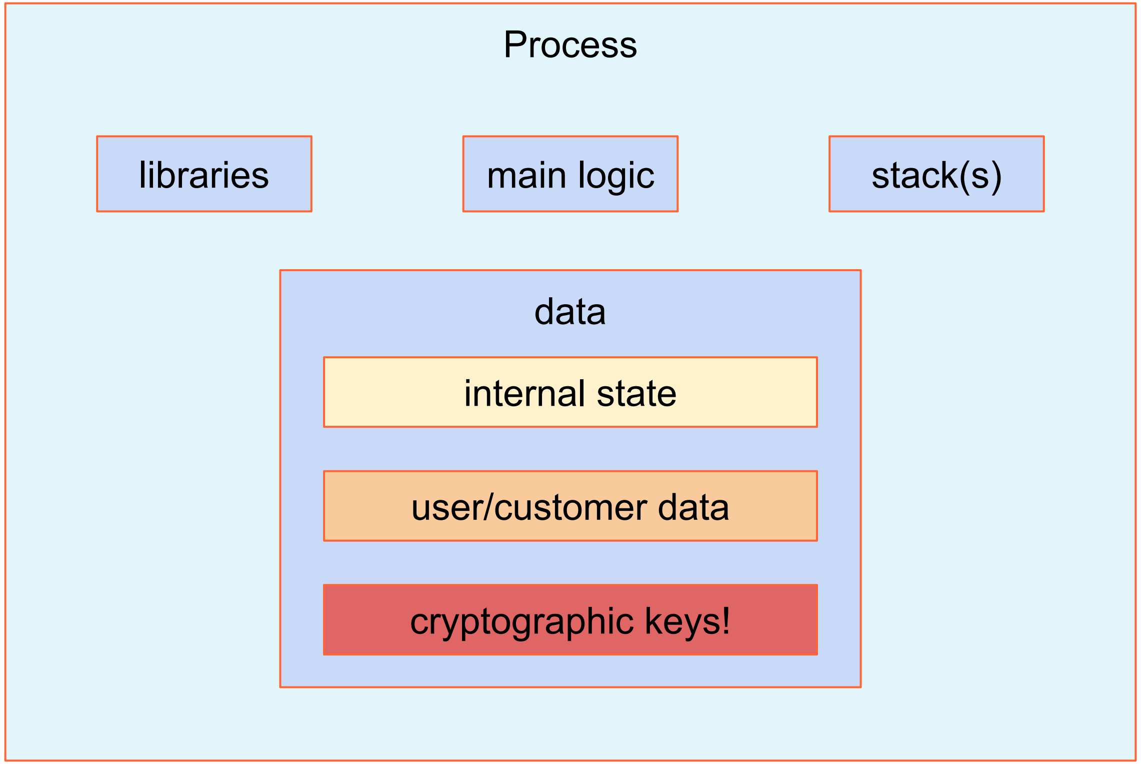

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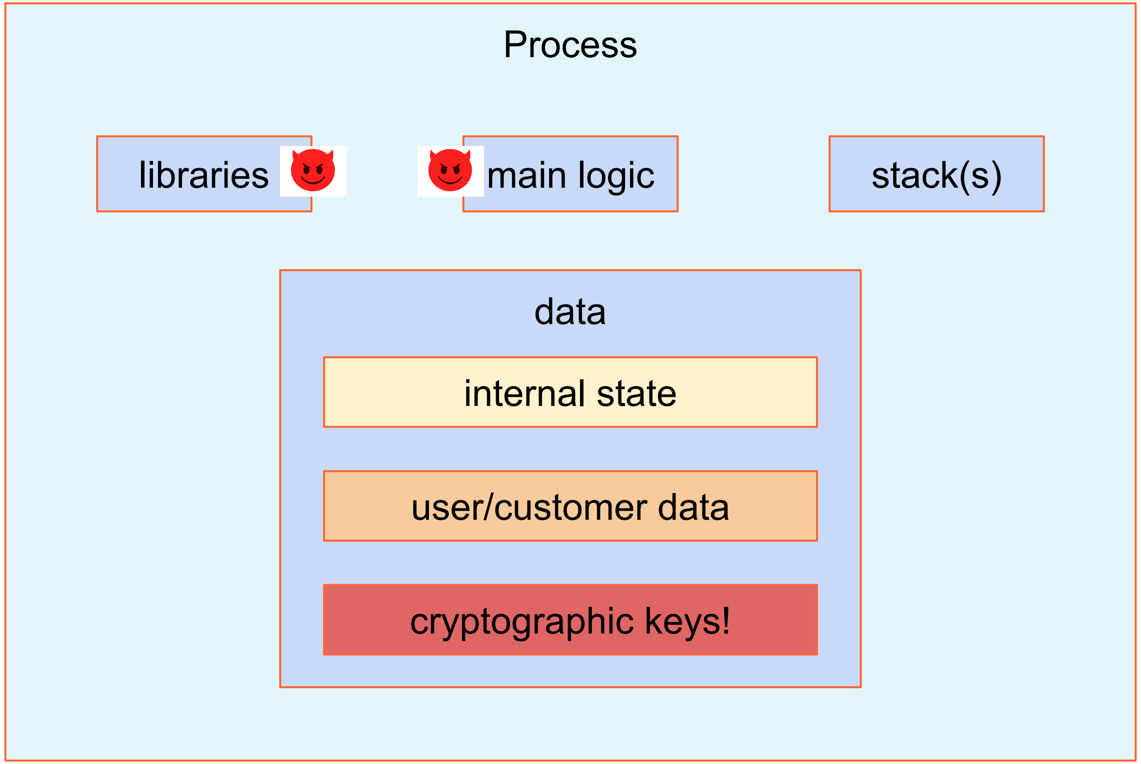

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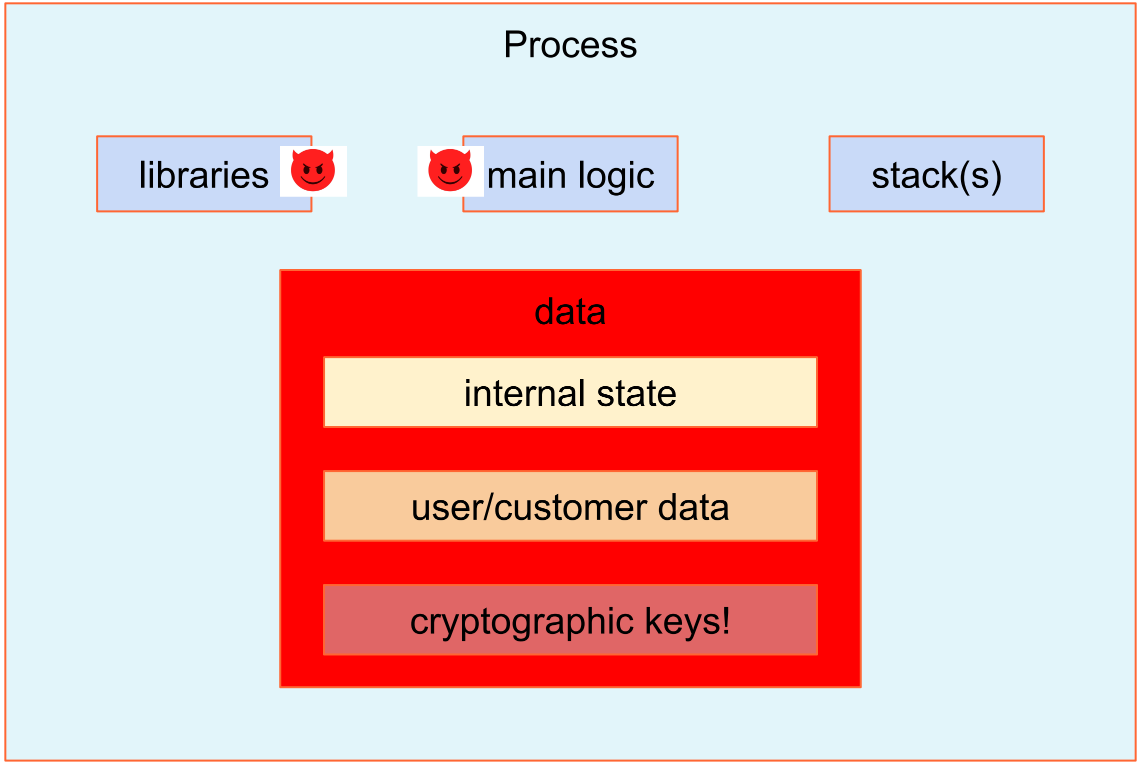
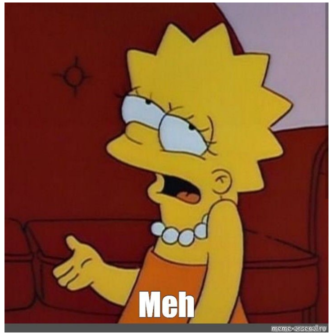


Not all process data is created equal

- Application internal state is compromised
  - Can be good or bad
  - Can lead to further compromise



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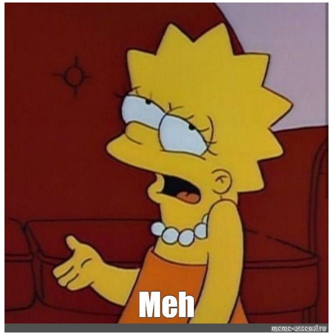

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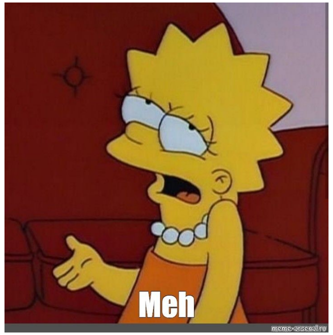
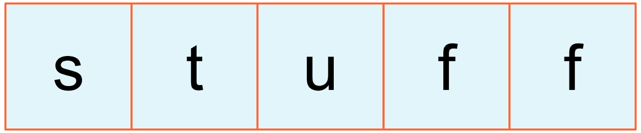
  - Privacy leaks
- Cryptographic key compromise
  - Data integrity compromise
  - Full security compromise
  - Total identity takeover



Untrusted inputs and out-of-bounds memory access



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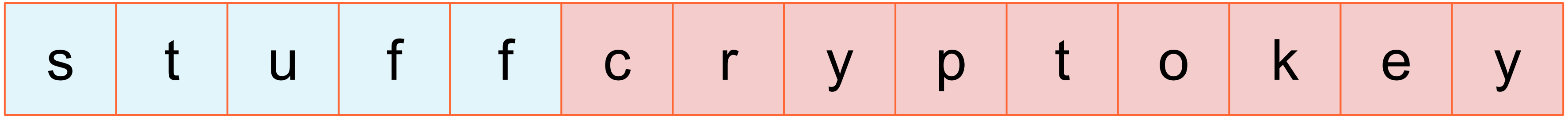

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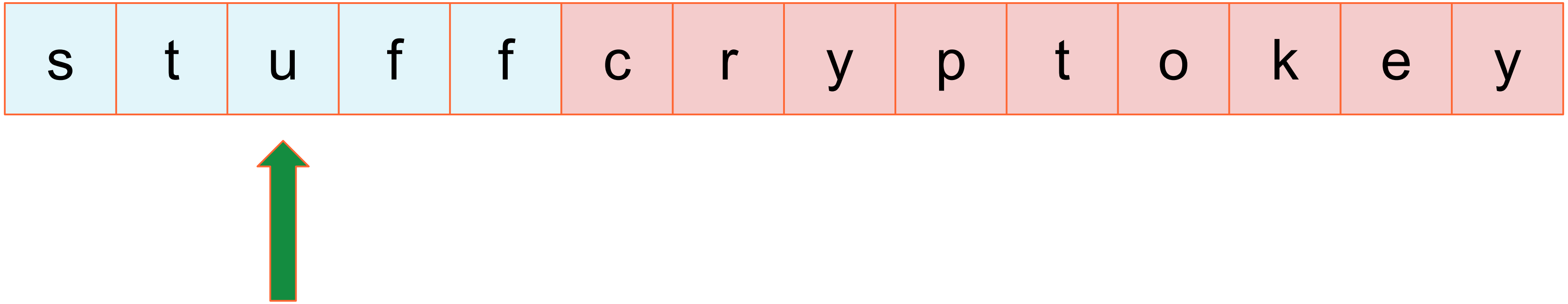

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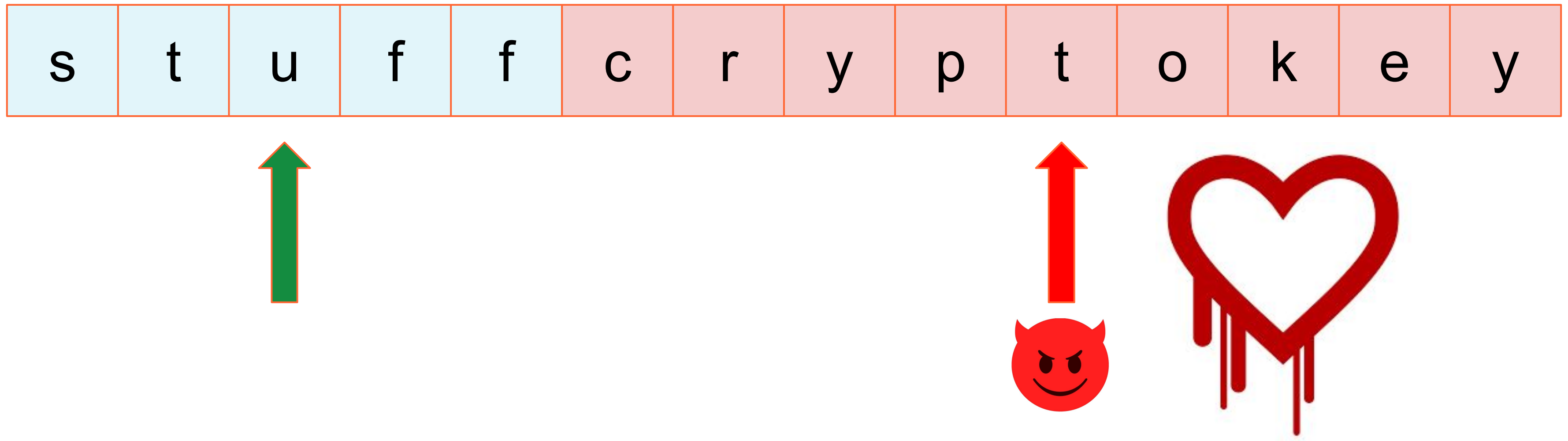

Arbitrary/remote code execution

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https://en.wikipedia.org/wiki/Log4Shell

Buffer reuse

```c
#include <stdio.h>
#include <stdint.h>

static void encrypt(void)
{
    uint8_t key[] = "hunter2";
    printf("encrypting with super secret key: %s\n", key);
}

static void log_completion(void)
{
    /* oh no, we forgot to init the msg */
    char msg[8];
    printf("not important, just fyi: %s\n", msg);
}
```

```c
int main(void)
{
    encrypt();
    /* notify that we're done */
    log_completion();
    return 0;

}
```

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```c
int main(void)
{
    encrypt();
    /* notify that we're done */
    log_completion();
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}
```
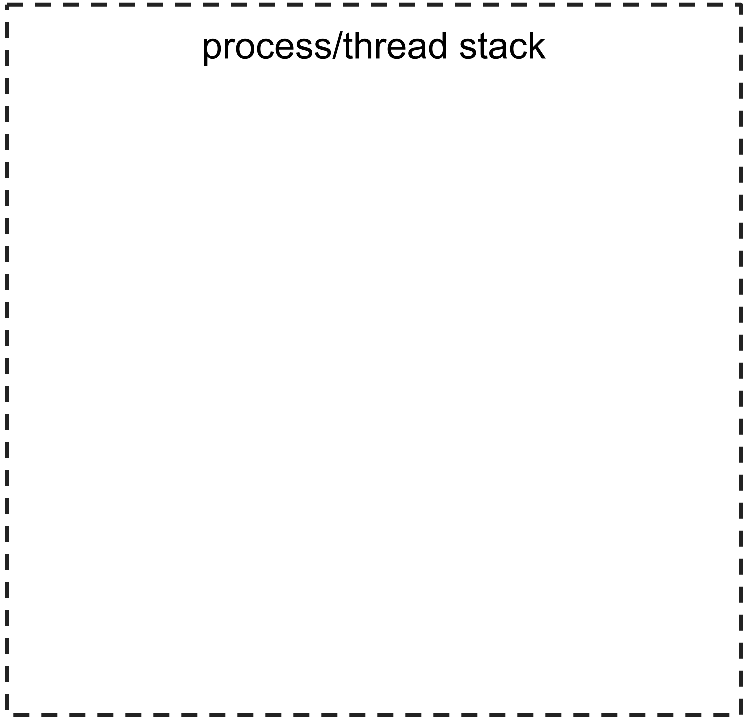

