Stony Brook University

Virtual Machine Introspection

Bhushan Jain

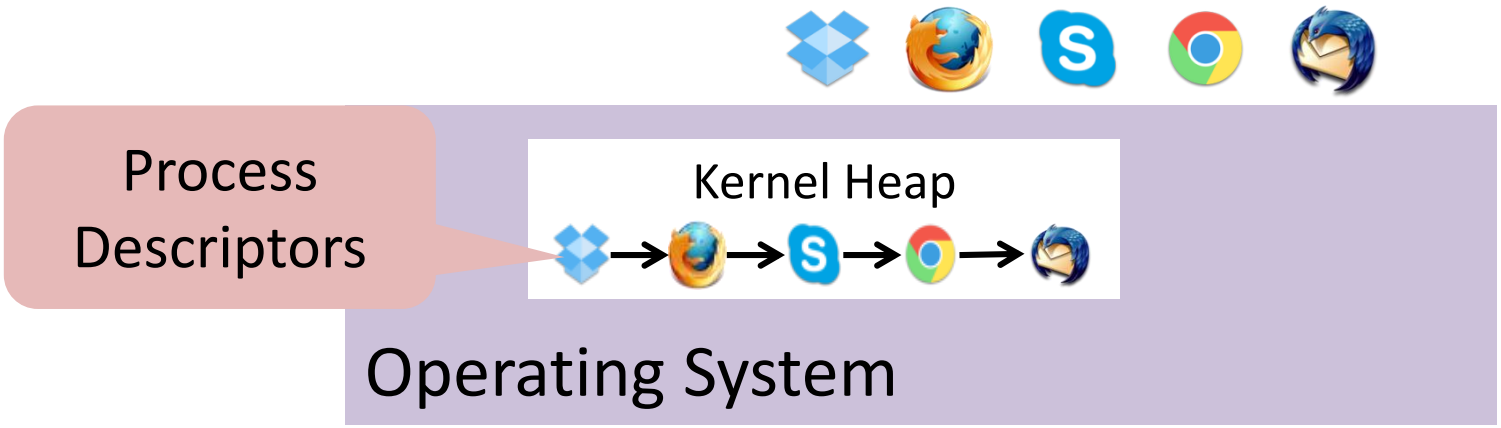
Computer Science Department

Stony Brook University

Traditional Environment

Operating System

Traditional Environment



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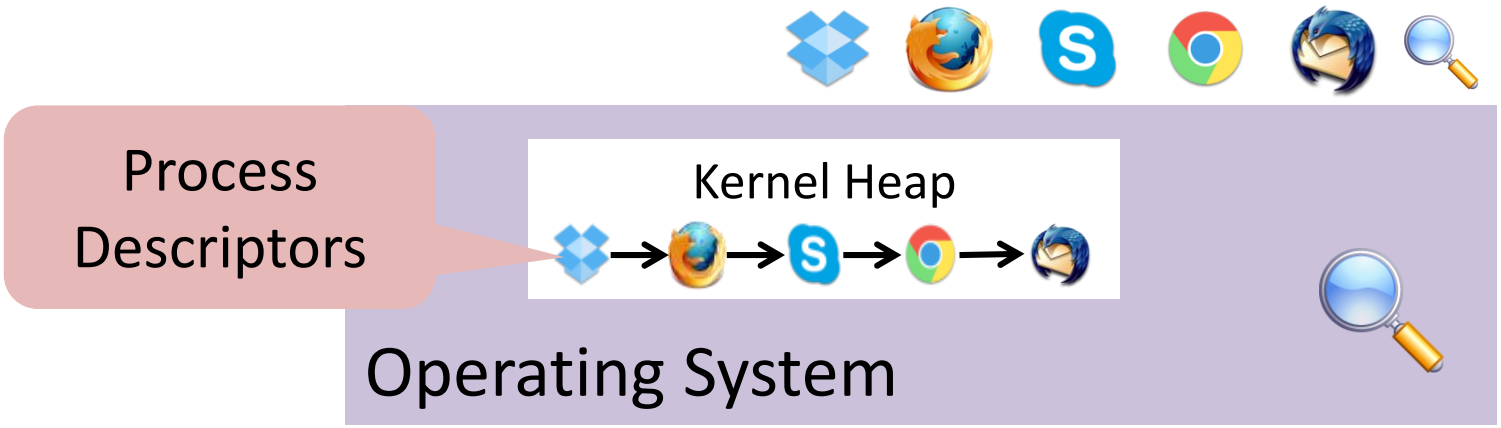