```
$ gcc -o broken broken.c
$ ./broken
encrypting with super secret key: hunter2
not important, just fyi: hunter2
```

Buffer reuse



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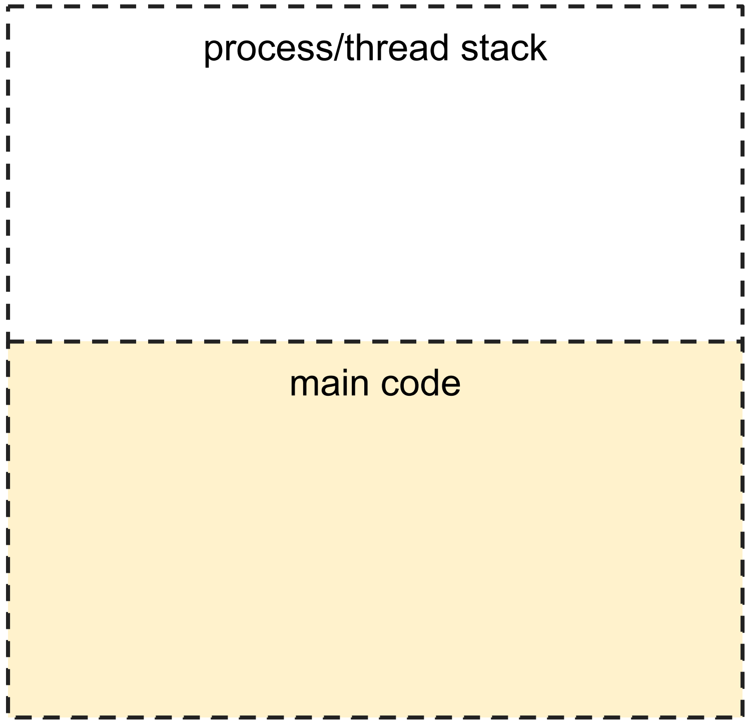

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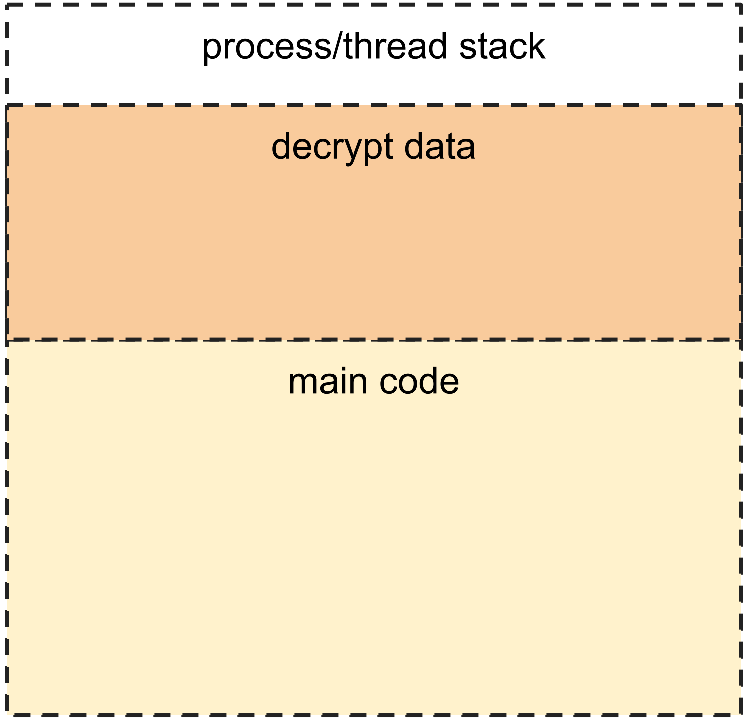

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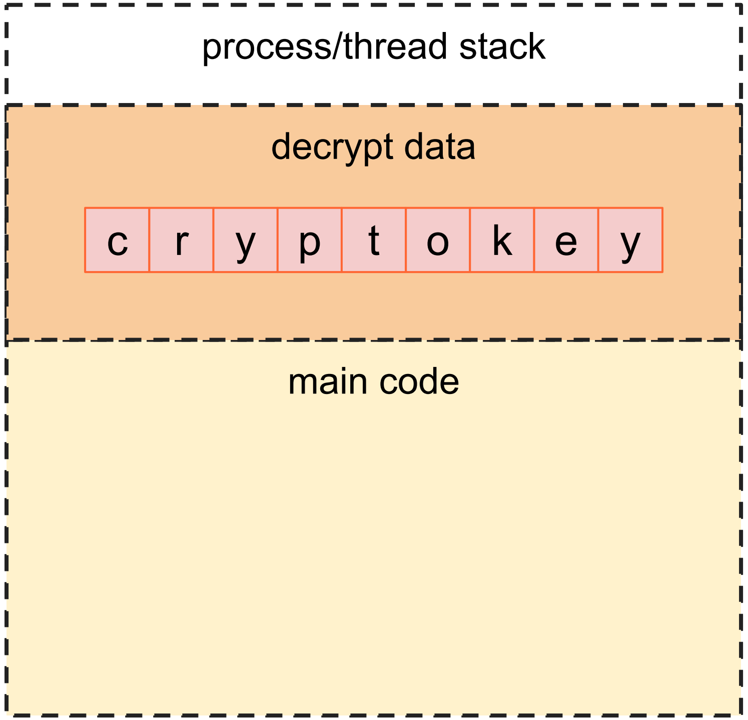

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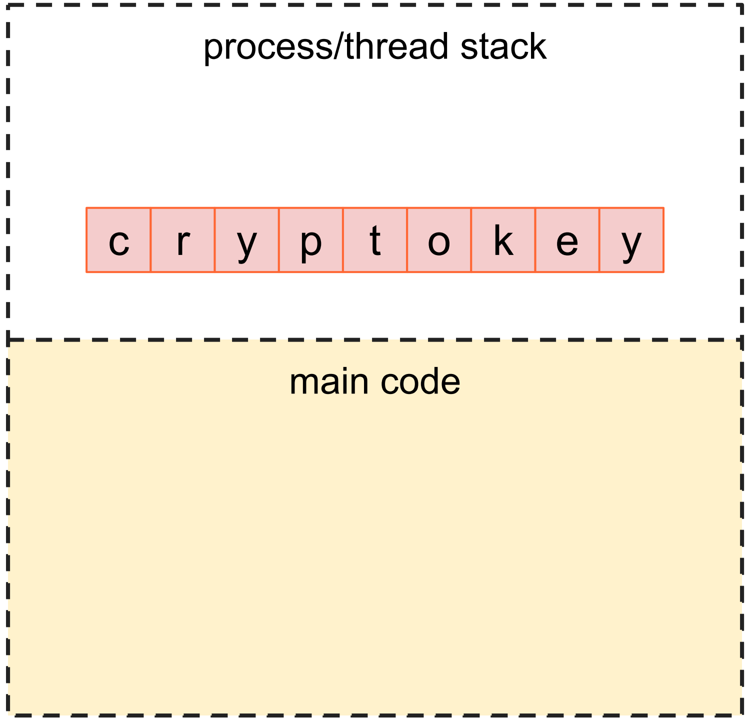

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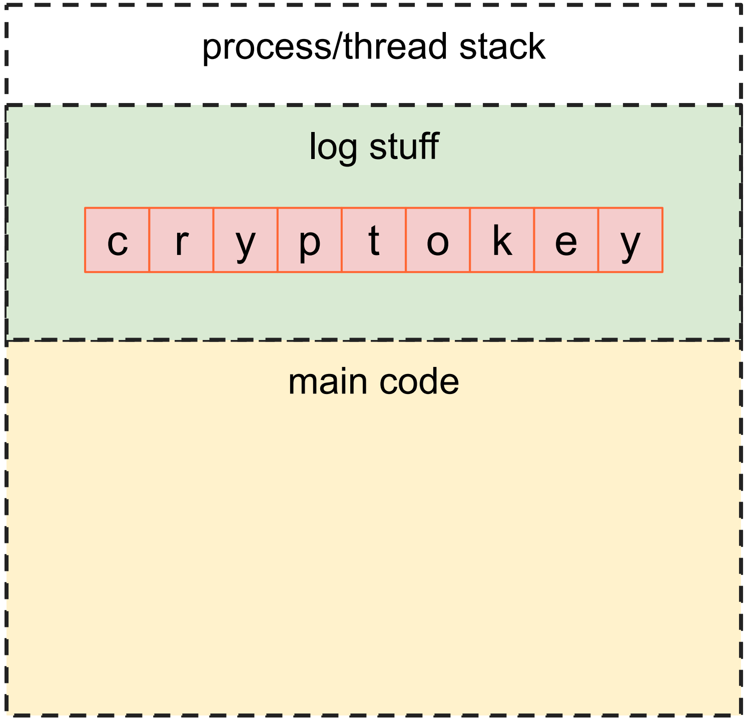

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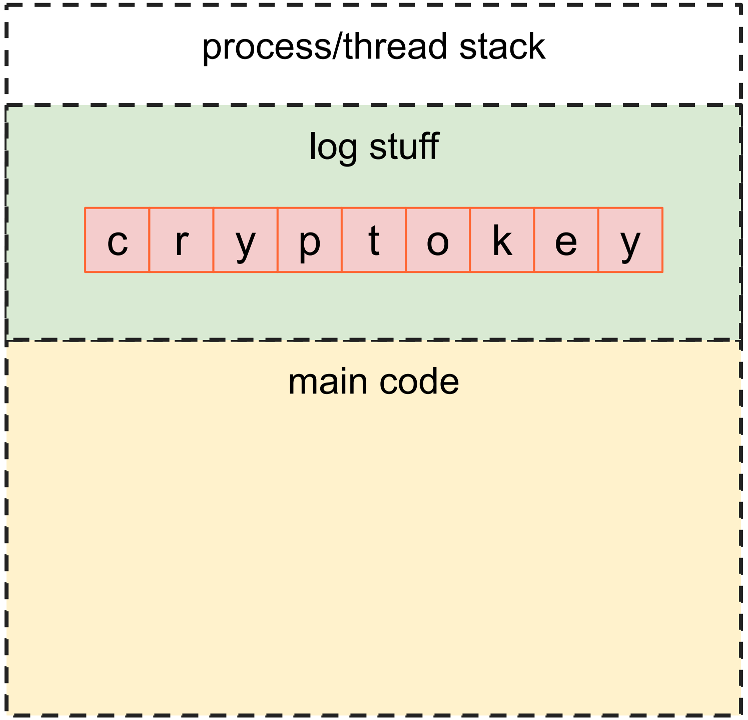
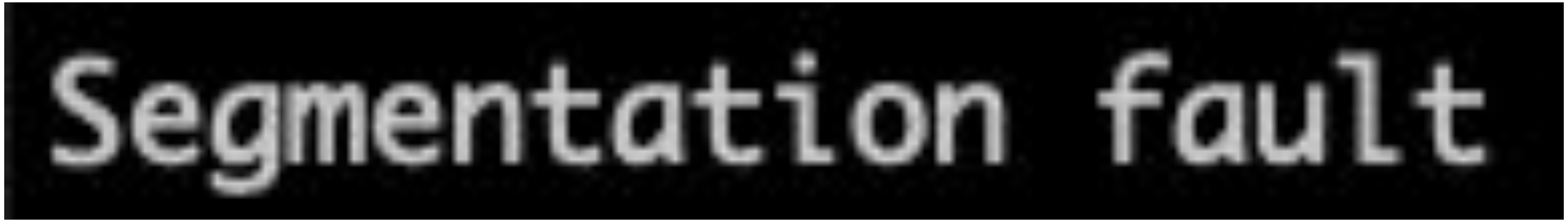


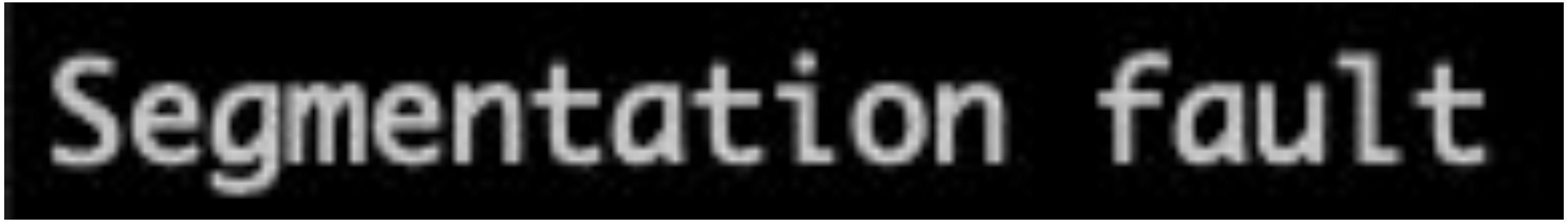
- Need to zero memory after key use
  - Both stack and heap
  - Challenging in garbage collected languages

Debugging info and tools



```
Segmentation fault
```

Debugging info and tools

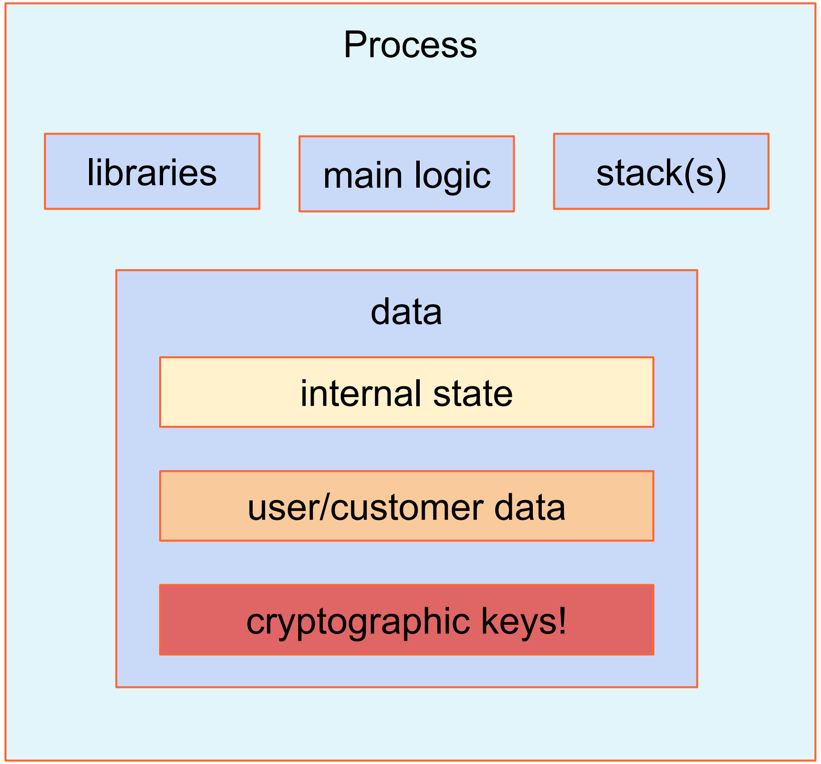