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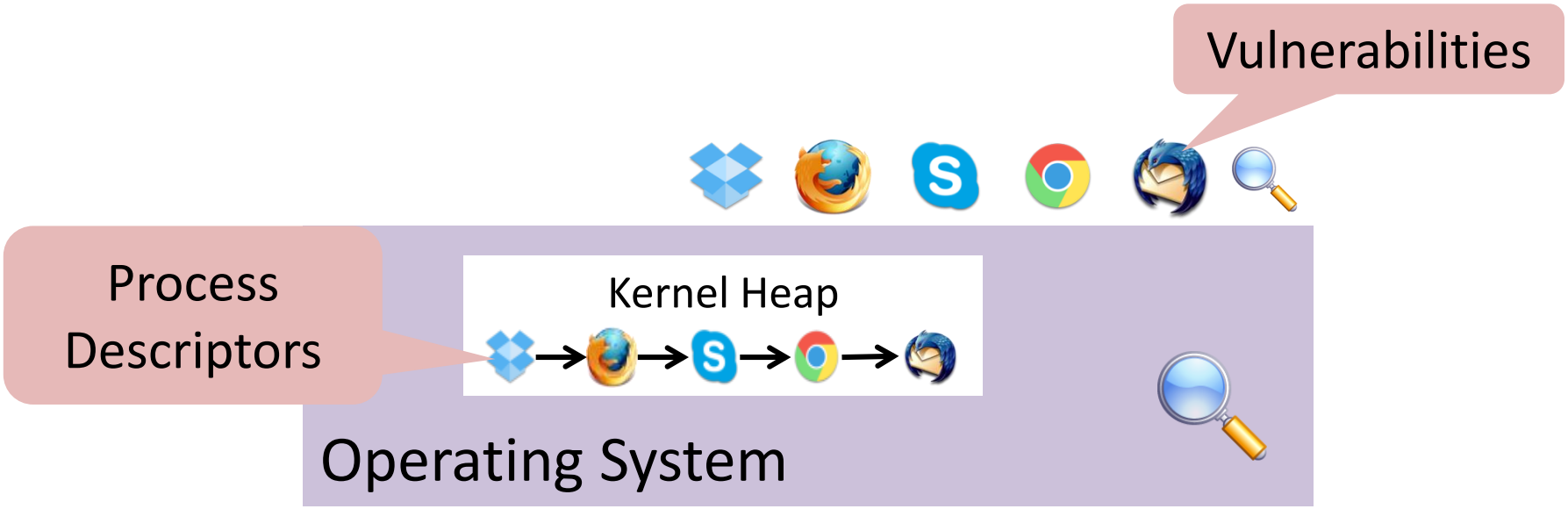