```
Segmentation fault
```

- logging
- coredumps
- gdb
- ptrace

Fix all the bugs?

Linux address spaces



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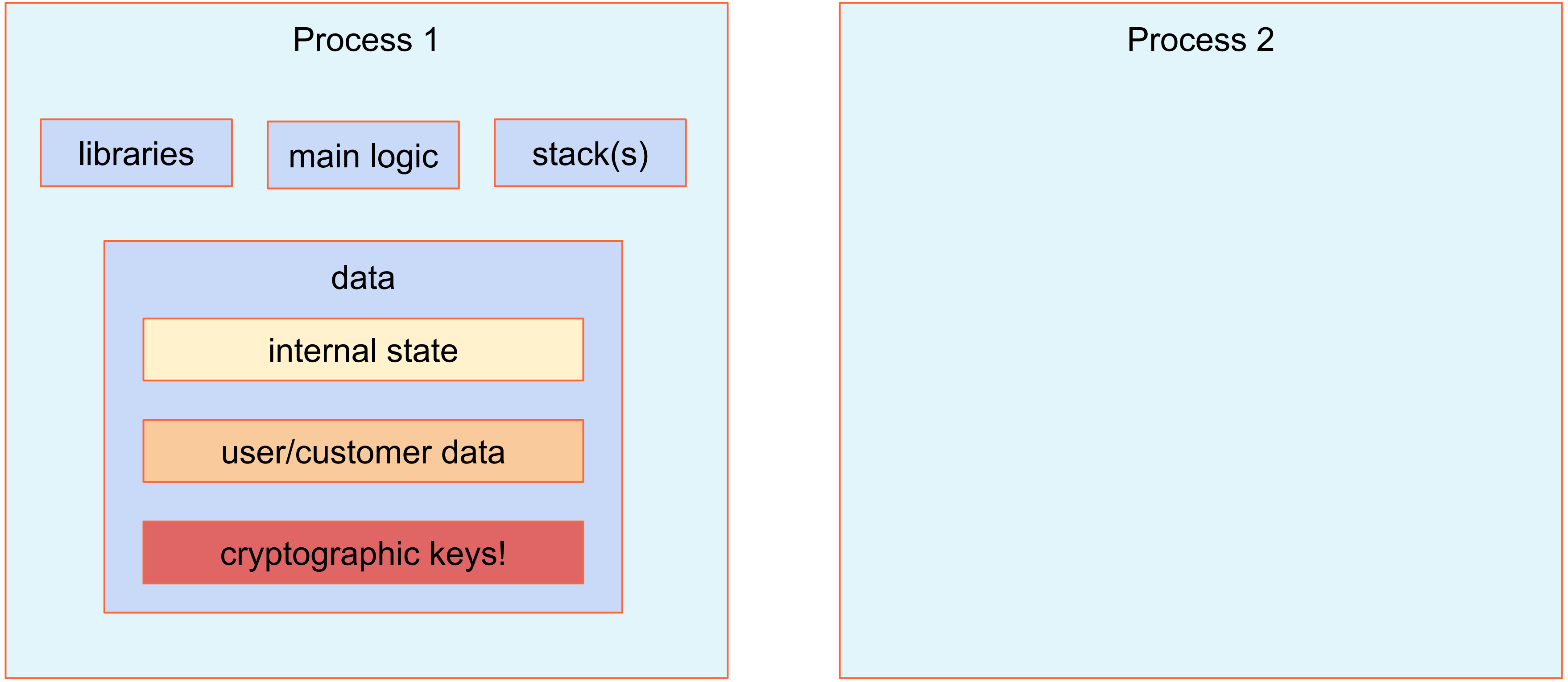

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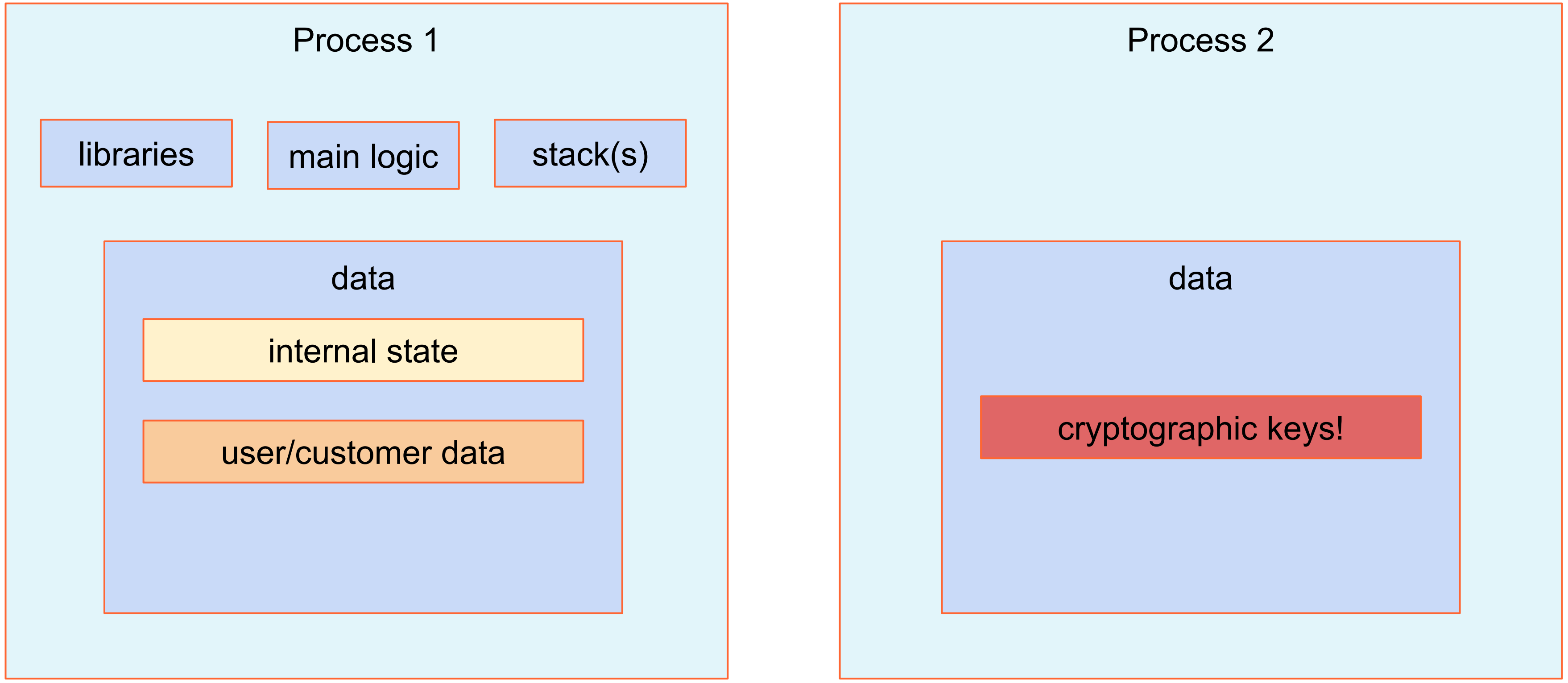

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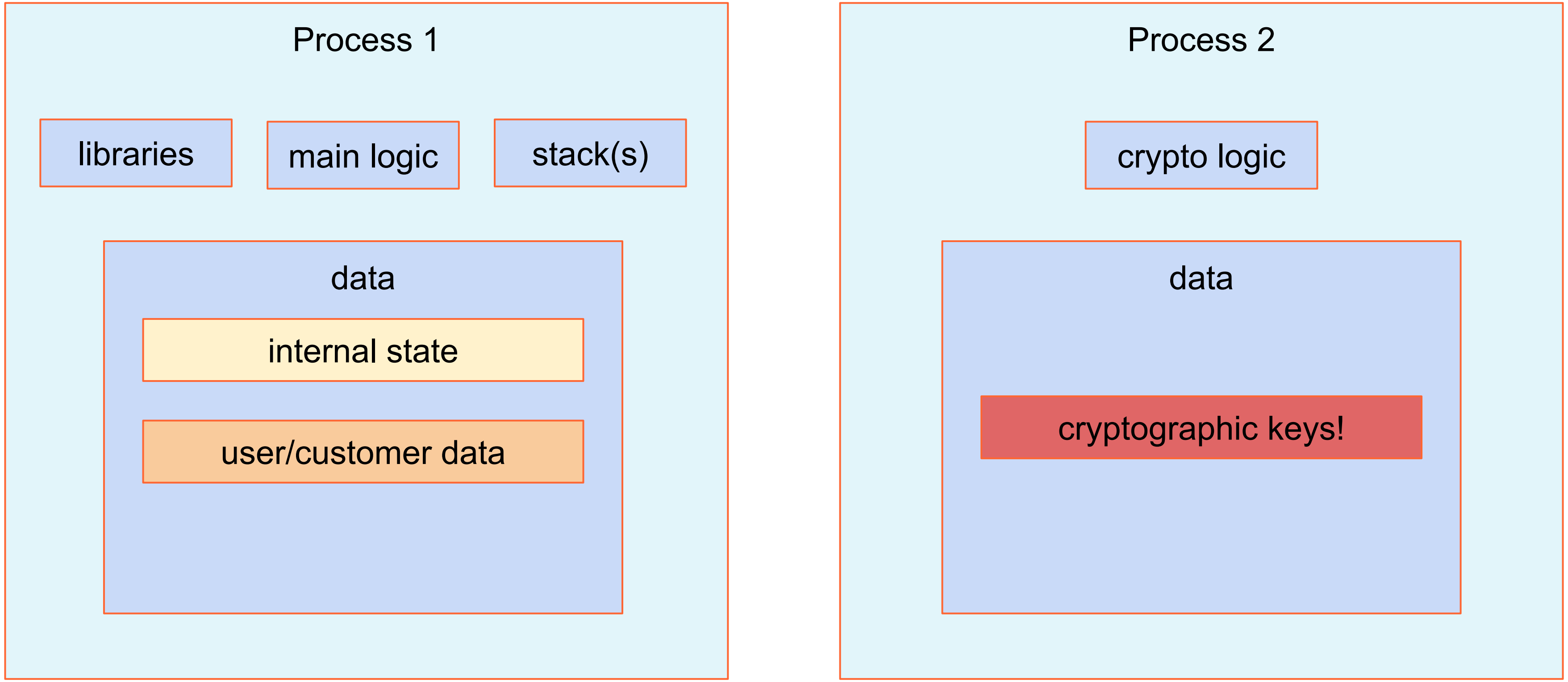

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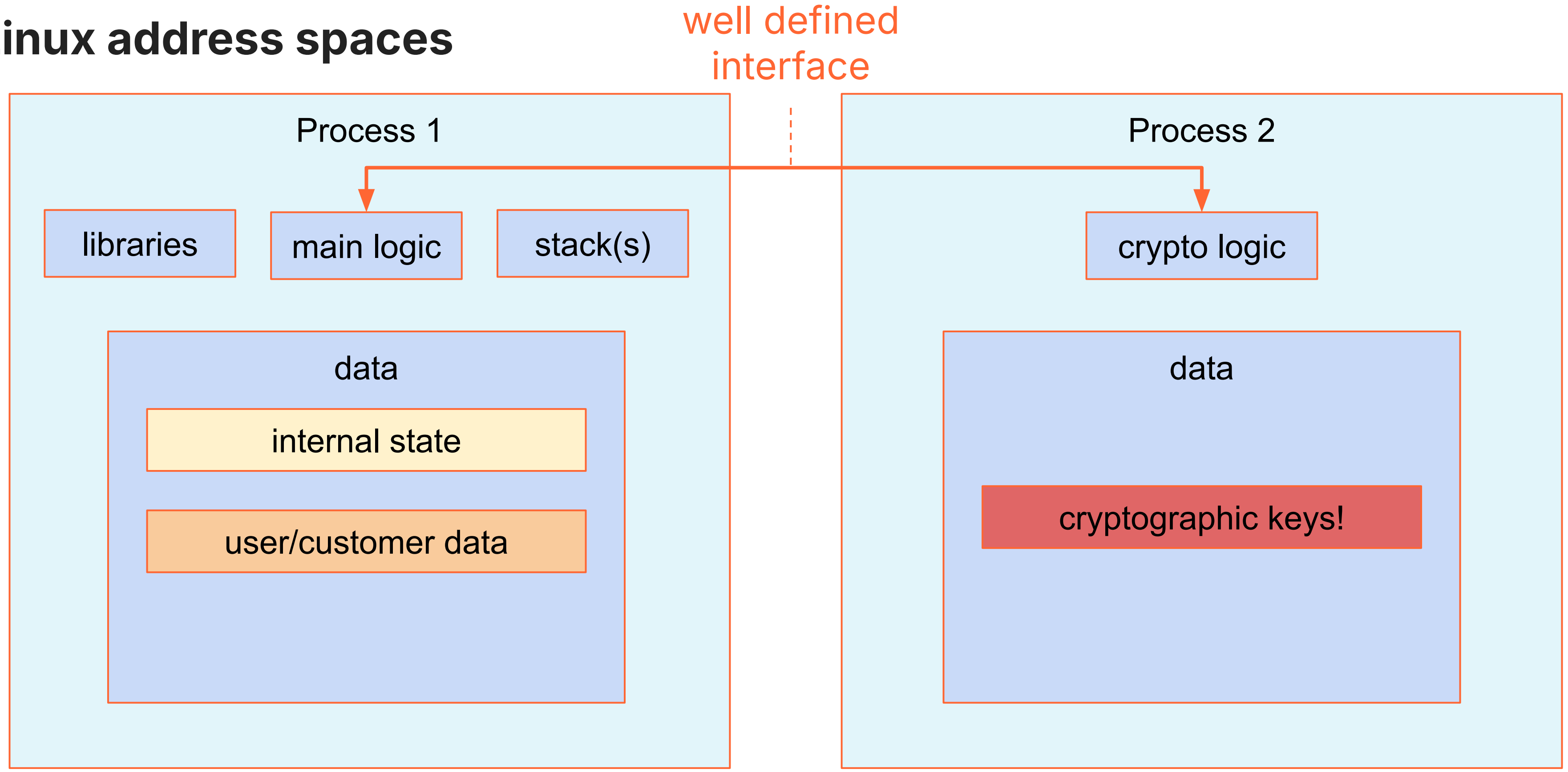

Key agent model

- Two processes: main and a helper "agent":
  - main process does not have access to the cryptographic material (ensured by the OS address space isolation)
  - main communicates with the "agent" through a well-defined interface to perform cryptographic operations
  - main processes untrusted input and is usually network-facing
  - "agent" does not process untrusted input and is usually not network facing

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  - main processes untrusted input and is usually network-facing
  - “agent” does not process untrusted input and is usually not network facing
- Think of the “agent” as a software security key
  - ssh-agent
  - gpg-agent

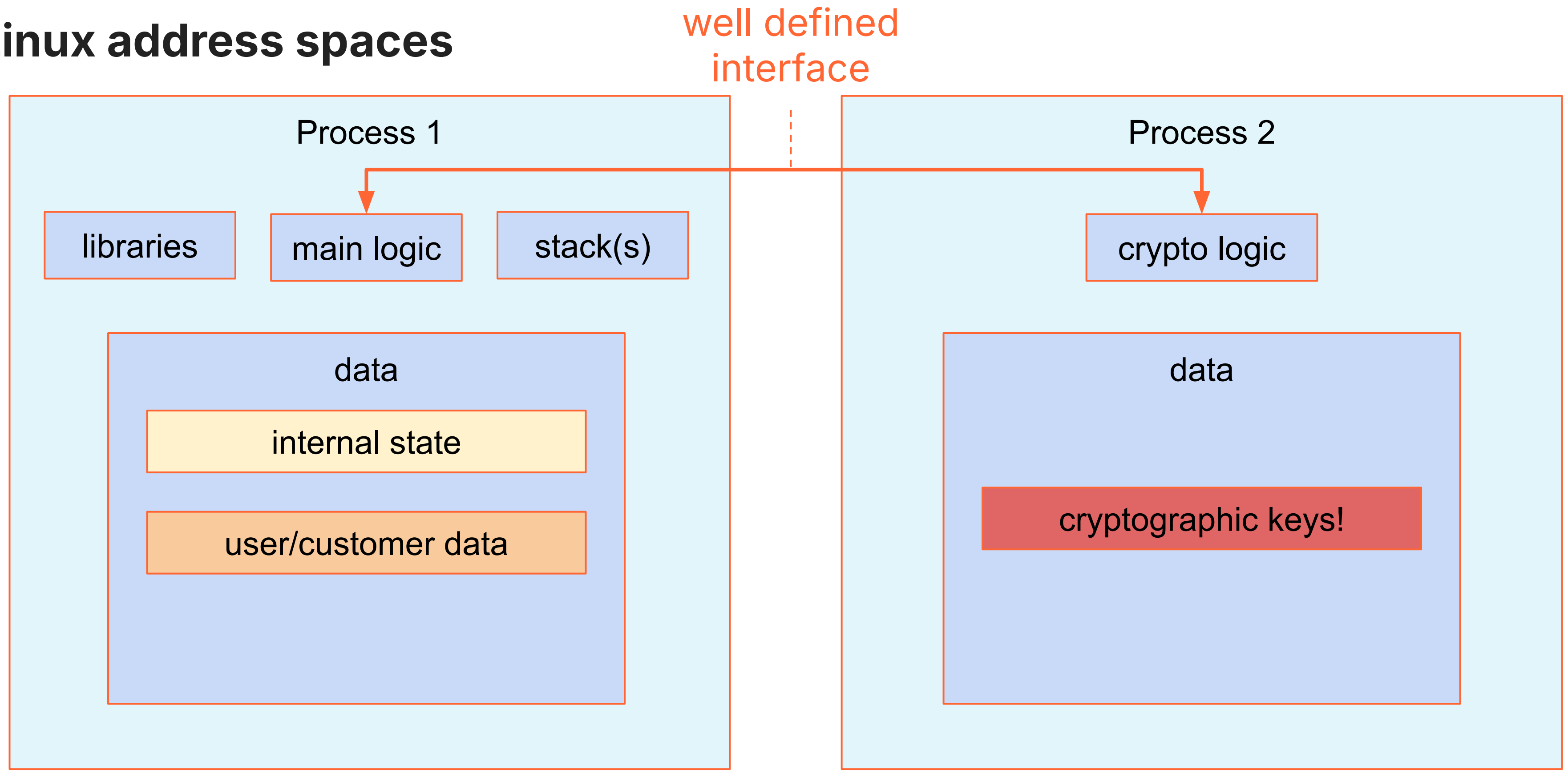
Key agent model

- Drawbacks
  - need to develop and maintain two programs/processes
  - need to design the “well-defined interface” between main and the agent
  - need to add communication support between the two processes (Unix sockets, shared memory etc)
  - need to somehow authenticate and enforce some ACLs of the main process in the agent

Linux Kernel key retention service

Or just Linux keystore

Linux address spaces



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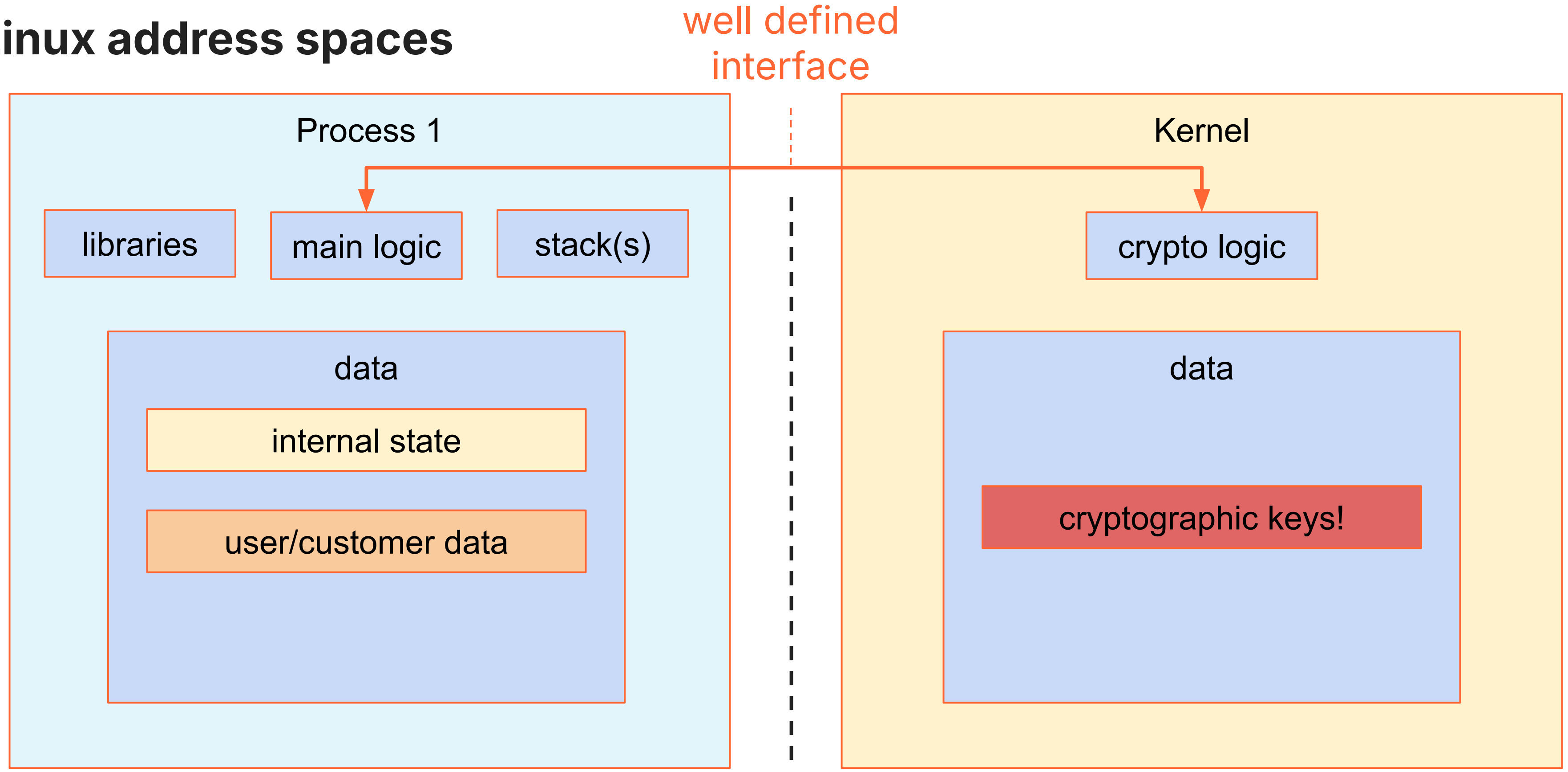

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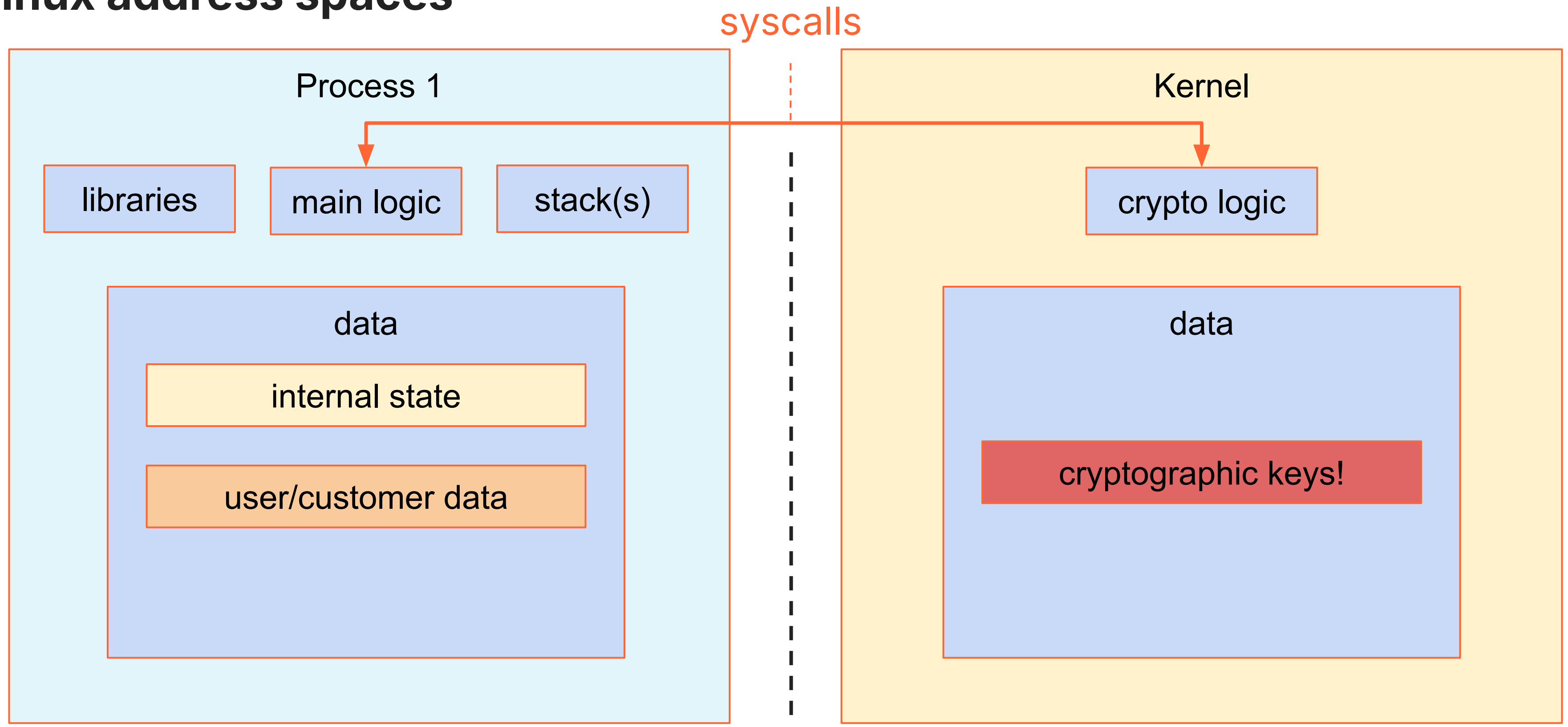

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- Can be used by userspace programs to manage their keys/secrets
    - keys are stored outside of the process address space
    - a well-defined system call interface to access and use the keys
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        - including LSM hooks
    - key lifecycle can be implicitly bound to the code lifecycle
        - ex. key autodestruction, when a process terminates

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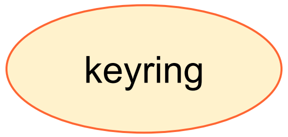
https://www.kernel.org/doc/html/latest/security/keys/core.html

Keys and keyrings



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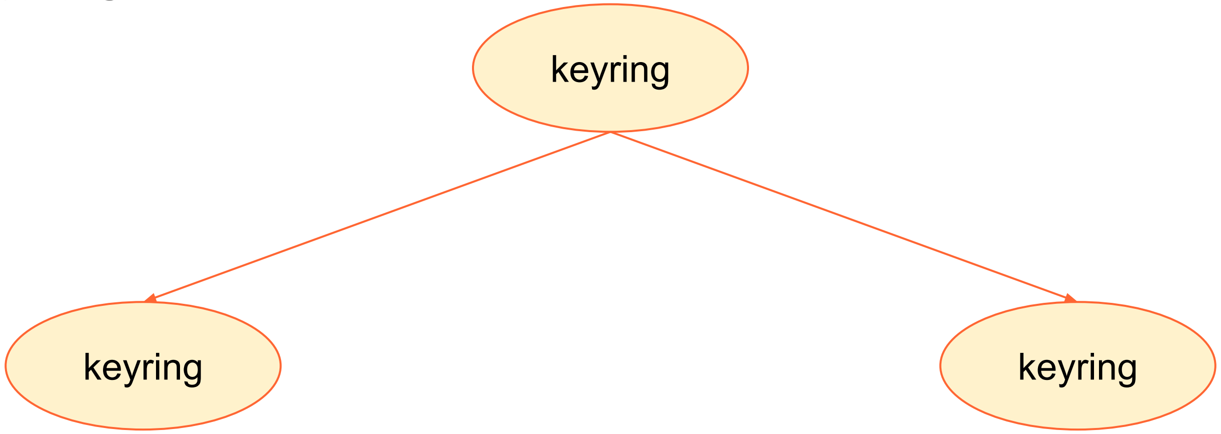
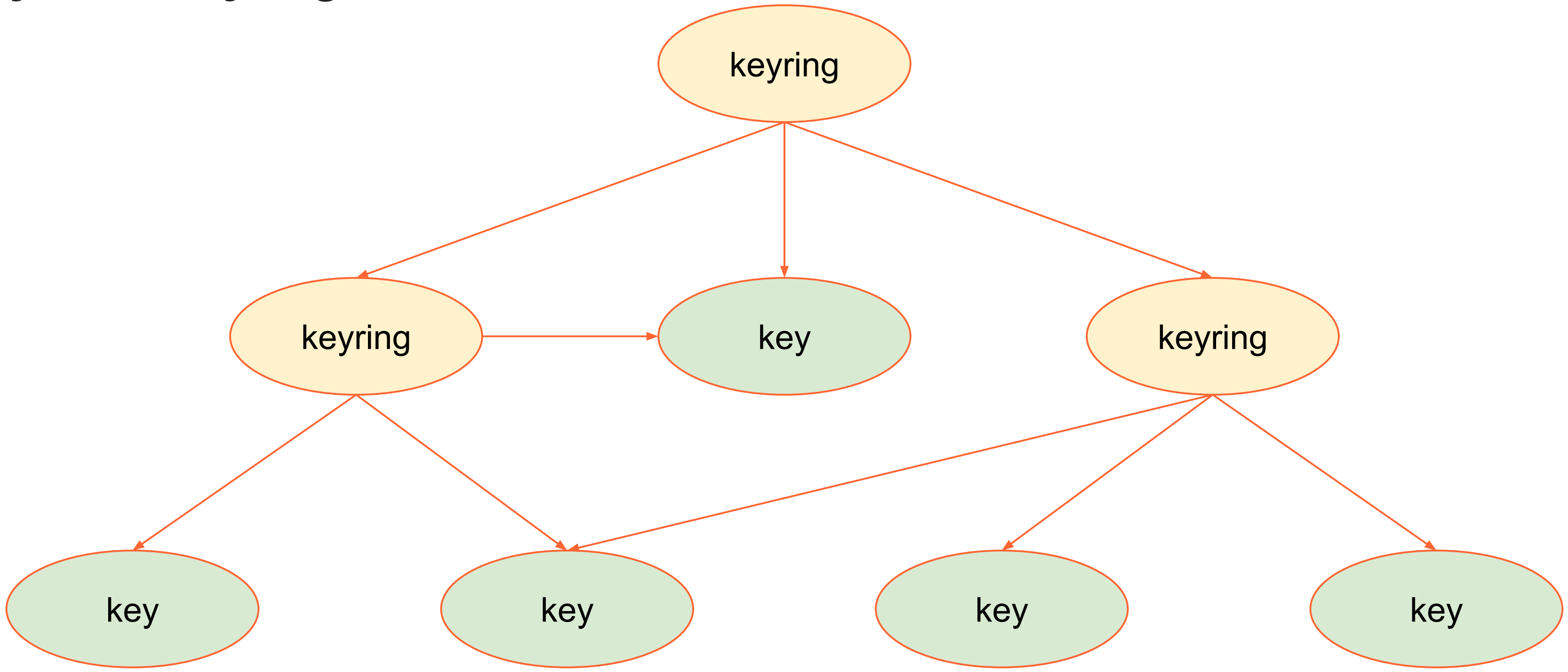


Keys and keyrings



Keys and keyrings

Keys

- contain actual cryptographic material or a pointer to it
- can be read/written to and used to perform cryptographic transformations
- can be of different types:
  - user
  - logon
  - asymmetric
  - encrypted
  - trusted
- similar to a file on a filesystem
  - but can be linked to many keyrings in the same time

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Keyrings

- contain links to keys and other keyrings
  - if a key is not linked to a single keyring, it is securely destroyed
- represent a collection of keys
- can be explicitly created or special:
  - thread
  - process
  - user
  - session
- may enforce key lifetime
- similar to a directory on a filesystem

Keys and keyrings

```
ignat@dev:~$ keyctl newring myring @u
850826109
```

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ignat@dev:~$ keyctl newring myring @u
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ignat@dev:~$ keyctl add user mykey hunter2 %:myring
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Session Keyring
 346094565 --alswrv   1000  1000  keyring: _ses
 517020096 --alswrv   1000 65534   \_ keyring: _uid.1000
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 975891189 --alswrv   1000  1000           \_ user: mykey
ignat@dev:~$ keyctl print %user:mykey
hunter2
```

Example: secret sharing

```
alice@dev:~$ id
uid=1001(alice) gid=1001(alice)
groups=1001(alice)
```

```
bob@dev:~$ id
uid=1002(bob) gid=1002(bob)
groups=1002(bob)
```

Example: secret sharing

```
alice@dev:~$ id
uid=1001(alice) gid=1001(alice)
groups=1001(alice)
alice@dev:~$ keyctl add user secret
hunter2 @u
791615806
```

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Example: secret sharing

```
alice@dev:~$ id
uid=1001(alice) gid=1001(alice)
groups=1001(alice)
alice@dev:~$ keyctl add user secret
hunter2 @u
791615806
```

```
bob@dev:~$ id
uid=1002(bob) gid=1002(bob)
groups=1002(bob)
bob@dev:~$ keyctl newring from-others @u
966722684
```

Example: secret sharing

```
alice@dev:~$ id
uid=1001(alice) gid=1001(alice)
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alice@dev:~$ keyctl add user secret
hunter2 @u
791615806
```

```
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groups=1002(bob)
bob@dev:~$ keyctl newring from-others @u
966722684
bob@dev:~$ keyctl setperm %:from-others
0x3f010004
```

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alice@dev:~$ keyctl show
Session Keyring
 931561702 --alswrv   1001  1001
keyring: _ses
 107607516 --alswrv   1001 65534   \_
keyring: _uid.1001
```

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0x3f010004
bob@dev:~$ keyctl print %user:secret
hunter2
```

Example: secret sharing

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0x3f010004
bob@dev:~$ keyctl print %user:secret
hunter2
bob@dev:~$ keyctl show @u
Keyring
 812825228 --alswrv   1002 65534
keyring: _uid.1002
 966722684 --alswrv   1002  1002   \_
keyring: from-others
 791615806 --alswrv   1001  1001
\_ user: secret
```

Special keyring types

- Process keyrings:
  - session keyring: current and all child processes
  - process keyring: private to the process
  - thread keyring: private to the thread

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  - user keyring: shared between all processes with a UID
  - user session keyring: similar to user keyring
- Persistent keyrings:
  - shared between all processes with a UID
  - does not get destroyed, when last process with a UID exits
  - “expires” after a timeout, if not accessed before
    - for various non-interactive tasks, like cron jobs

Session keyring example

```
ignat@dev:~$ keyctl add user secret hunter2 @s
603482993
```

Session keyring example

```
ignat@dev:~$ keyctl add user secret hunter2 @s
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ignat@dev:~$ keyctl show
Session Keyring
 464596277 --alswrv   1000  1000  keyring: _ses
 517020096 --alswrv   1000 65534   \_ keyring: _uid.1000
 603482993 --alswrv   1000  1000   \_ user: secret
```

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```

```
ignat@dev:~$ sudo bpftrace -e 'kprobe:user_destroy { printf("destroying key %d\n", ((struct
key *)arg0)->serial) }'
Attaching 1 probe...
```

Session keyring example

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ignat@dev:~$ keyctl add user secret hunter2 @s
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logout
Connection to dev closed.
```

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Connection to dev closed.
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Session Keyring
 464596277 --alswrv   1000  1000  keyring: _ses
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 603482993 --alswrv   1000  1000   \_ user: secret
ignat@dev:~$ exit
logout
Connection to dev closed.
$ ssh dev
ignat@dev:~$ keyctl show
Session Keyring
 523682608 --alswrv   1000  1000  keyring: _ses
 517020096 --alswrv   1000 65534   \_ keyring: _uid.1000
```

```
ignat@dev:~$ sudo bpftrace -e 'kprobe:user_destroy { printf("destroying key %d\n", ((struct
key *)arg0)->serial) }'
Attaching 1 probe...
destroying key 603482993
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ignat@dev:~$ keyctl add user secret hunter2 @s
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ignat@dev:~$ exit
logout
Connection to dev closed.
$ ssh dev
ignat@dev:~$ keyctl show
Session Keyring
 523682608 --alswrv   1000  1000  keyring: _ses
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```