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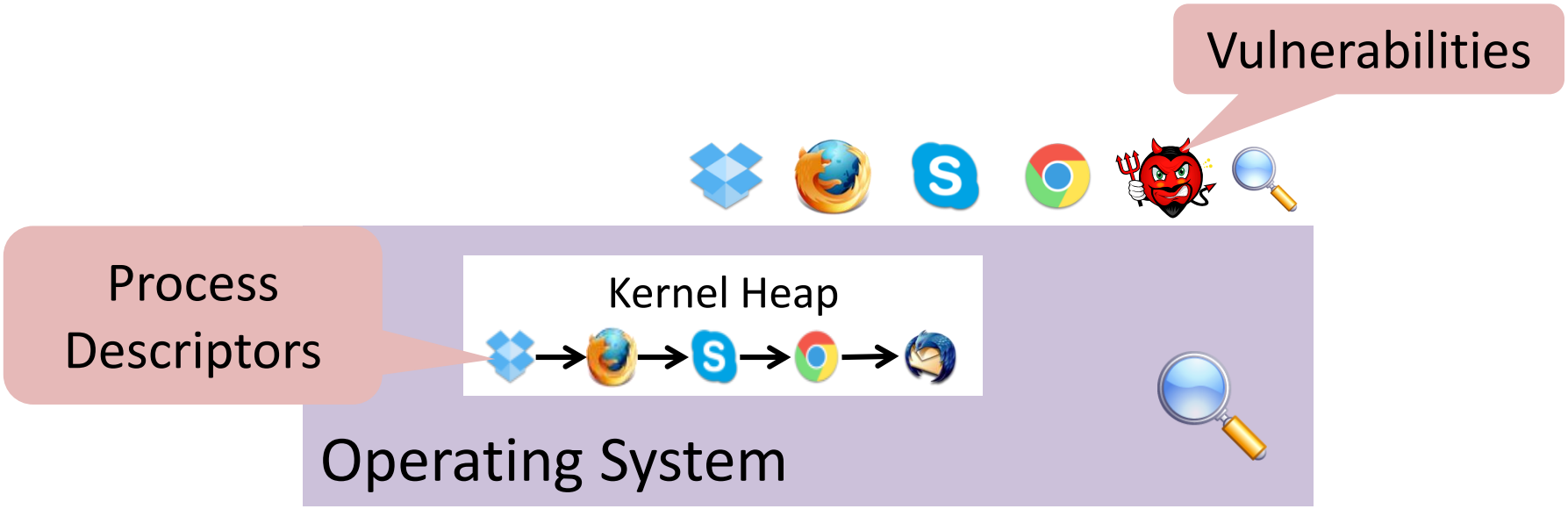

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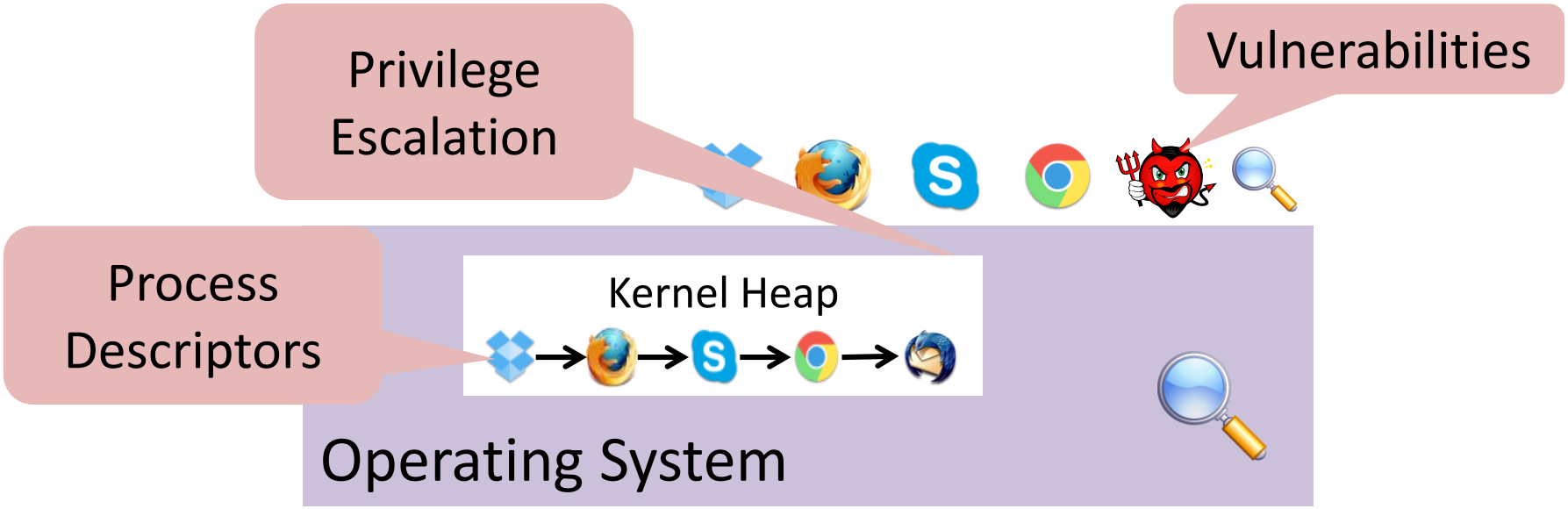

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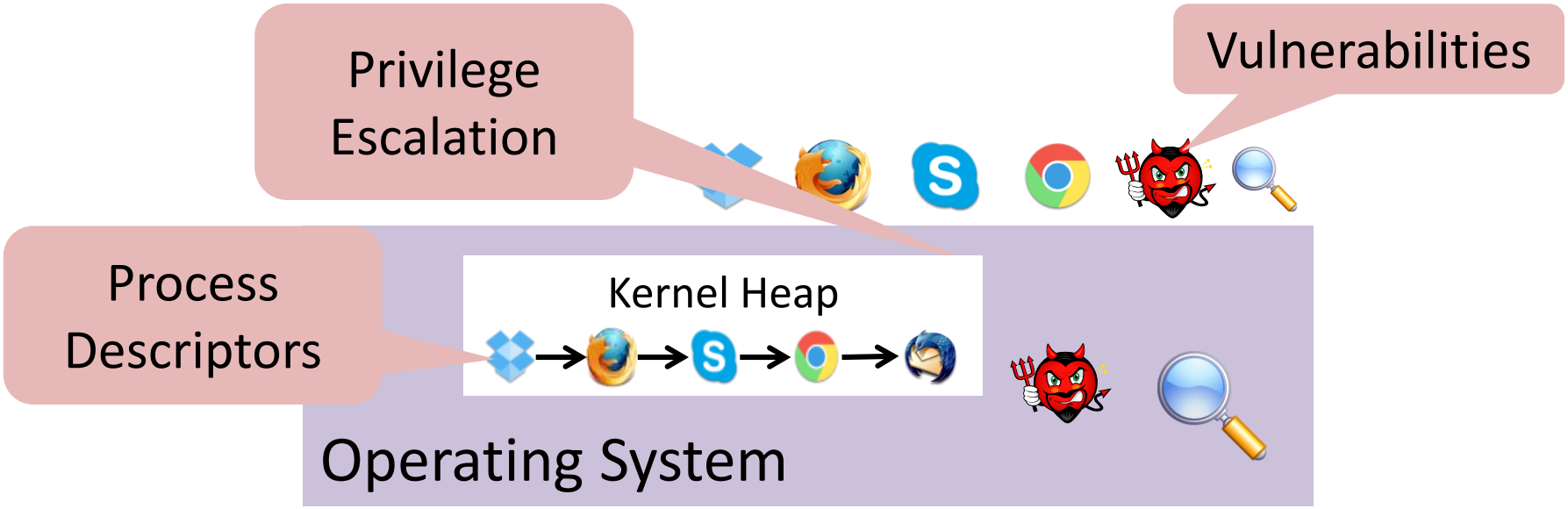