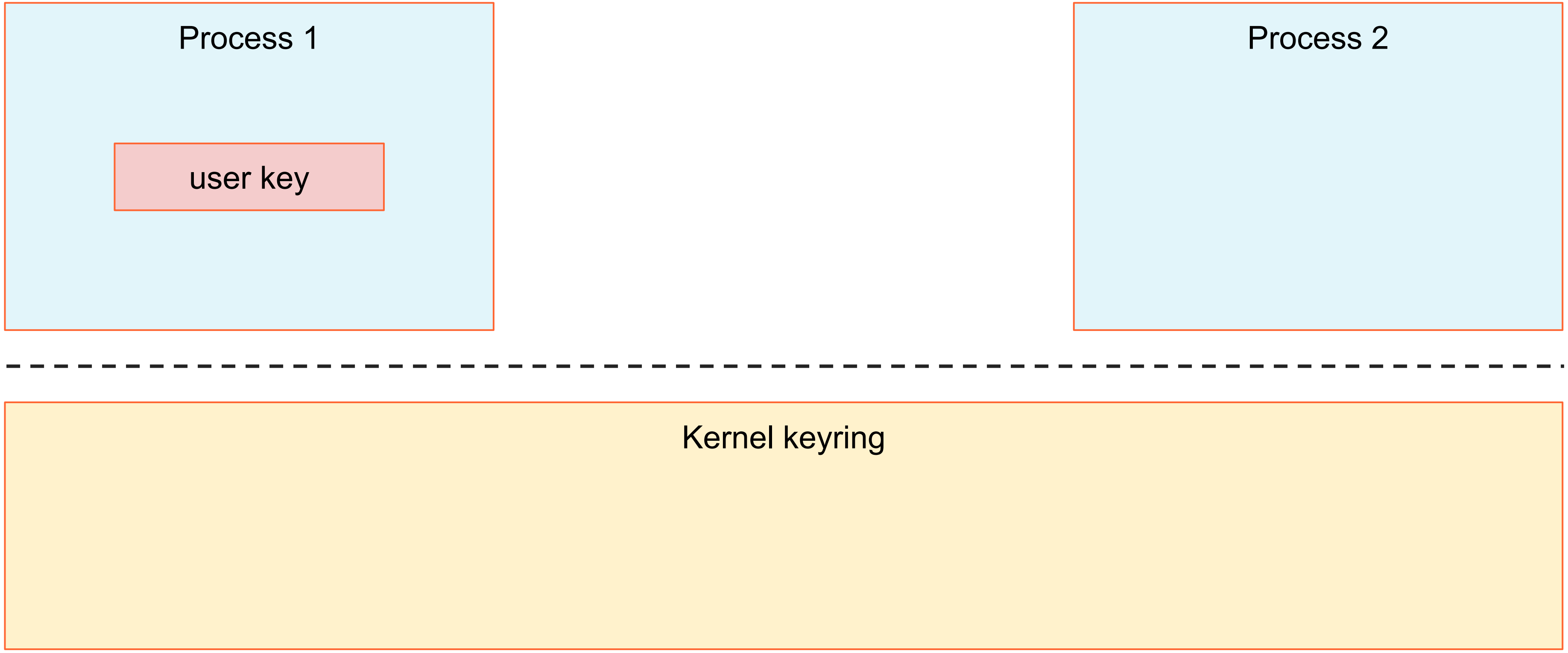
```
ignat@dev:~$ sudo bpftrace -e 'kprobe:user_destroy { printf("destroying key %d\n", ((struct
key *)arg0)->serial) }'
Attaching 1 probe...
destroying key 603482993
```

Special keyring types

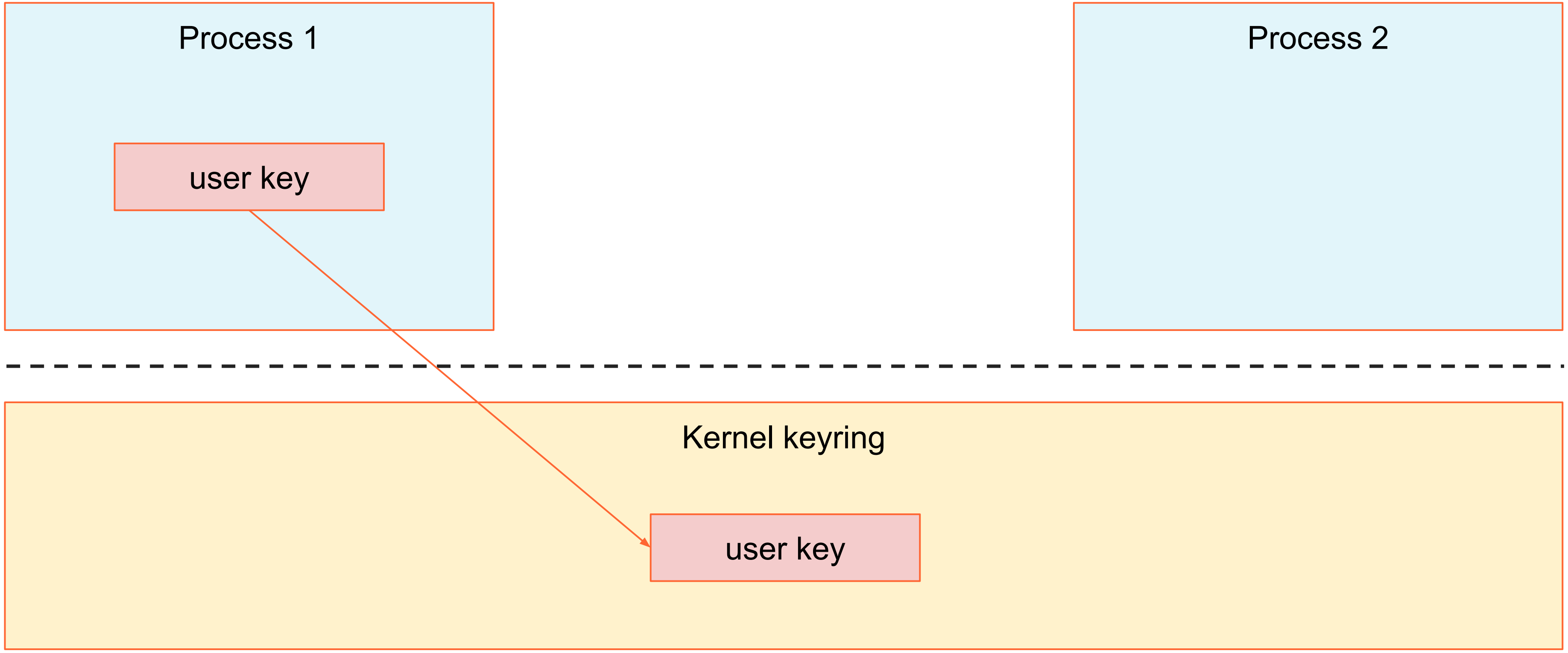
By selecting the appropriate keyring type you can ensure the keys will be securely destroyed, when not needed

Even if the application crashes!

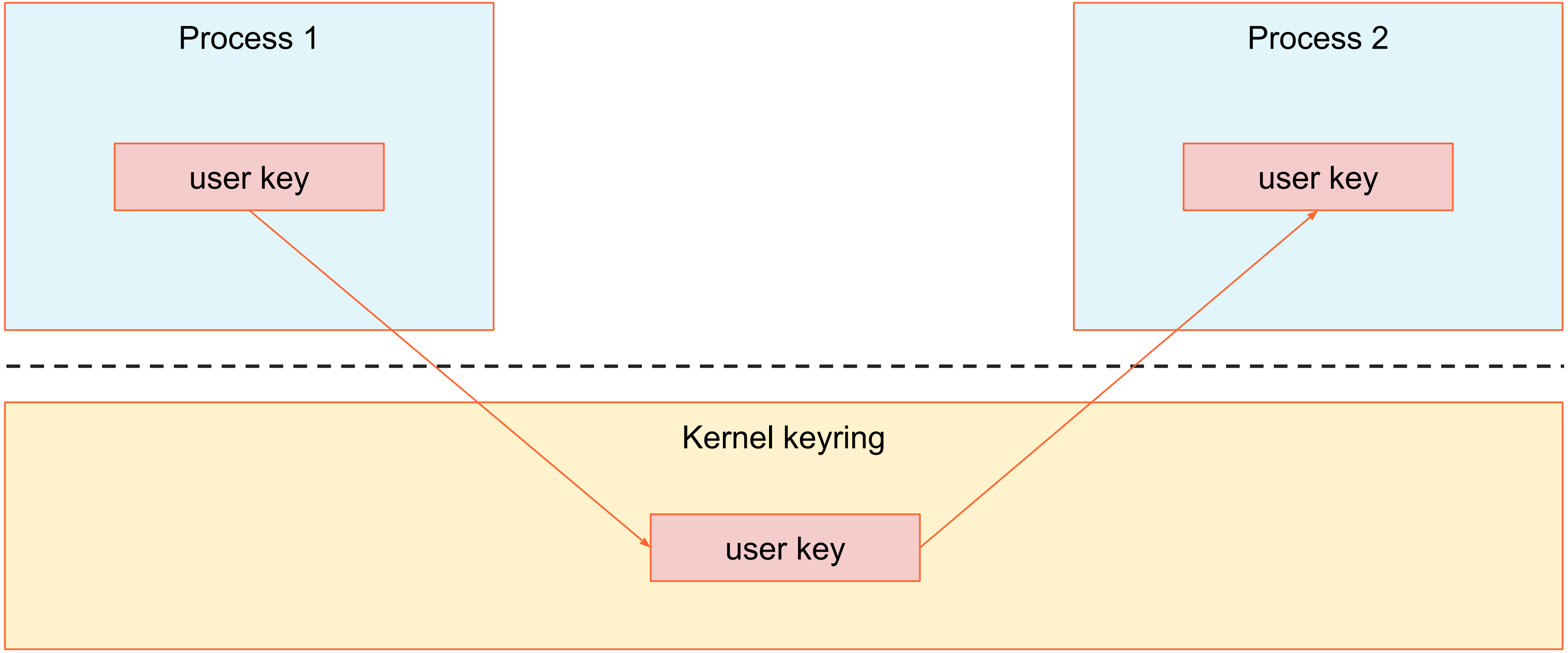
User keys



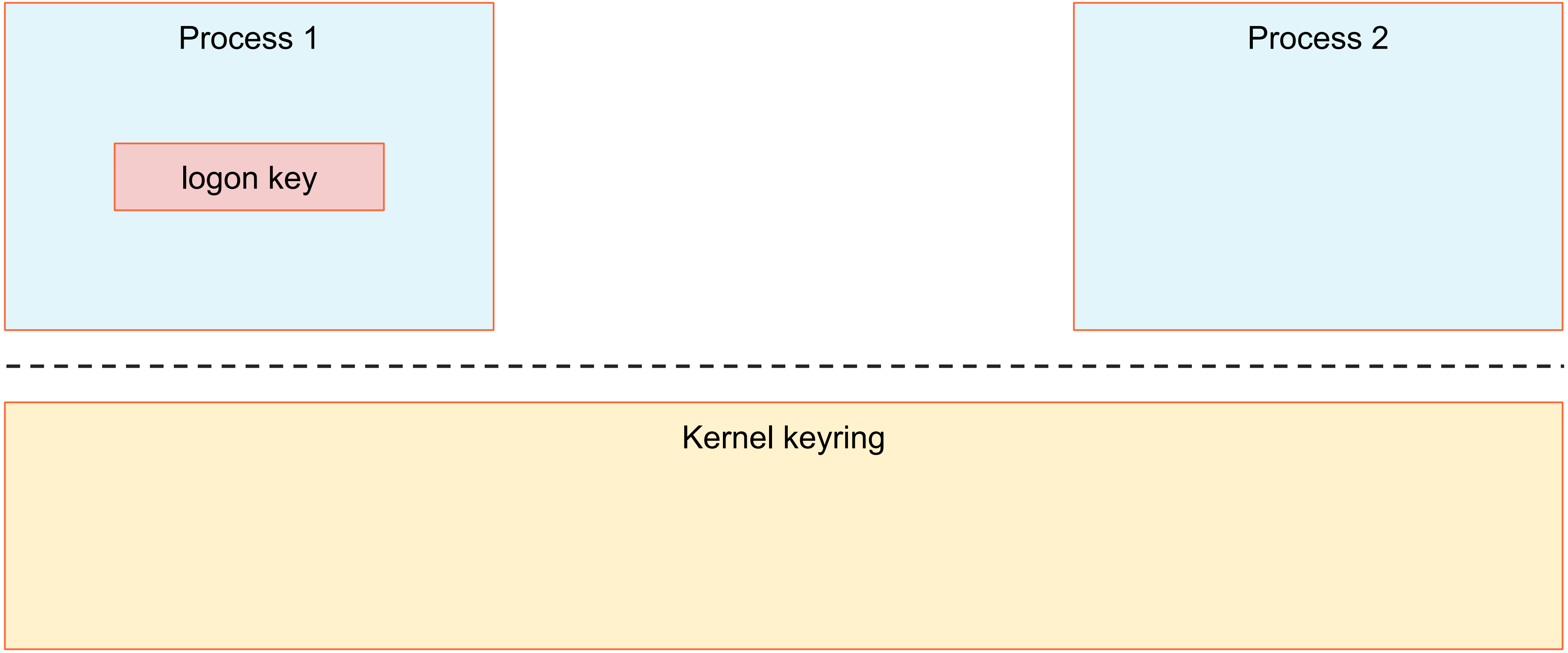
User keys



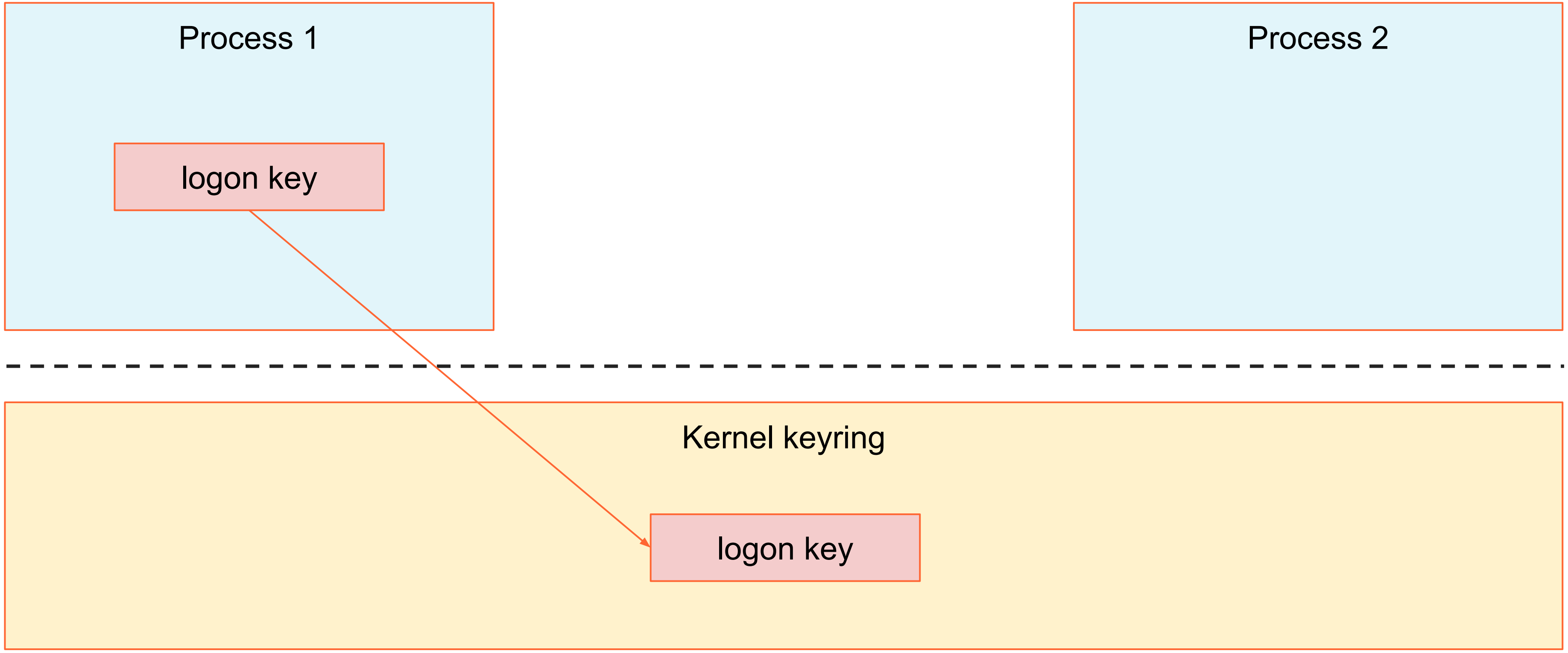
User keys


Process 1
user key
Process 2
user key
Kernel keyring
user key

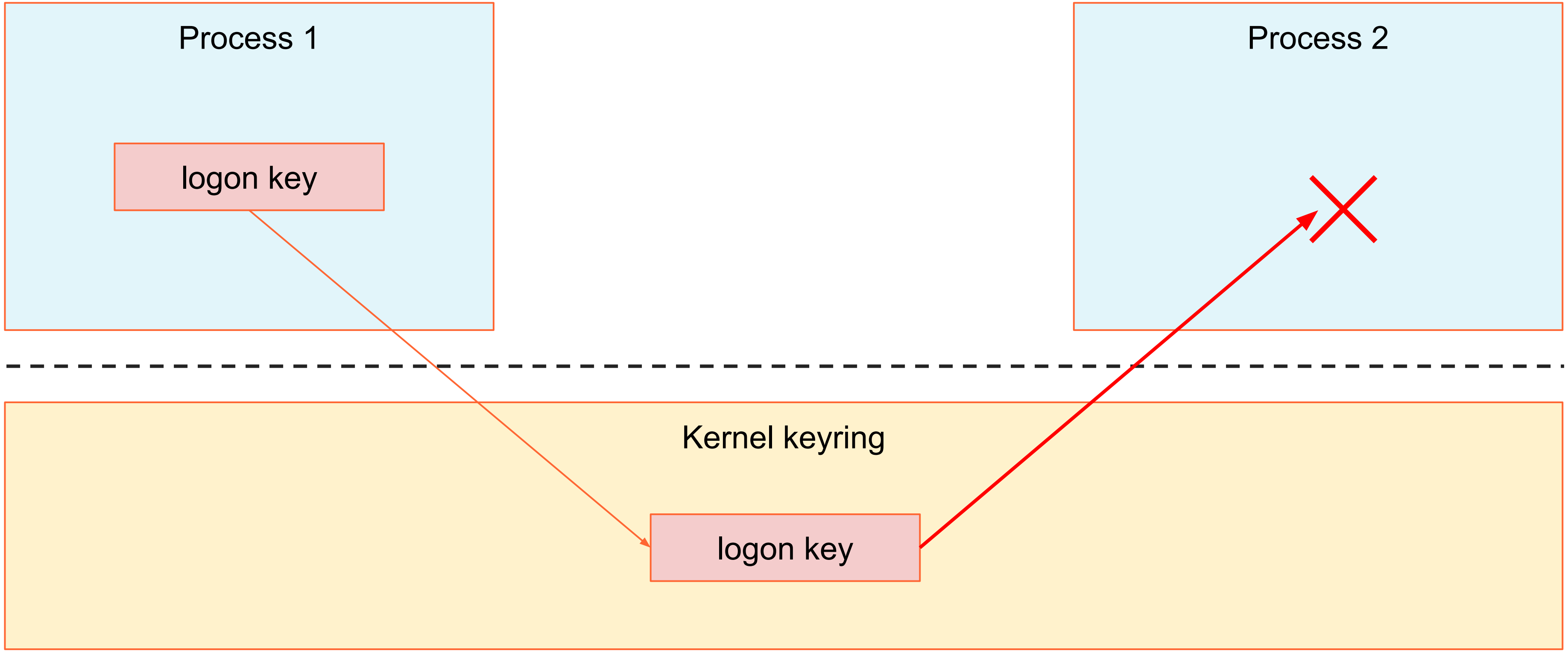
Logon keys



Logon keys

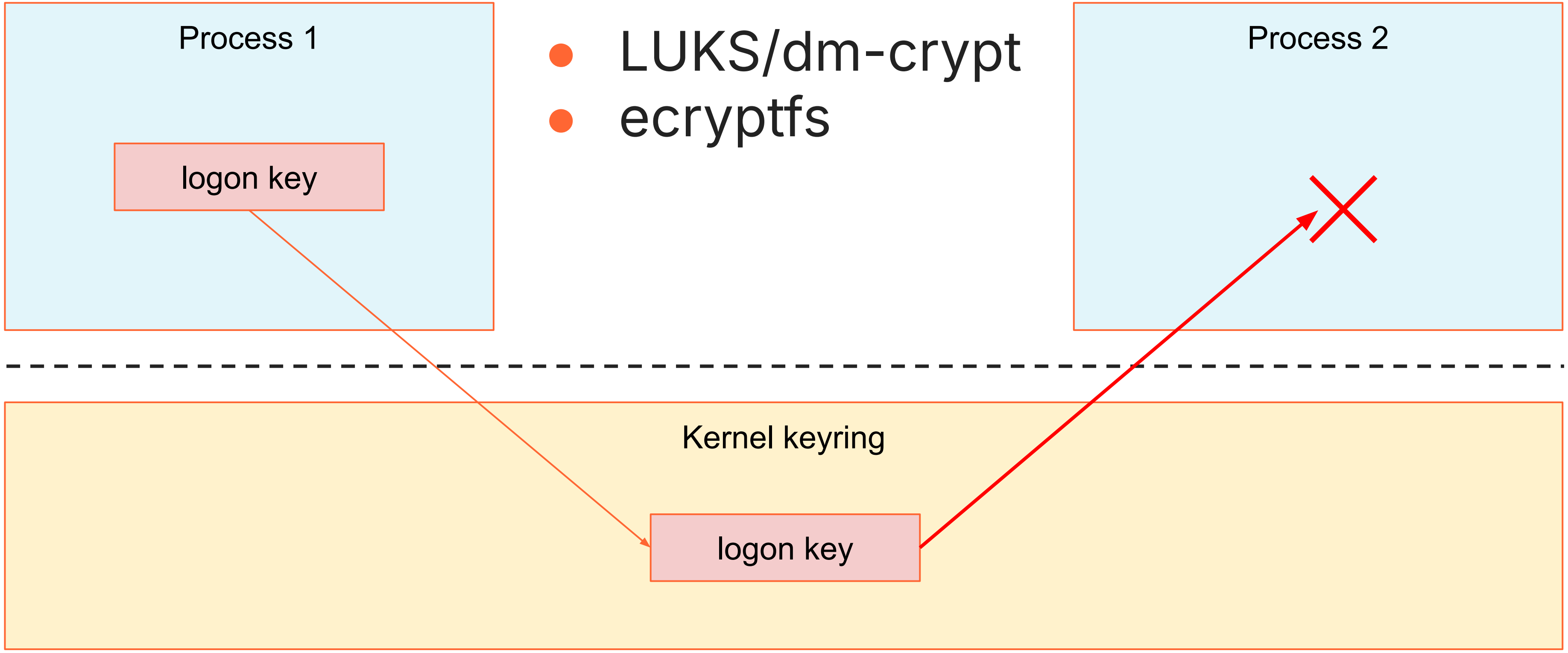


Logon keys



Logon keys

- LUKS/dm-crypt
- ecryptfs



Logon keys in LUKS/dm-crypt

```
ignat@dev:~$ sudo dmsetup table
luks-sda: 0 937670320 crypt aes-xts-plain64
:64:logon:cryptsetup:8f5af694-c4ce-4ed0-89a8-386f67980f70-d0 0
8:0 32768
luks-sdb: 0 937670320 crypt aes-xts-plain64
:64:logon:cryptsetup:e76176e1-b819-40a8-b92a-618cce2cffe5-d0 0
8:16 32768
```

Logon keys in LUKS/dm-crypt

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luks-sdb: 0 937670320 crypt aes-xts-plain64
:64:logon:cryptsetup:e76176e1-b819-40a8-b92a-618cce2cffe5-d0 0
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```
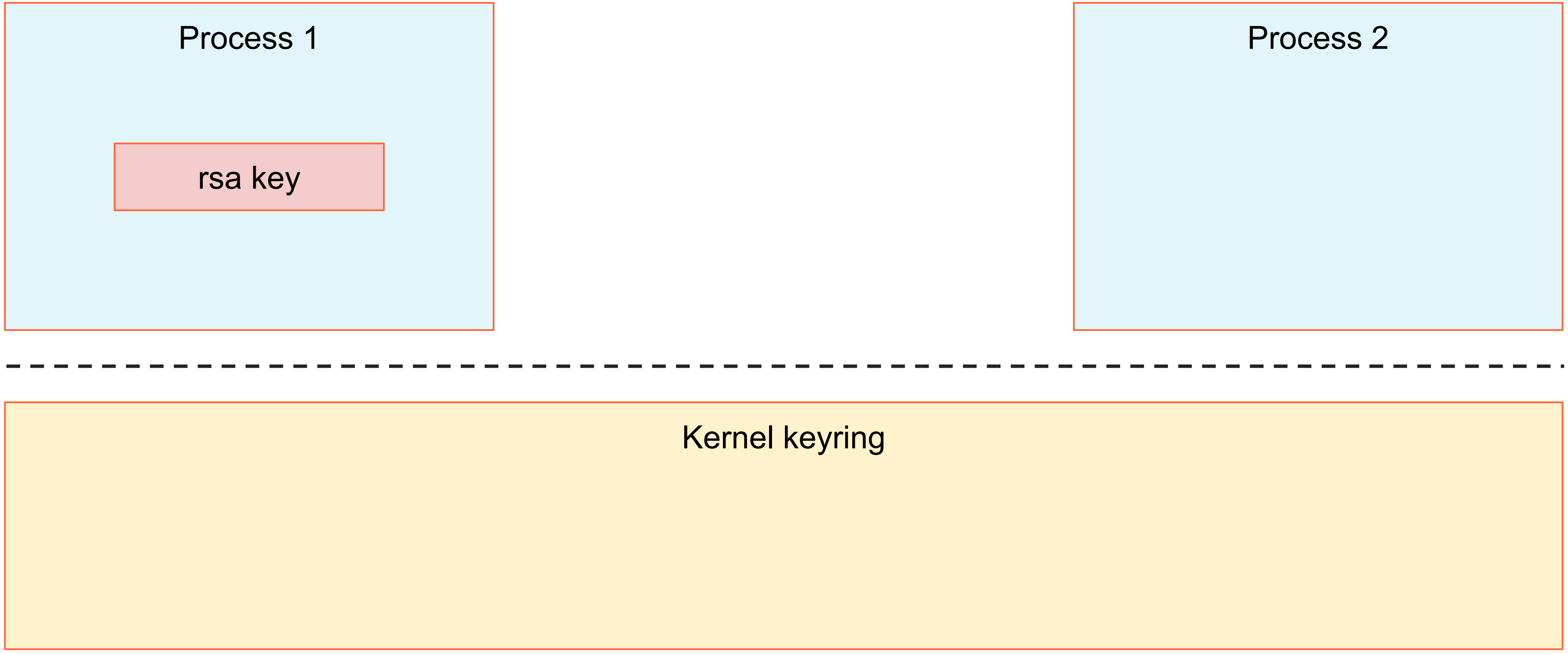
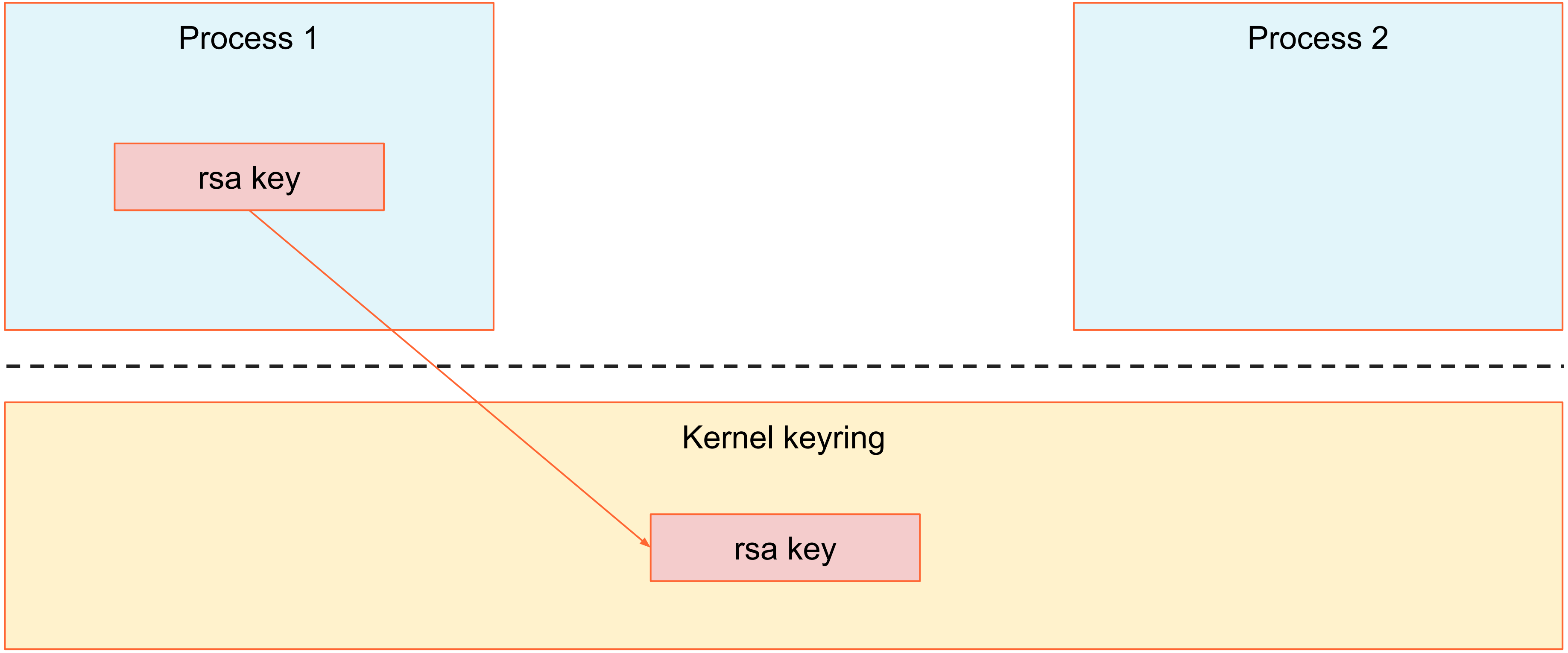
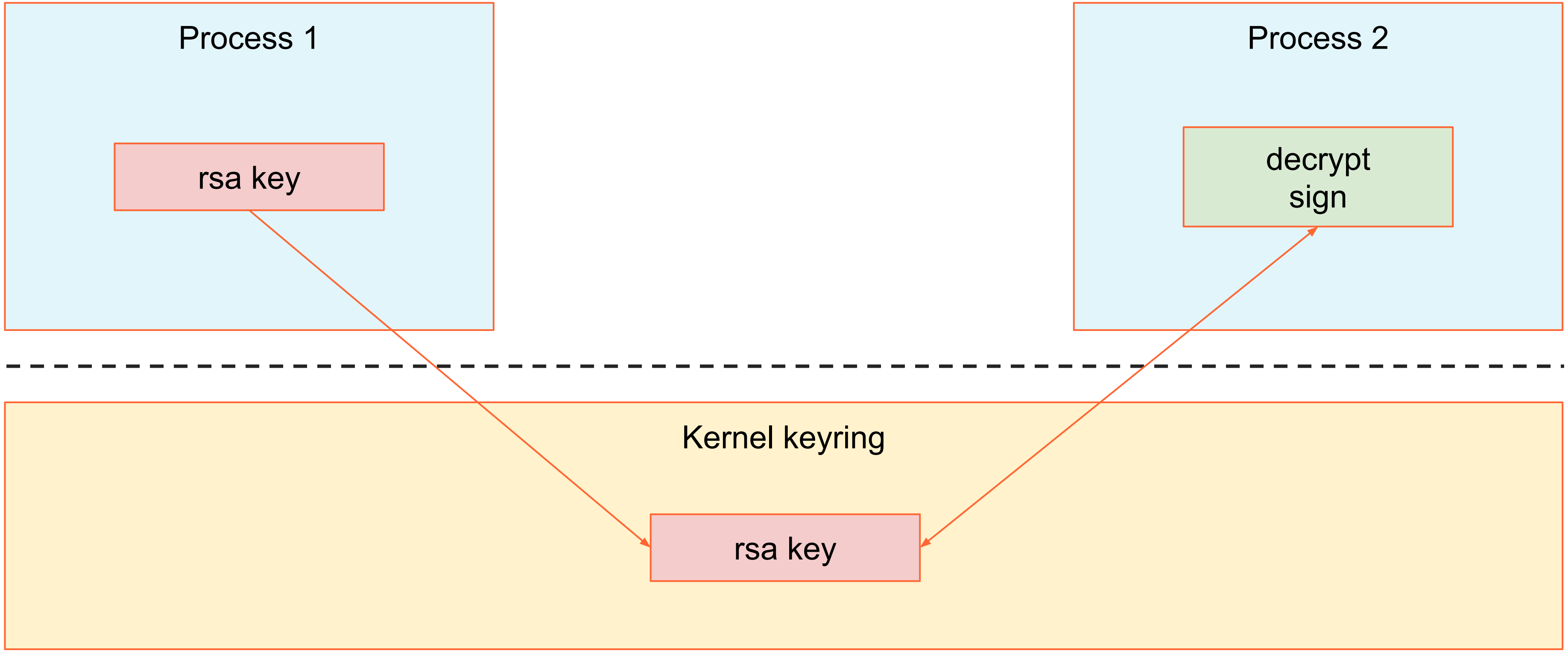

Asymmetric keys



Asymmetric keys



Asymmetric keys



Asymmetric key example (ssh-agent replacement)

```
ignat@dev:~$ openssl genrsa -out priv.pem
Generating RSA private key, 2048 bit long modulus (2 primes)
..........+++++
...........+++++
e is 65537 (0x010001)
ignat@dev:~$ openssl rsa -in priv.pem -pubout -out pub.pem
writing RSA key
```

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ignat@dev:~$ openssl pkcs8 -in priv.pem -topk8 -outform DER -nocrypt -out
priv.p8
```

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ignat@dev:~$ cat priv.p8 | keyctl padd asymmetric "rsa-key" @s
717848853
```