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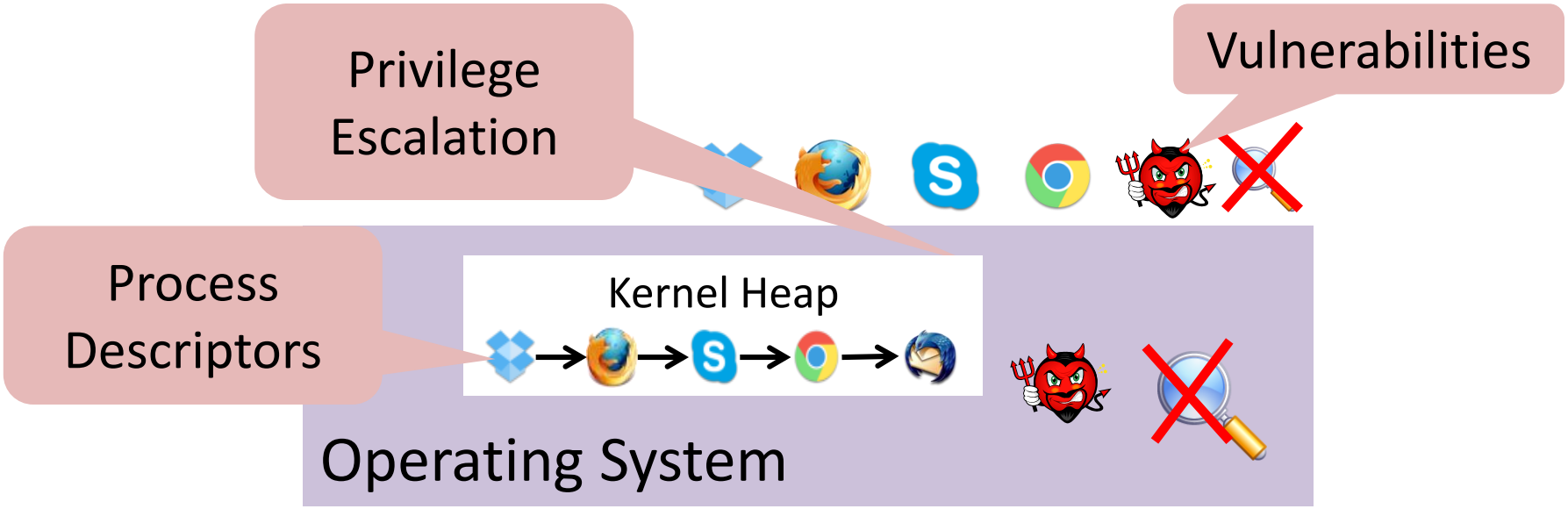