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ignat@dev:~$ echo abc | openssl sha256 -binary > abc.sha256
ignat@dev:~$ keyctl pkey_sign %asymmetric:rsa-key 0 abc.sha256 enc=pkcs1
hash=sha256 >abc.sig
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ignat@dev:~$ echo abc | openssl sha256 -verify pub.pem -signature abc.sig
Verified OK
```

Asymmetric key example (ssh-agent replacement)

https://blog.cloudflare.com/the-linux-kernel-key-retention-service-and-why-you-should-use-it-in-your-next-application/

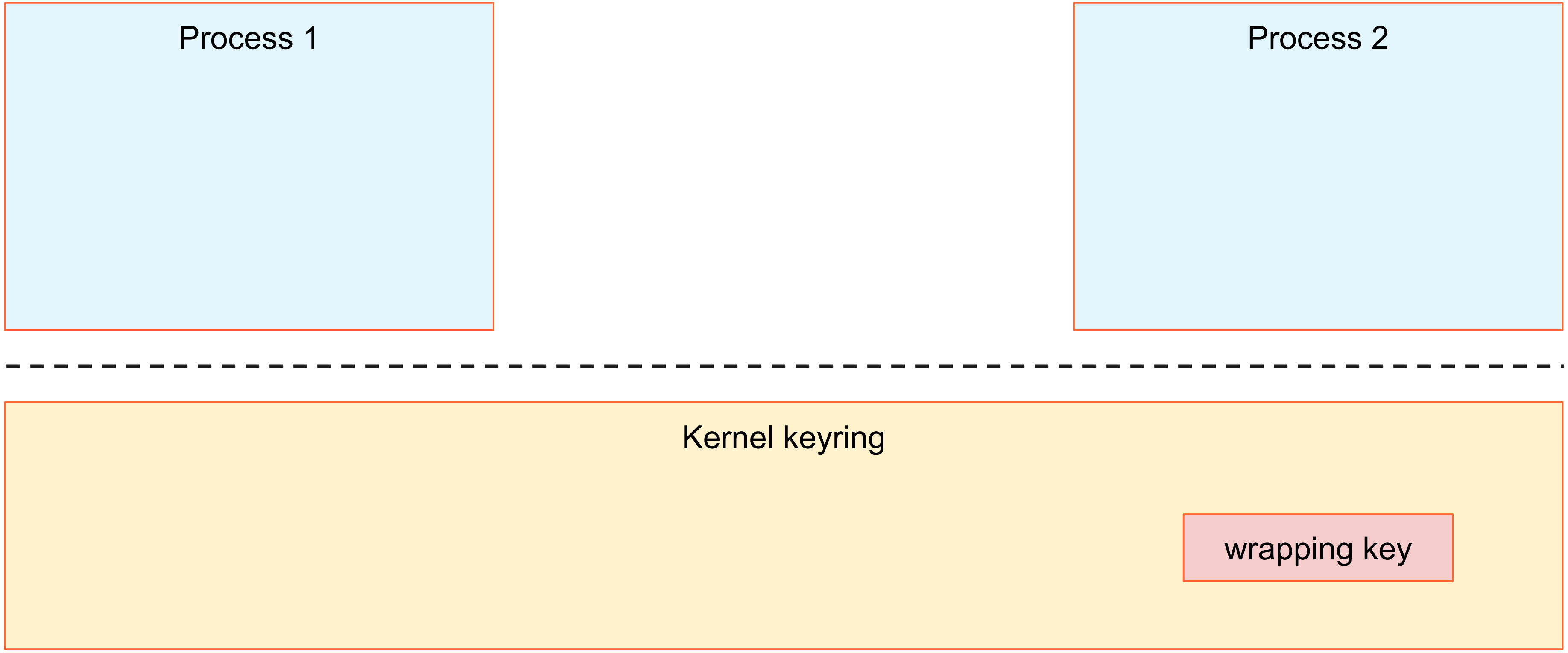
Keystore as a key management building block

Secure key distribution and provisioning

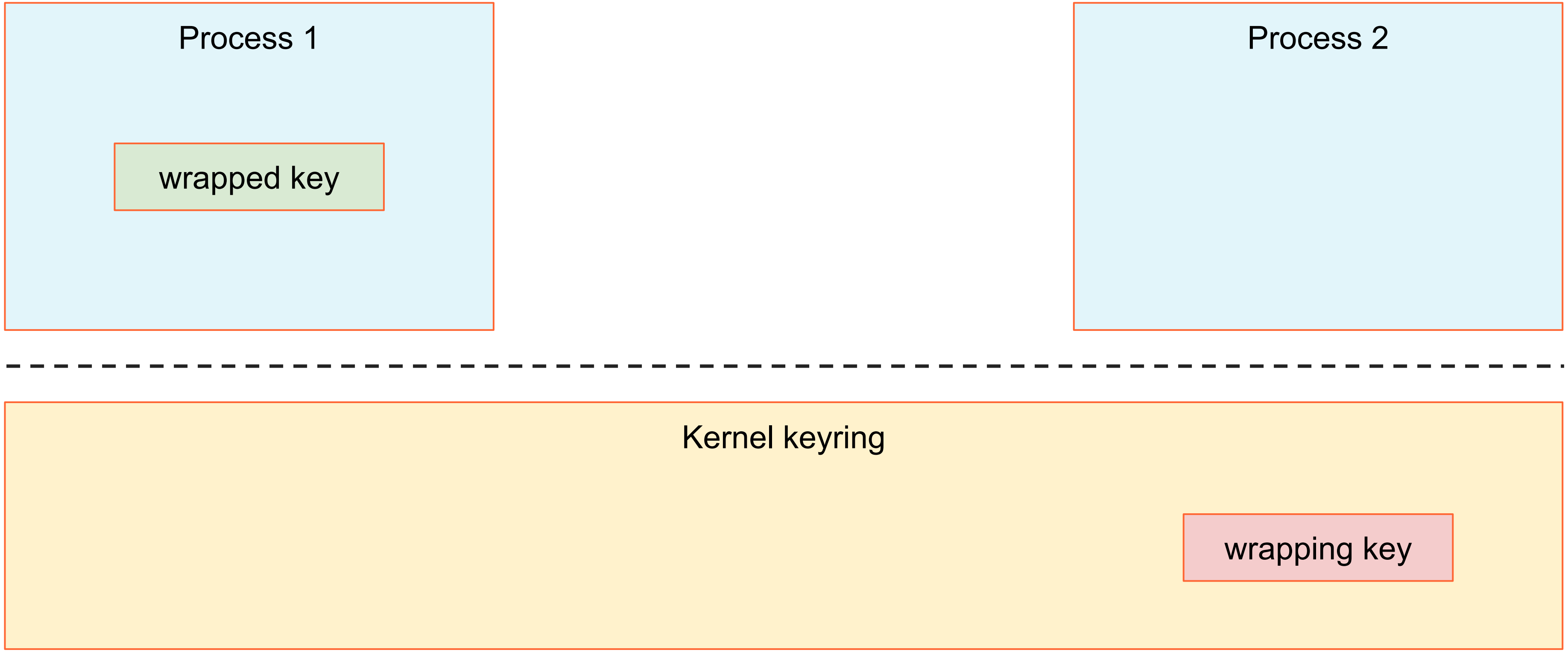
Minimizing cryptographic material exposure

How can we provision application keys without the cryptographic material ever being exposed to the userspace applications?

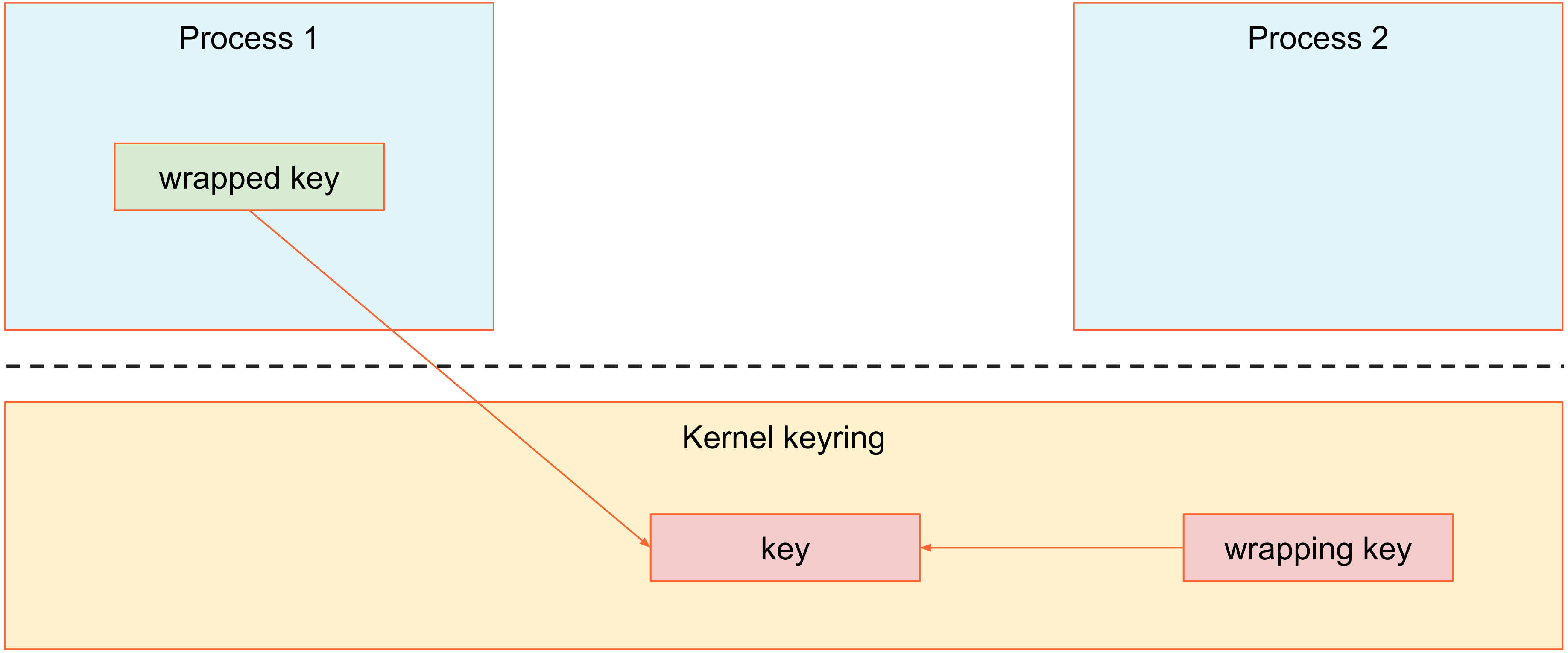
Encrypted keys



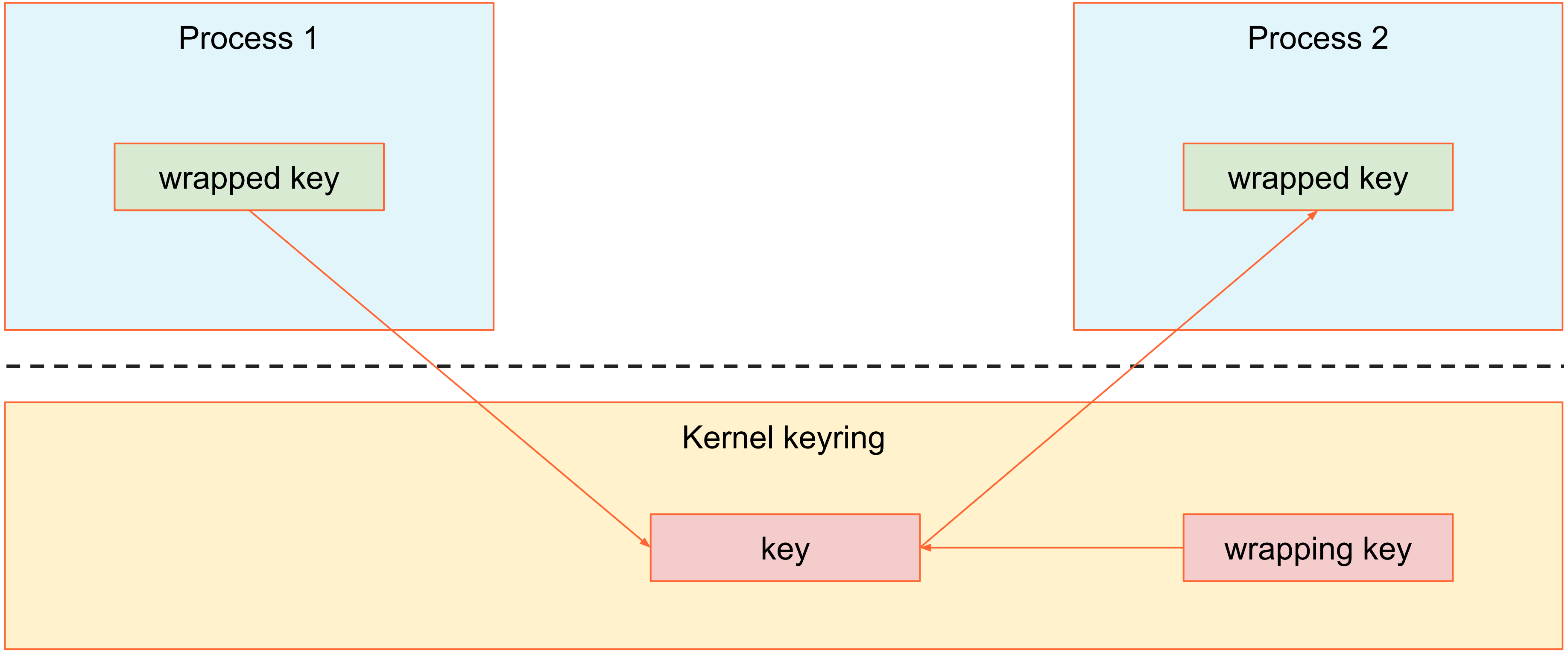
Encrypted keys



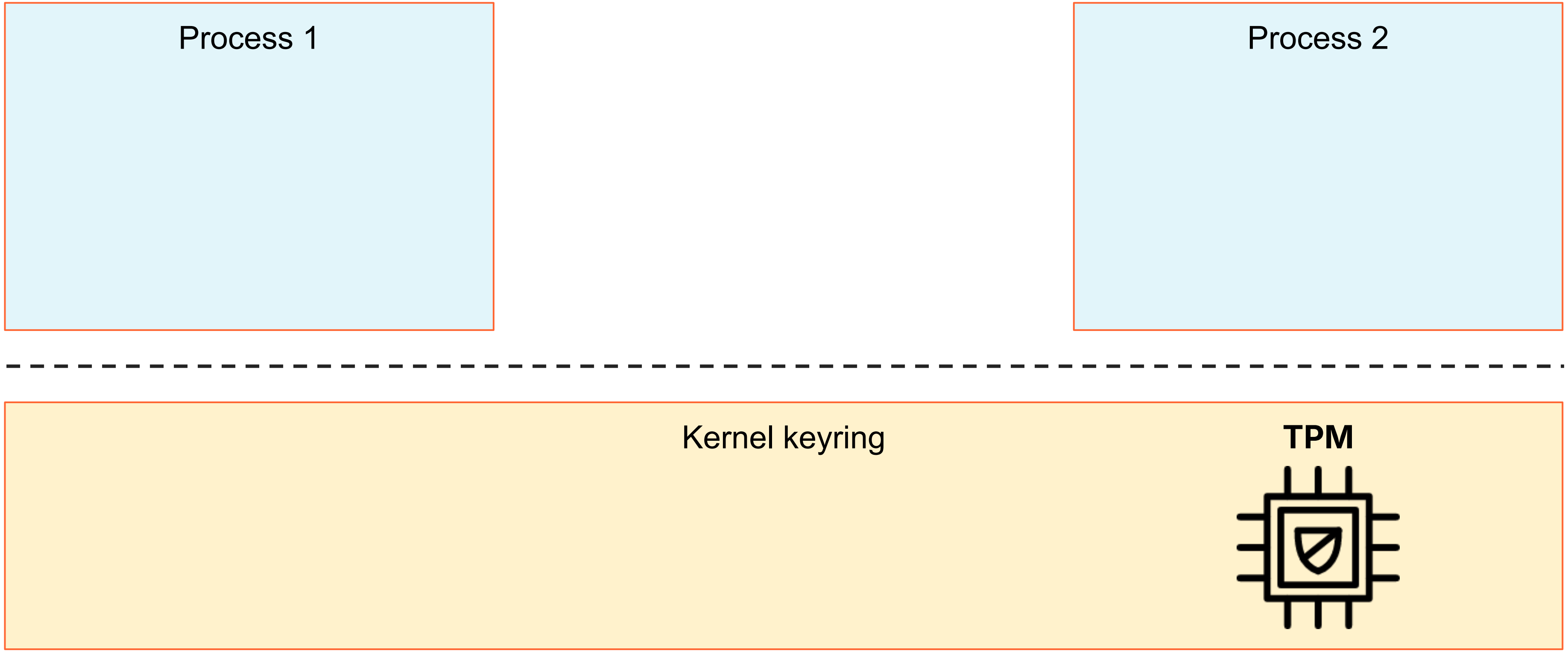
Encrypted keys



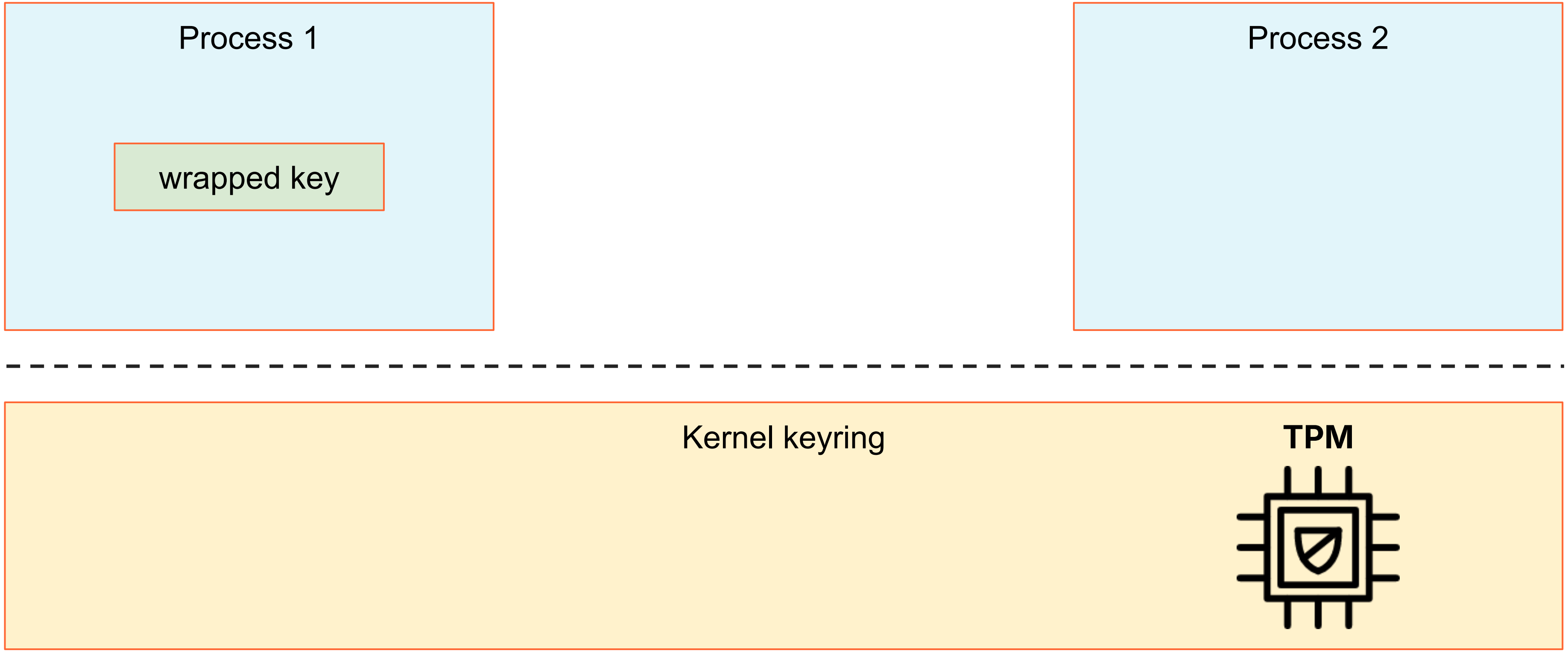
Encrypted keys



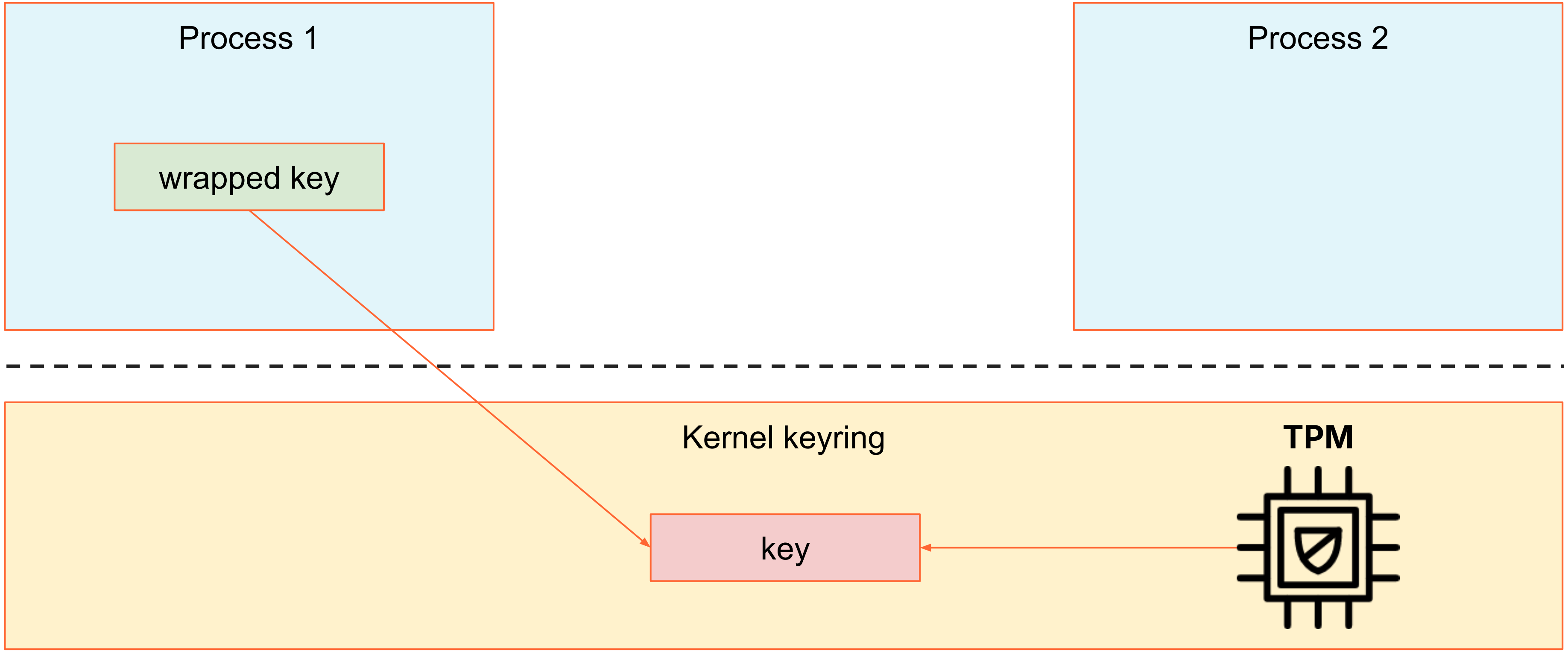
Trusted keys



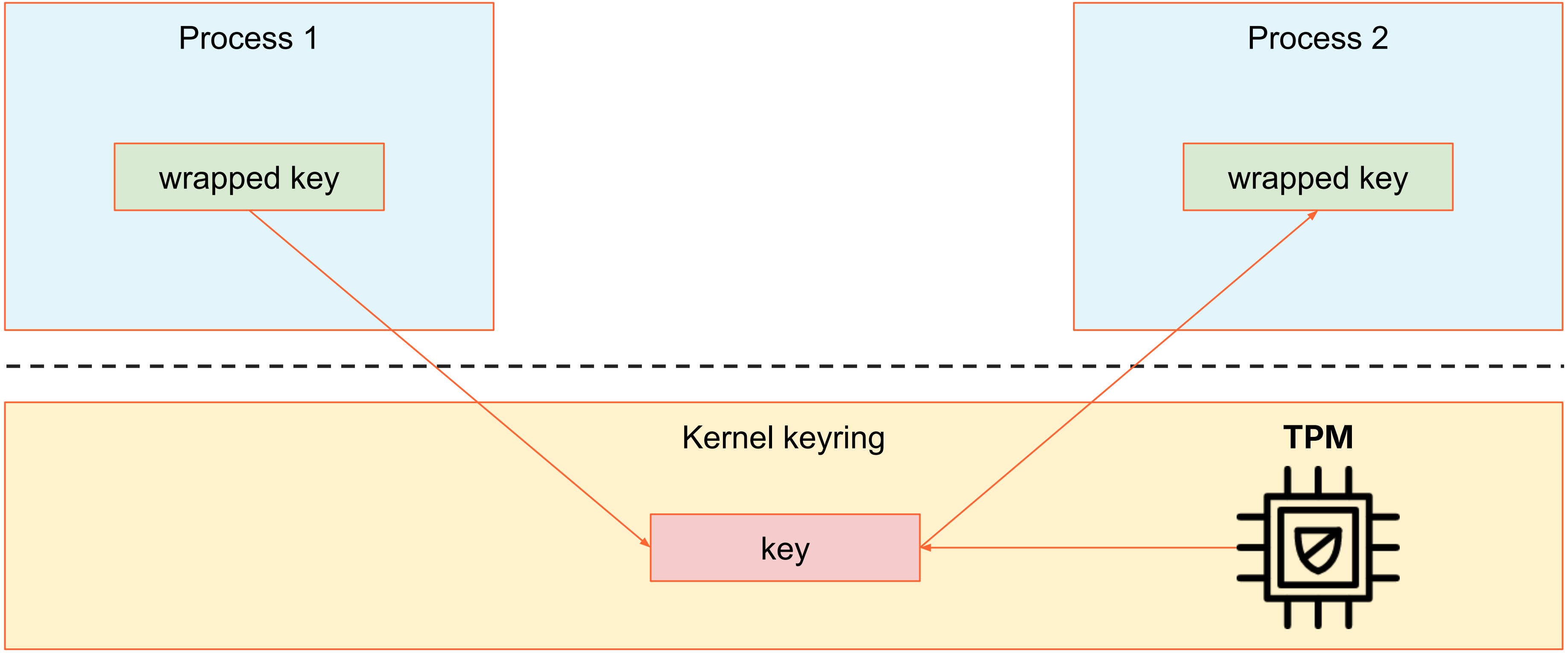
Trusted keys



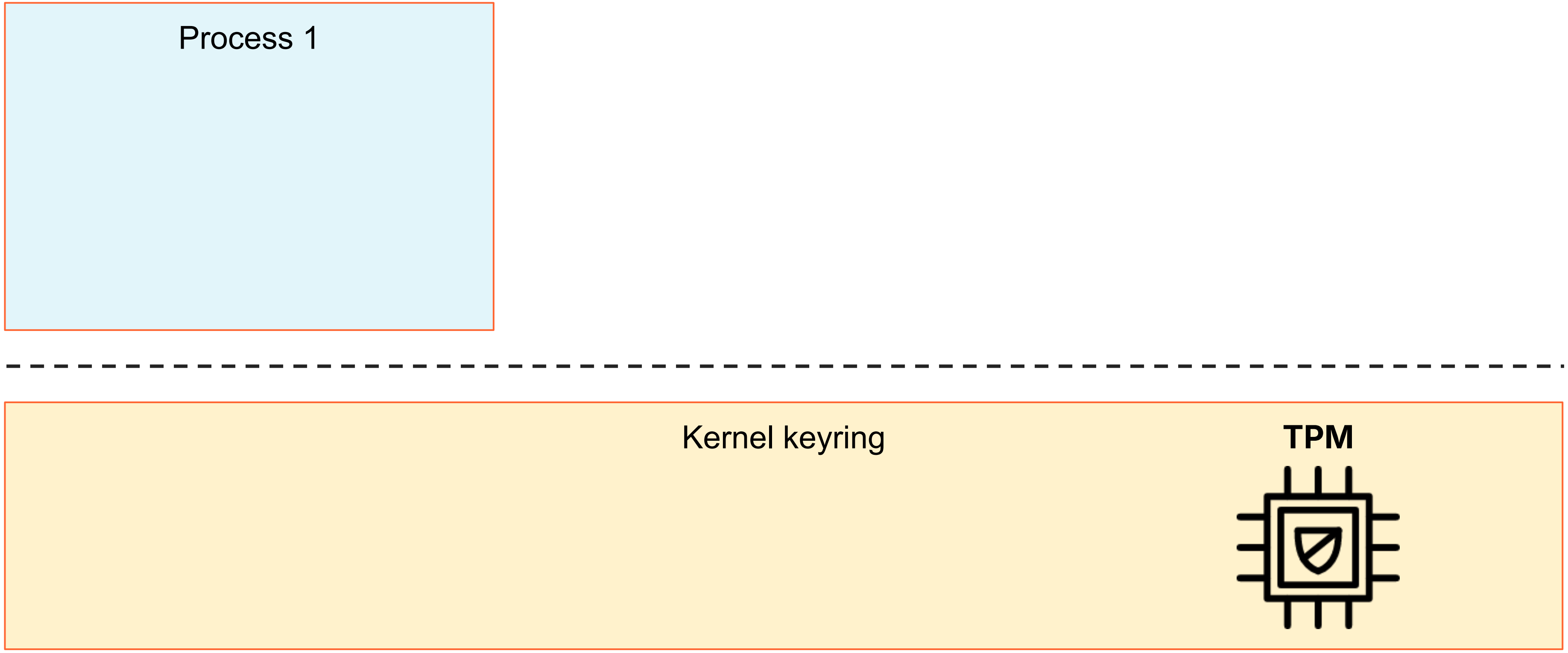
Trusted keys



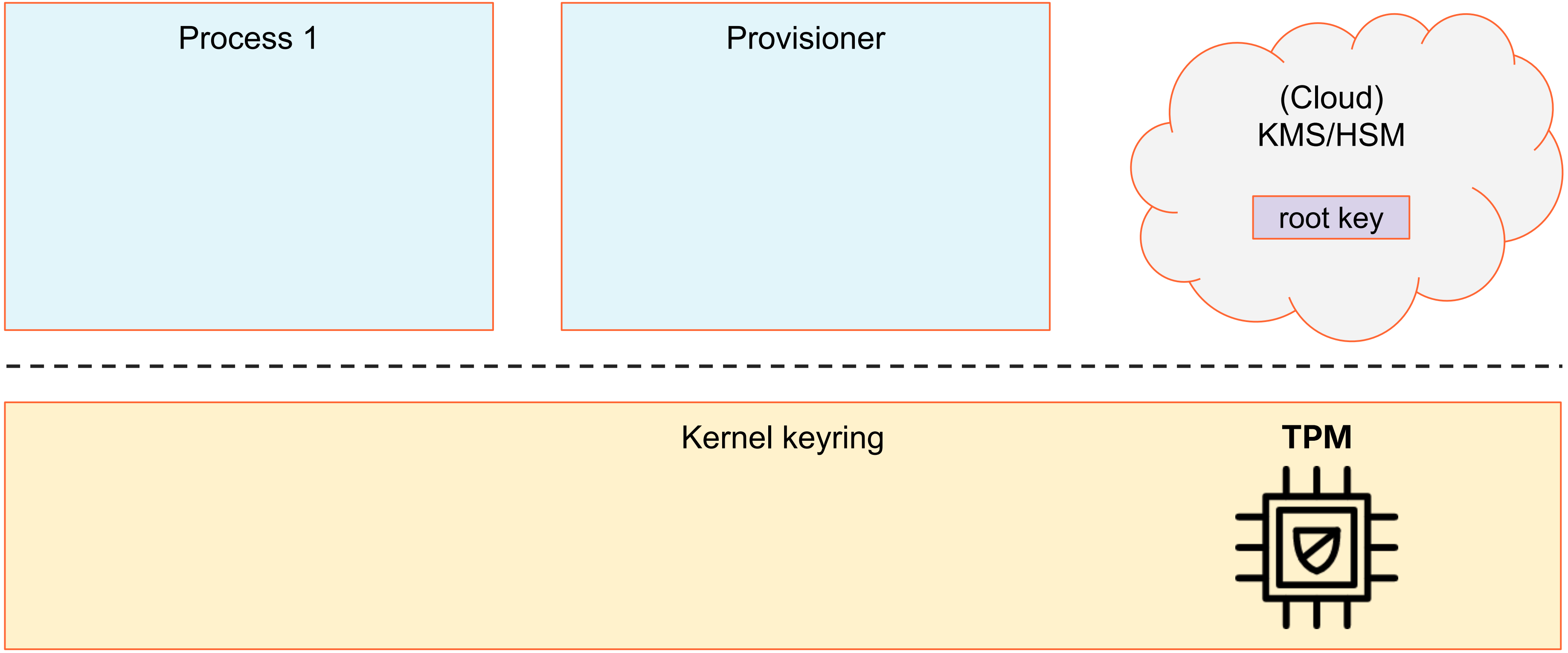
Trusted keys



Combined schema



Combined schema



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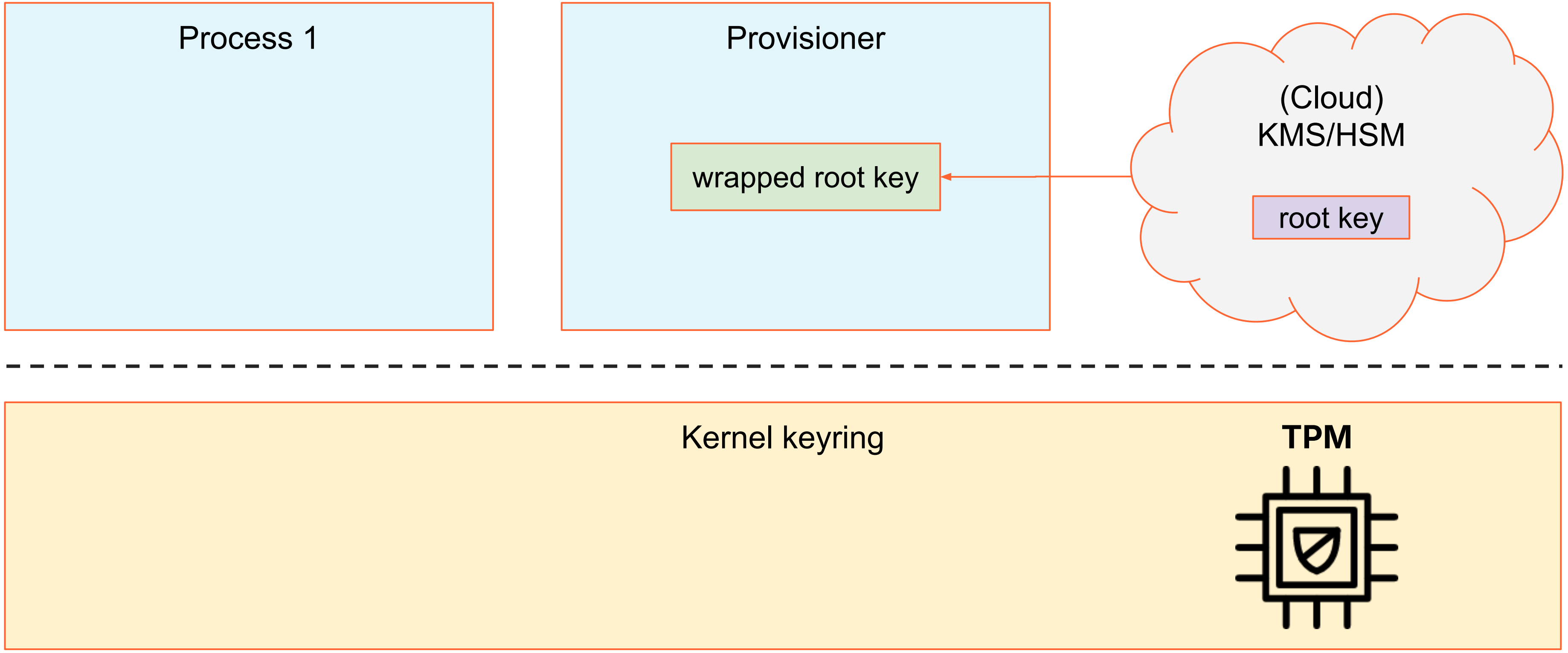

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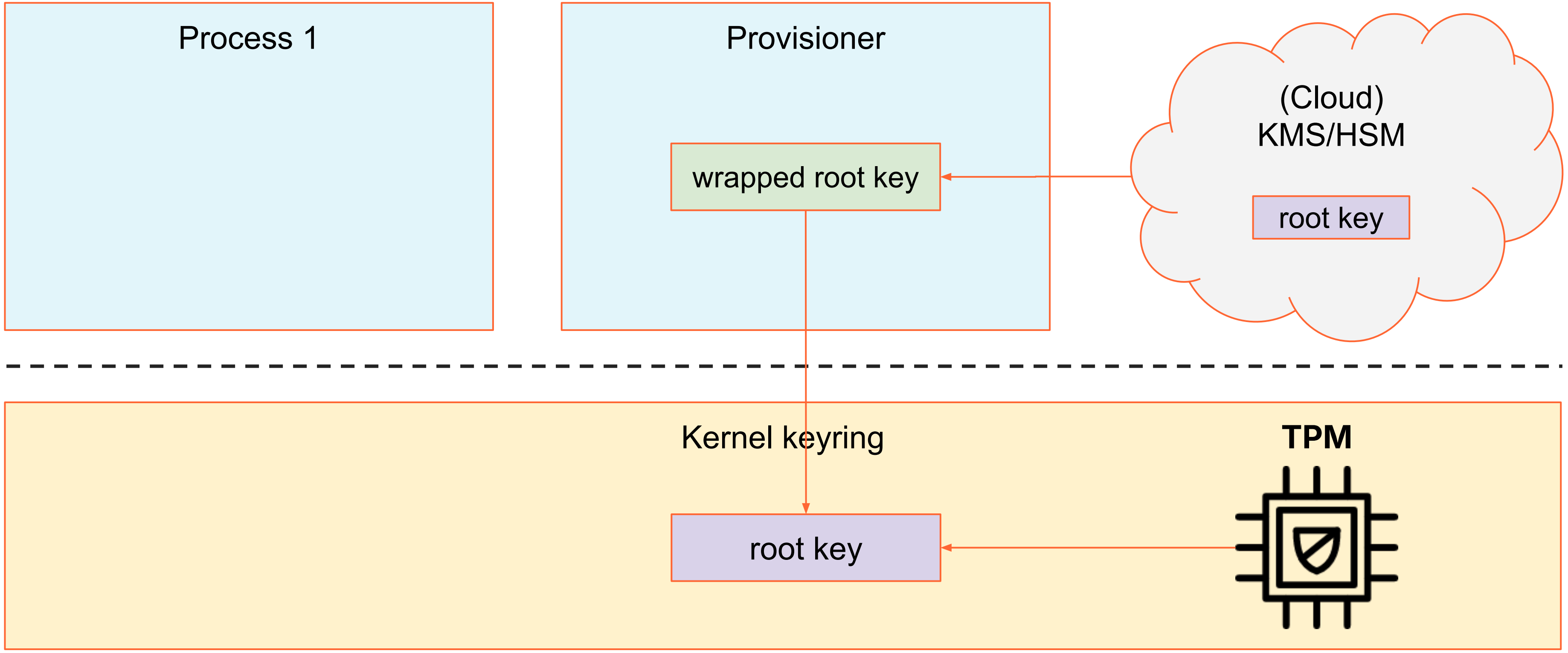

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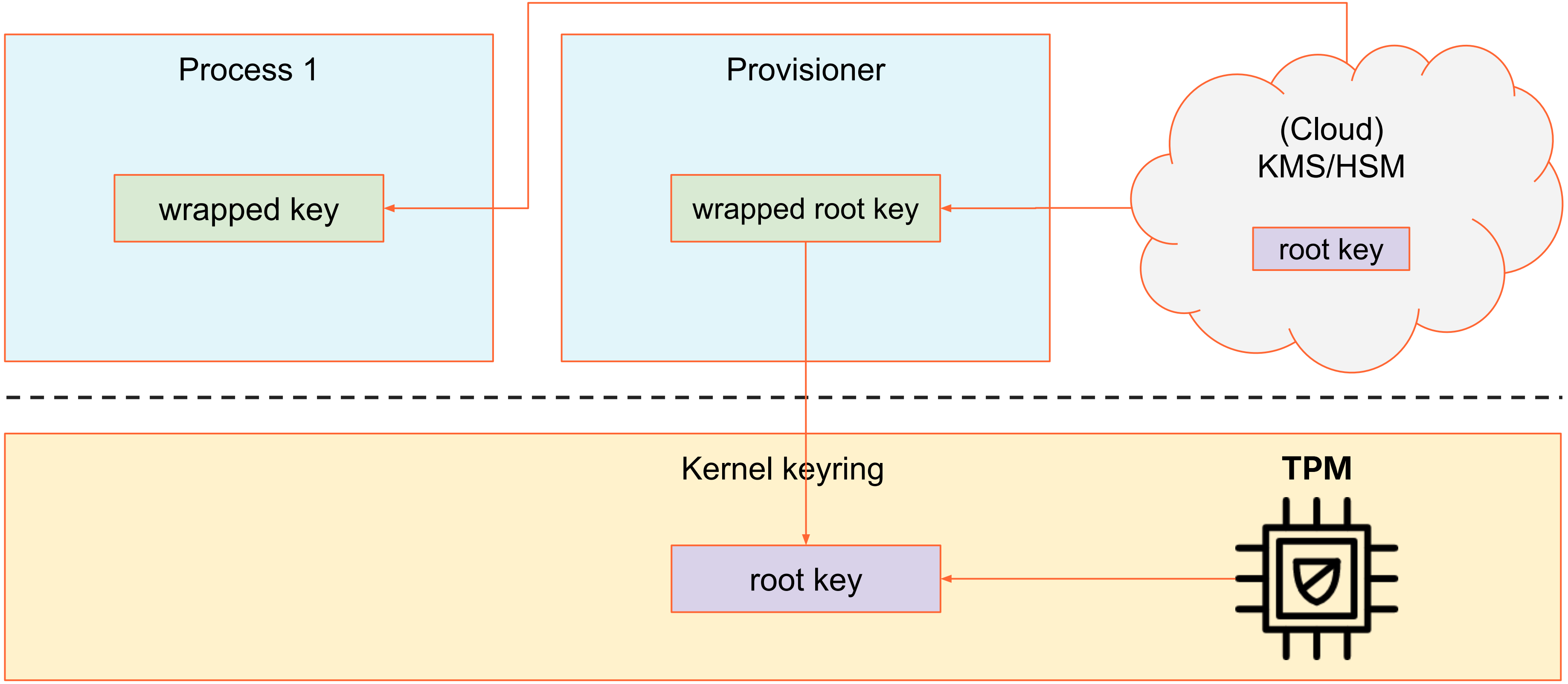

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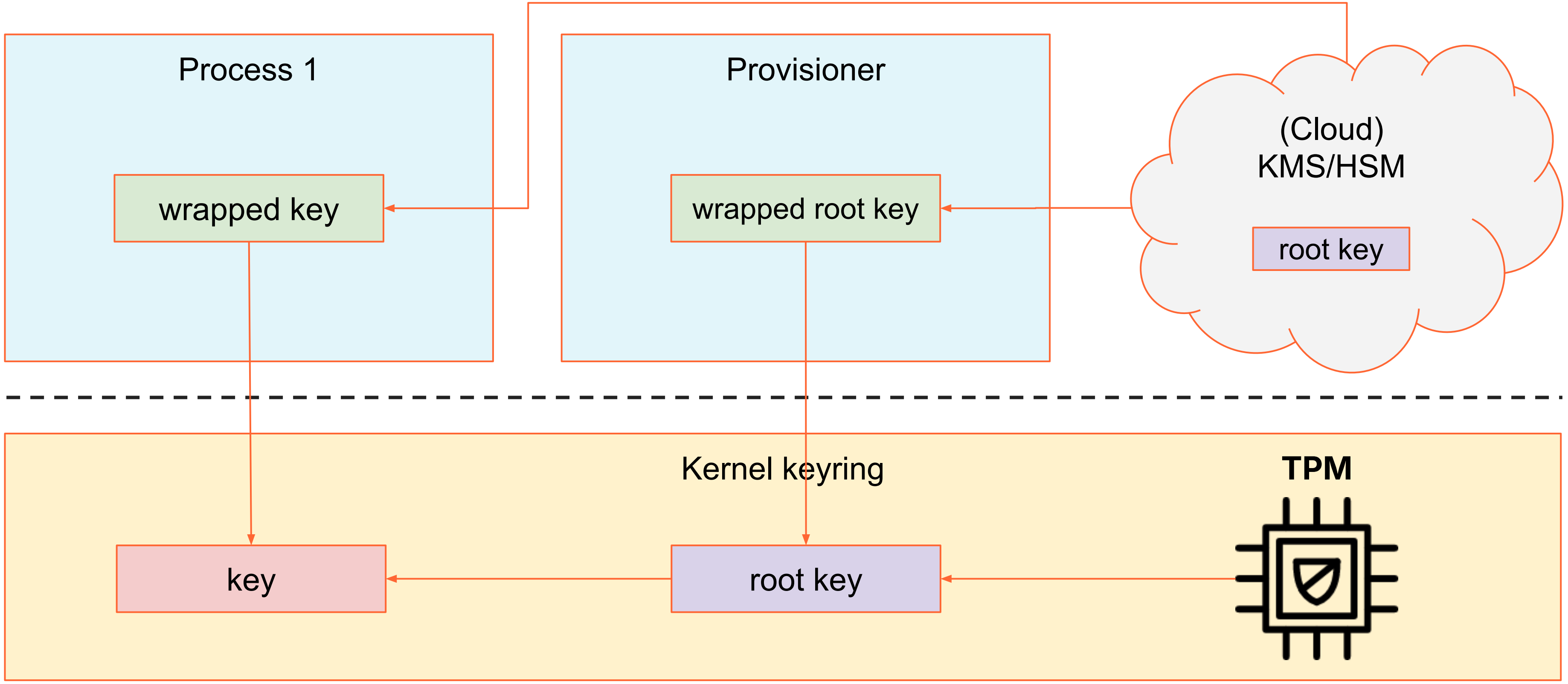

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CLOUDFLARE

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        - KMS/HSM URI endpoints in each application configuration
        - application code for client ↔ KMS/HSM communication protocol
    - little administrative control of the created Kernel key objects