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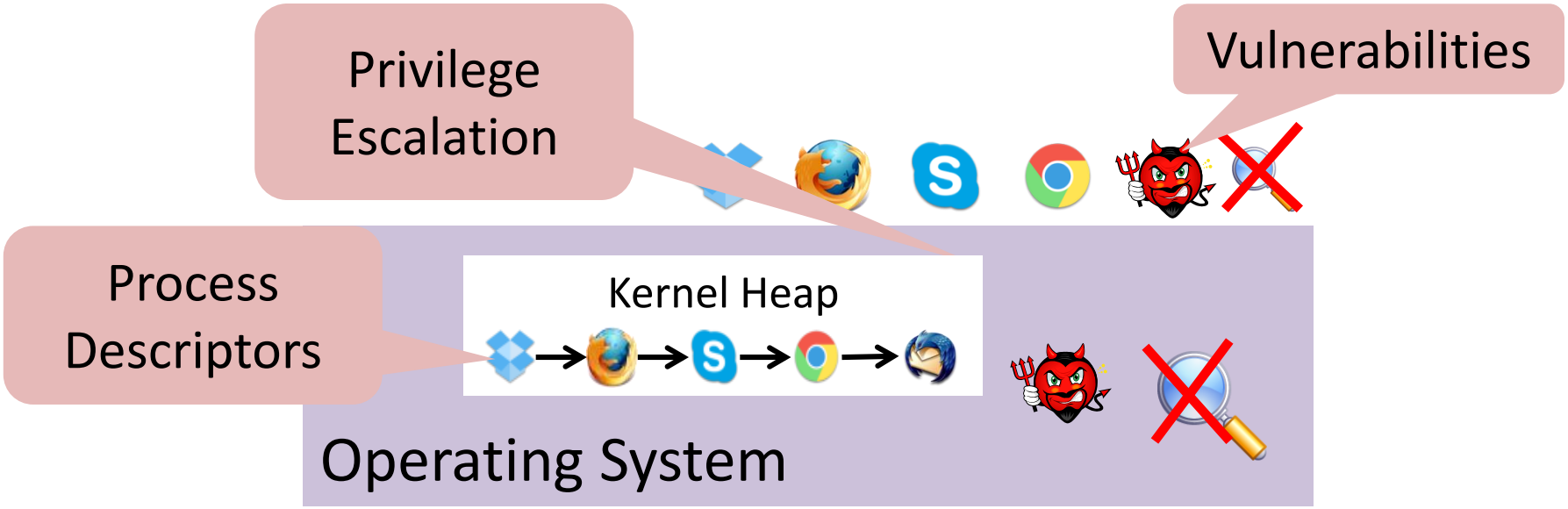
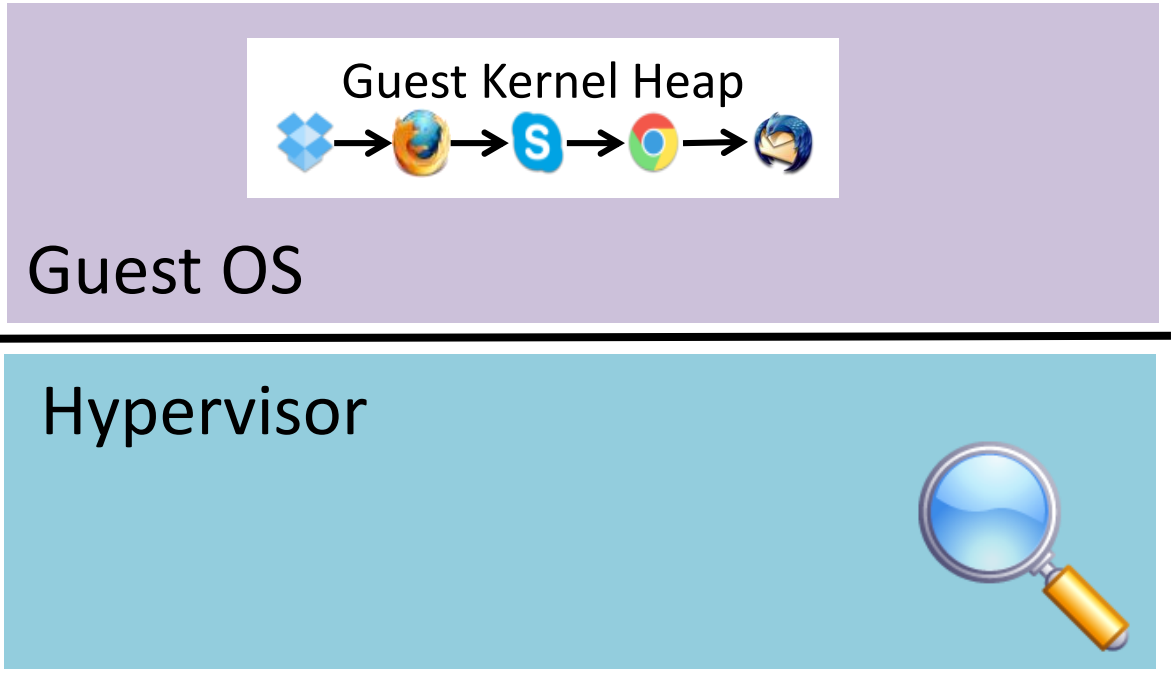
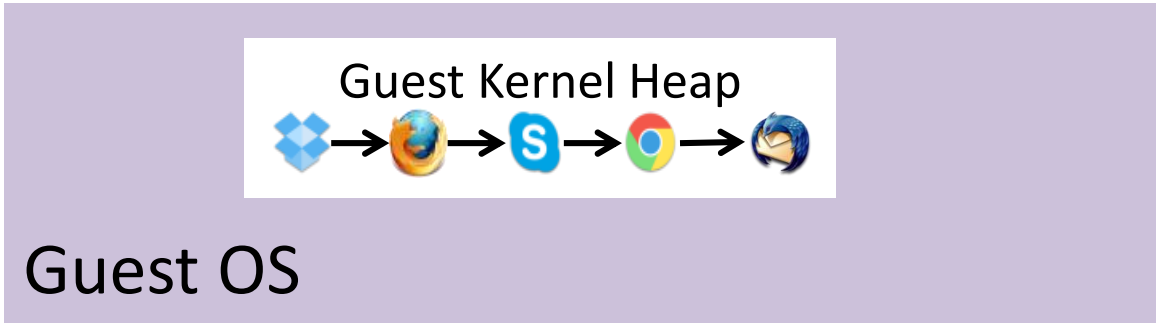