        - invalid key permissions may even leak the key
    - KMS/HSM needs to somehow authenticate each requesting application

Linux Kernel key provisioning

- `add_key(2)`
  - adds the key to the specified keyring with the provided payload
  - payload is interpreted according to the key type
    - nothing for user/logon
    - private/public for asymmetric
    - wrapped for encrypted/trusted
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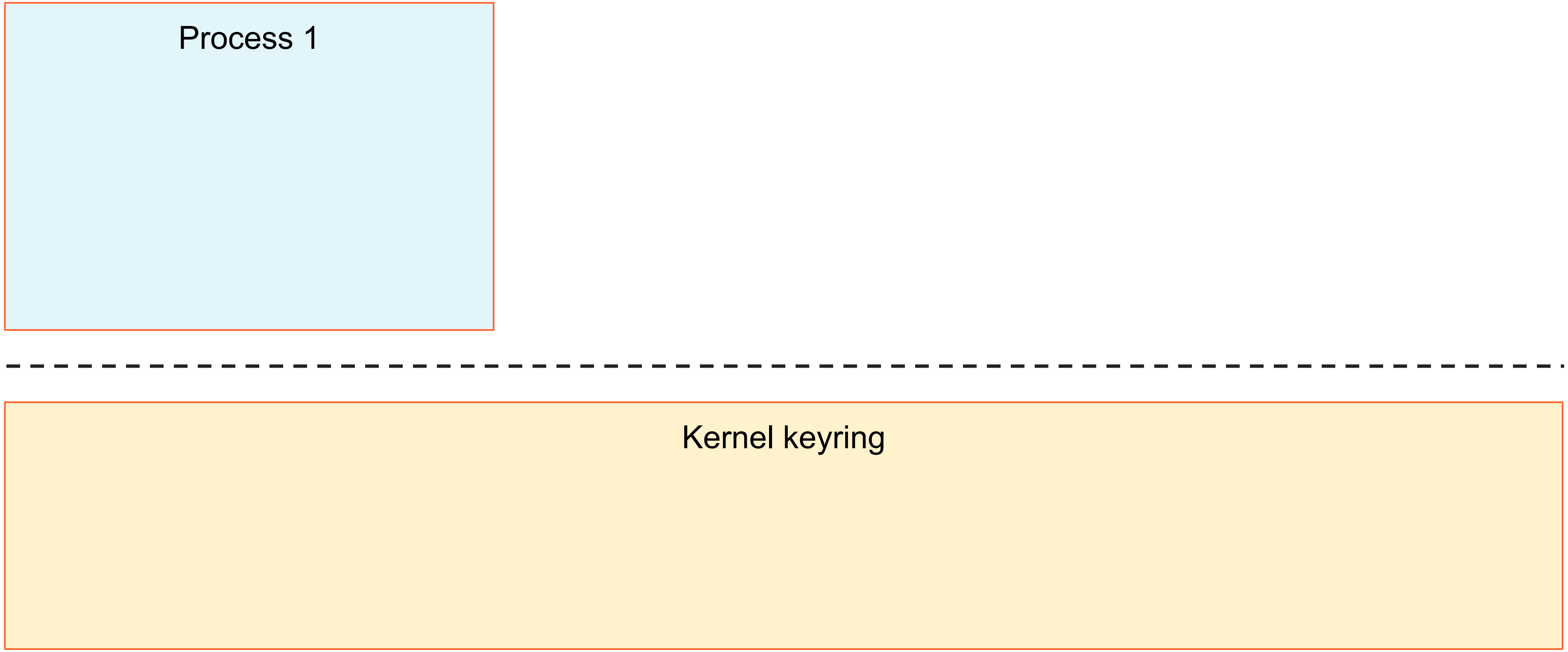
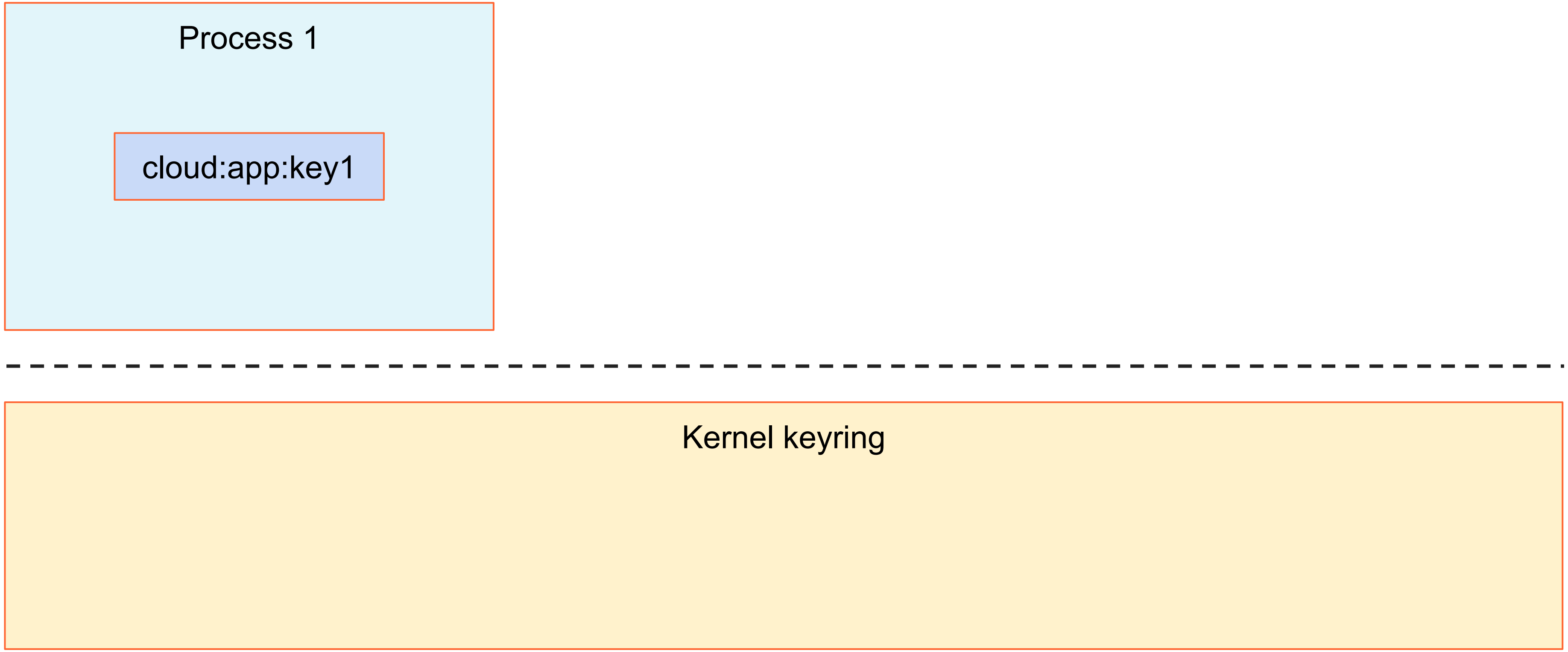
  - https://man7.org/linux/man-pages/man2/add_key.2.html
- `request_key(2)`
  - a key is requested from the kernel based on a string id
    - the kernel is expected to provide the payload
  - if the kernel cannot satisfy the request, it calls a “helper” program
    - the helper program can hook into external KMS/HSM
    - the helper program can adjust key permissions
  - a more centralised and transparent API to add keys to the keyring
  - https://man7.org/linux/man-pages/man2/request_key.2.html

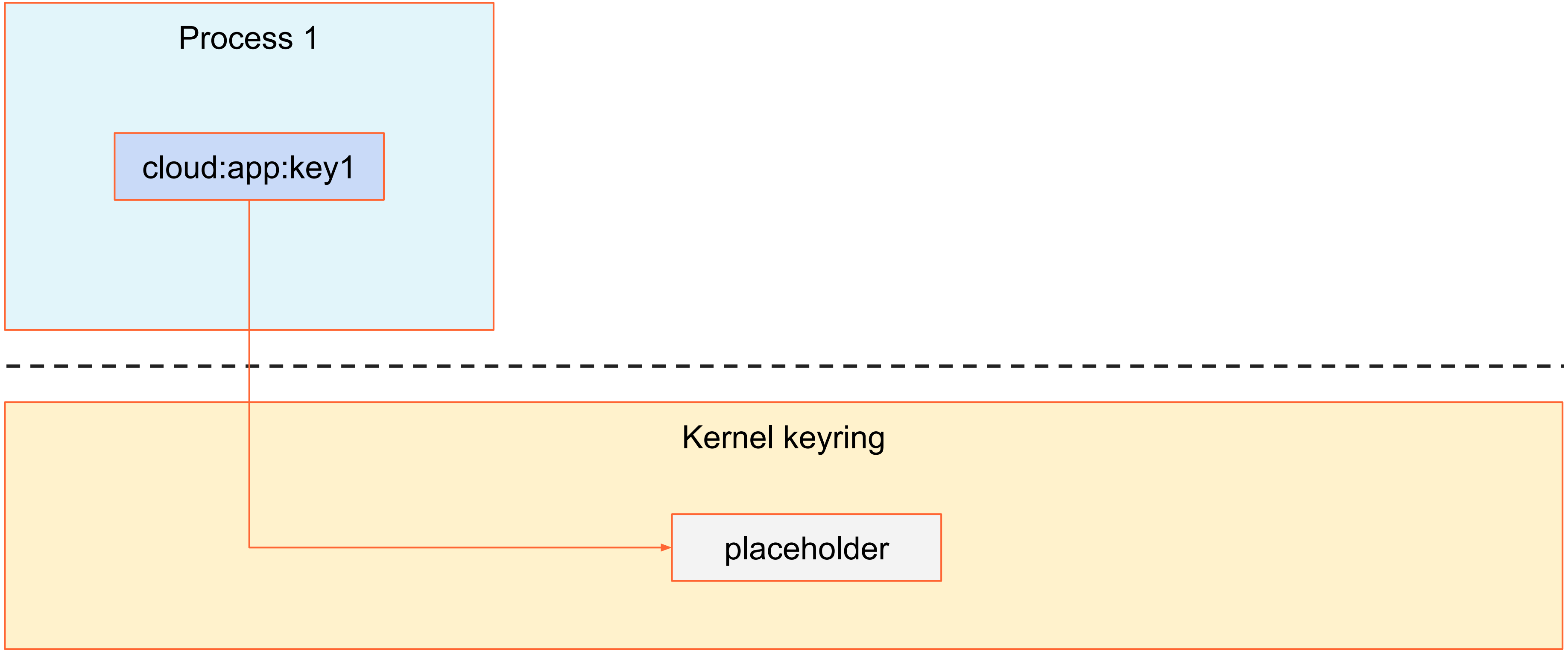
request_key(2) syscall



request_key(2) syscall



request_key(2) syscall



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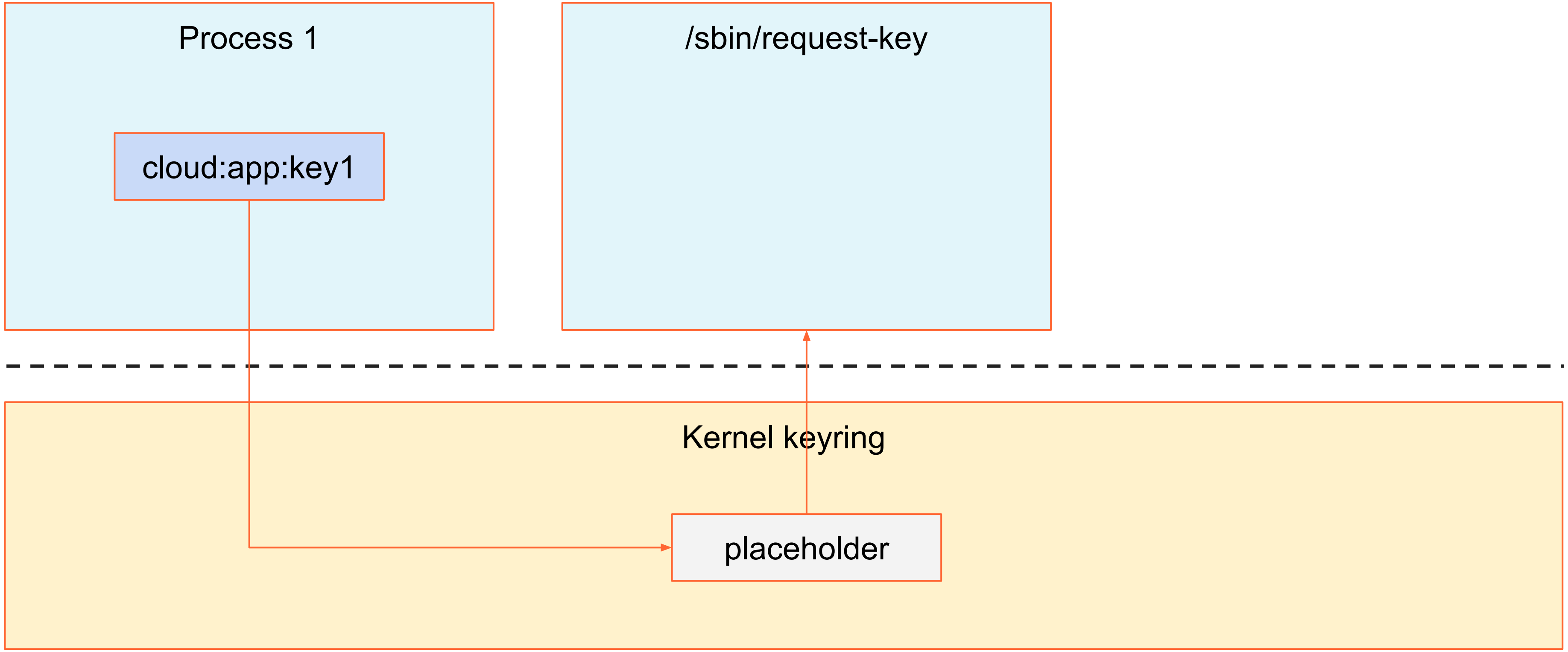

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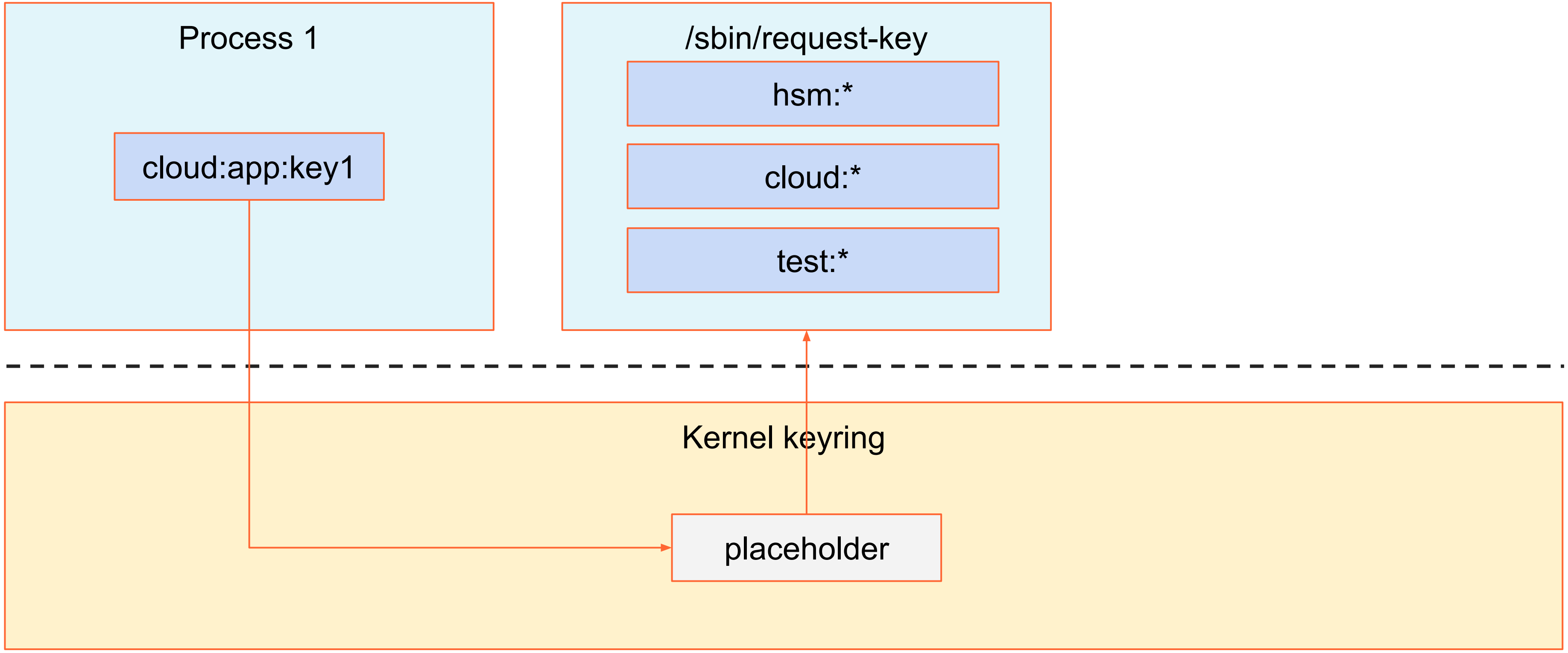

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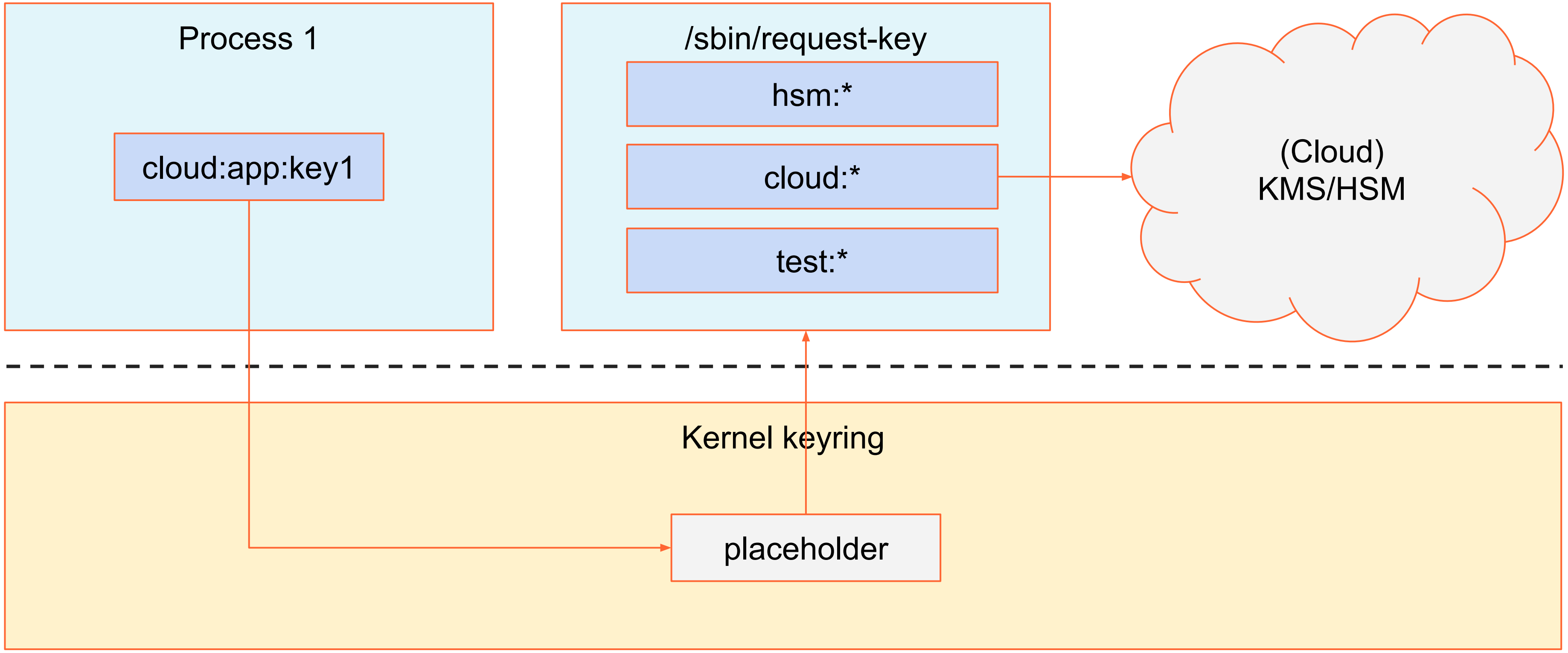

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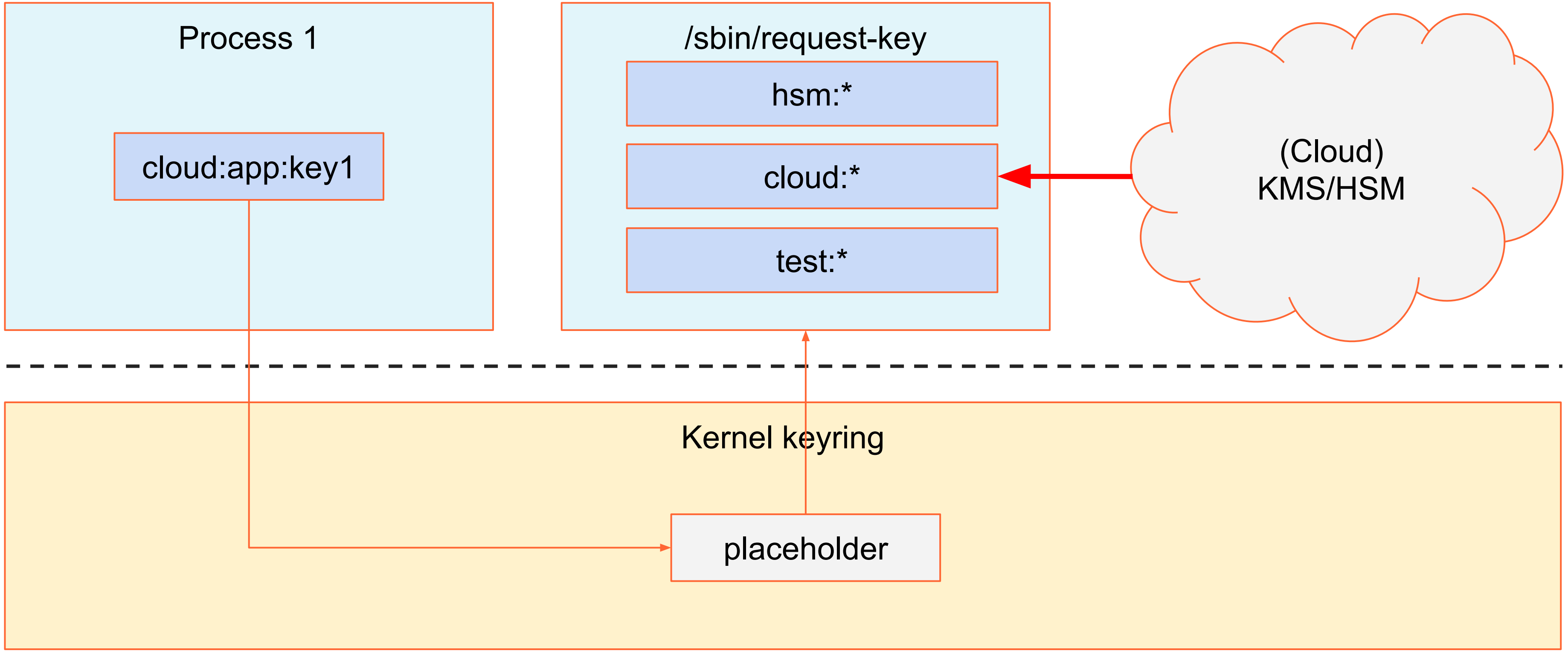
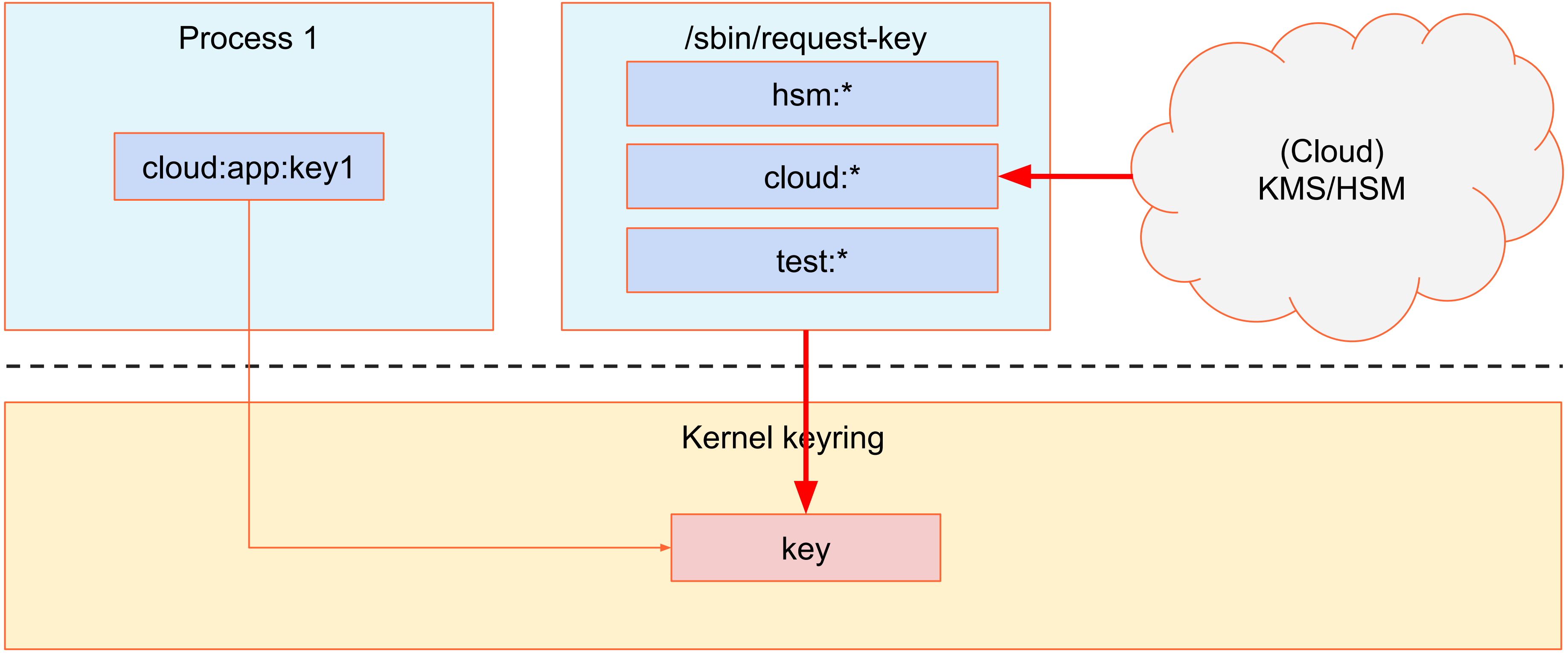


request_key(2) syscall



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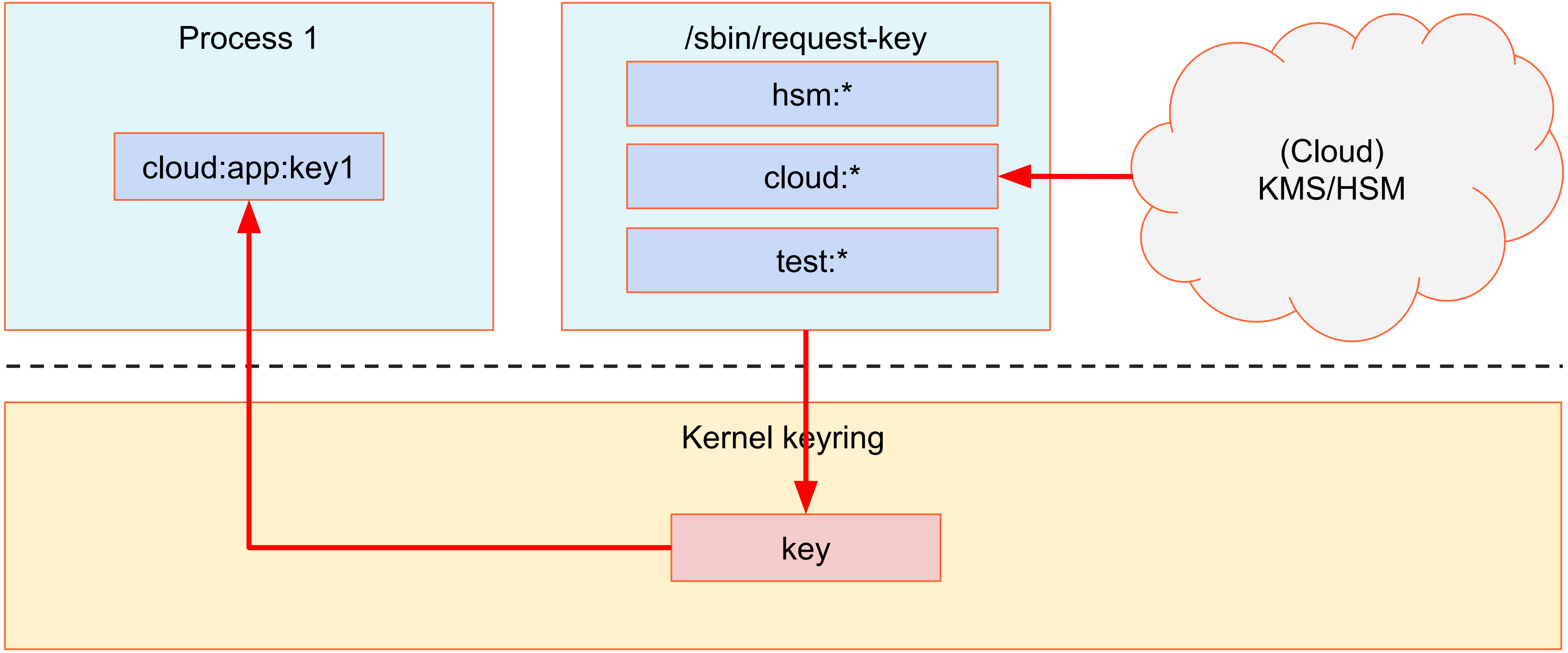

request_key(2) advantages

- A single centralised OS API to request keys for applications
  - no KMS/HSMs connection strings, URIs etc in the config
  - just a “free-form” string id
  - fully decoupled from key storage backends

request_key(2) advantages

- A single centralised OS API to request keys for applications
  - no KMS/HSMs connection strings, URIs etc in the config
  - just a “free-form” string id