Security monitors can be easily subverted by rootkits

Layered Security



Layered Security



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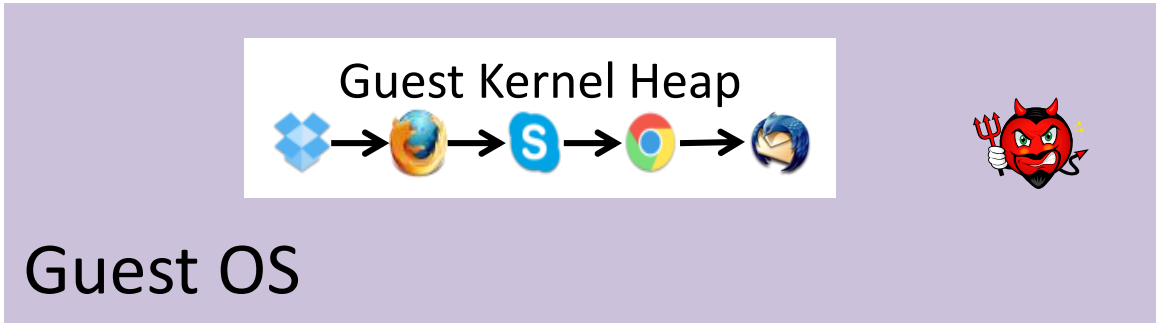

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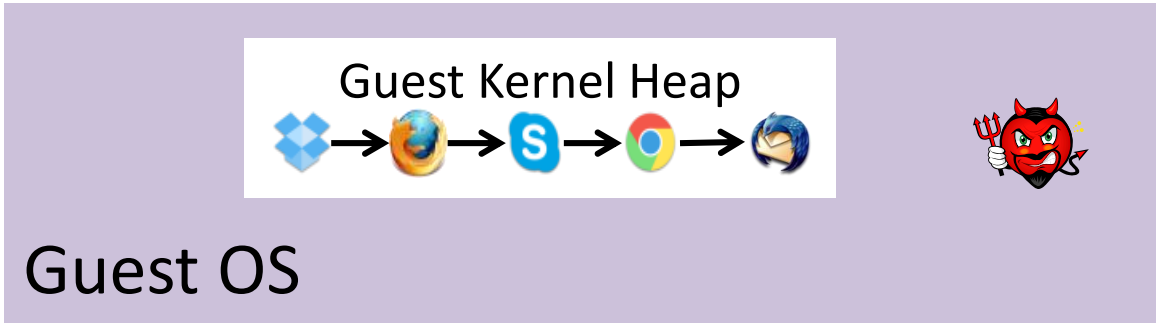