  - fully decoupled from key storage backends
- A more secure way to instantiate keys in the Kernel
  - only the Kernel created process can instantiate the requested key
  - callout process can perform additional security checks
    - ex. requestor uid, gid, pid, executable path, package name etc.
  - can support multiple key storage backends
    - backends can be swapped transparently to the applications
  - only the callout process needs to be authenticated on the backend
  - backend connectors can be written in any language

Minimizing cryptographic material exposure

With `request_key(2)` support the key management and distribution becomes a core service of the operating system

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https://gist.github.com/ignatk/9038d139e983ca355136aec7ec2d9bfc

TPM derived keys via request_key(2)

```
ignat@dev:~$ cat /etc/request-key.d/derived.conf
create * tpm2:derived:* * |/home/ignat/git/tpm-derived-keys/derived.py %t
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302248702
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:hex:21e346d301e9a3be6053505bd753cf68515fd152b5665ead6a4ec253371d2716
```

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ignat@dev:~$ keyctl unlink 302248702
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:hex:93130b4be4bc1a8fbc1d9fec3374ad5dc56984199821193 52fd3c2e4ee22e577
```

TPM derived keys via request_key(2)

```
ignat@dev:~$ ./keyctl request2 user tpm2:derived:test "32 csum" @s
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:hex:15257529326a3b5874d2e4165245a2c4a758b3e6c549e876e3b808fe8a748c80
```

Links

- https://www.kernel.org/doc/html/latest/security/keys/core.html
- https://www.kernel.org/doc/html/latest/security/keys/trusted-encrypted.html
- https://man7.org/linux/man-pages/man7/keyrings.7.html
- https://man7.org/linux/man-pages/man7/asymmetric.7.html
- https://man7.org/linux/man-pages/man1/keyctl.1.html
- https://blog.cloudflare.com/the-linux-kernel-key-retention-service-and-why-you-should-use-it-in-your-next-application/

Thank you!

Questions?