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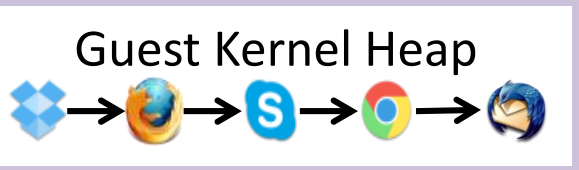
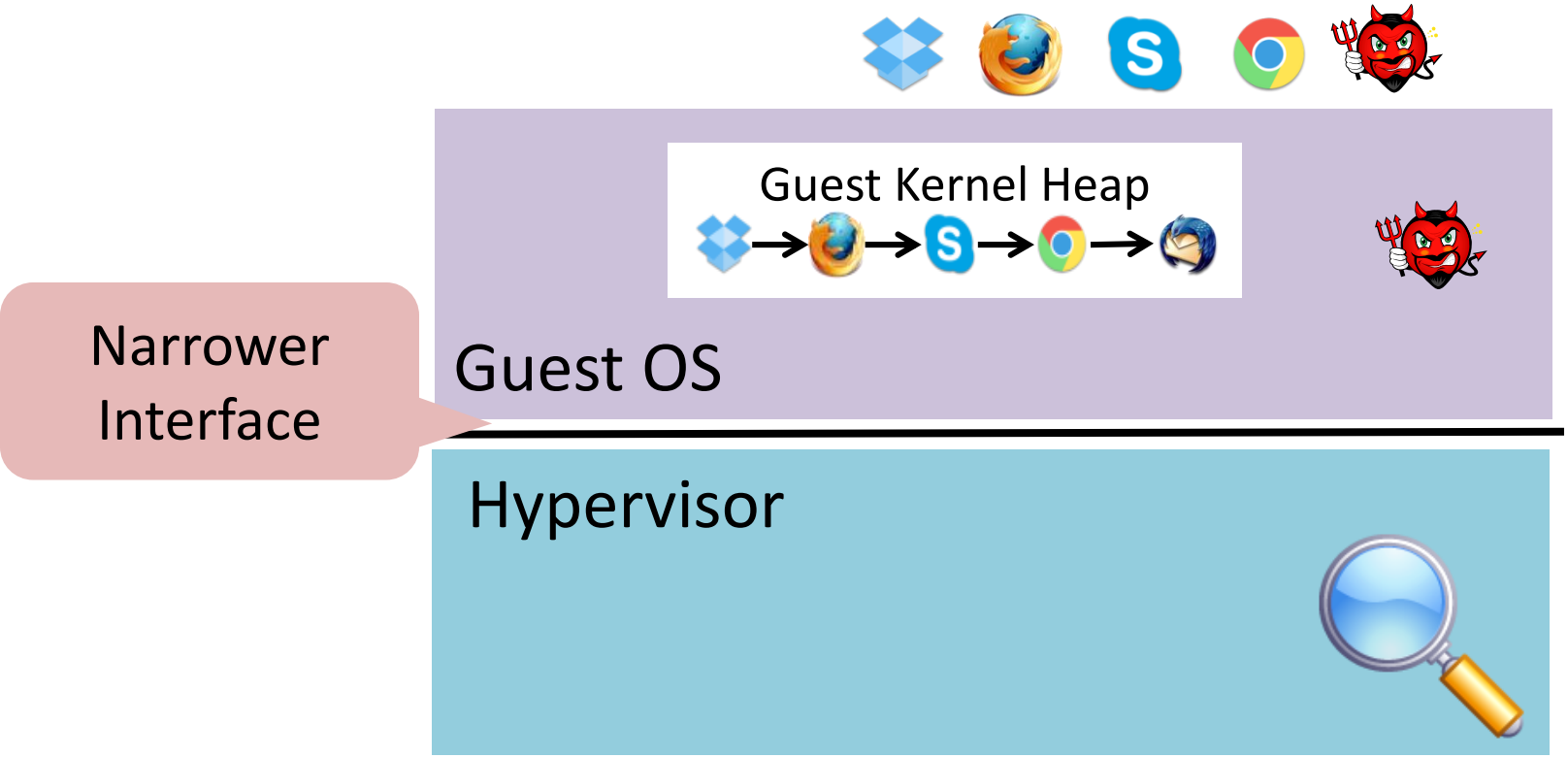


Guest OS

Narrower Interface

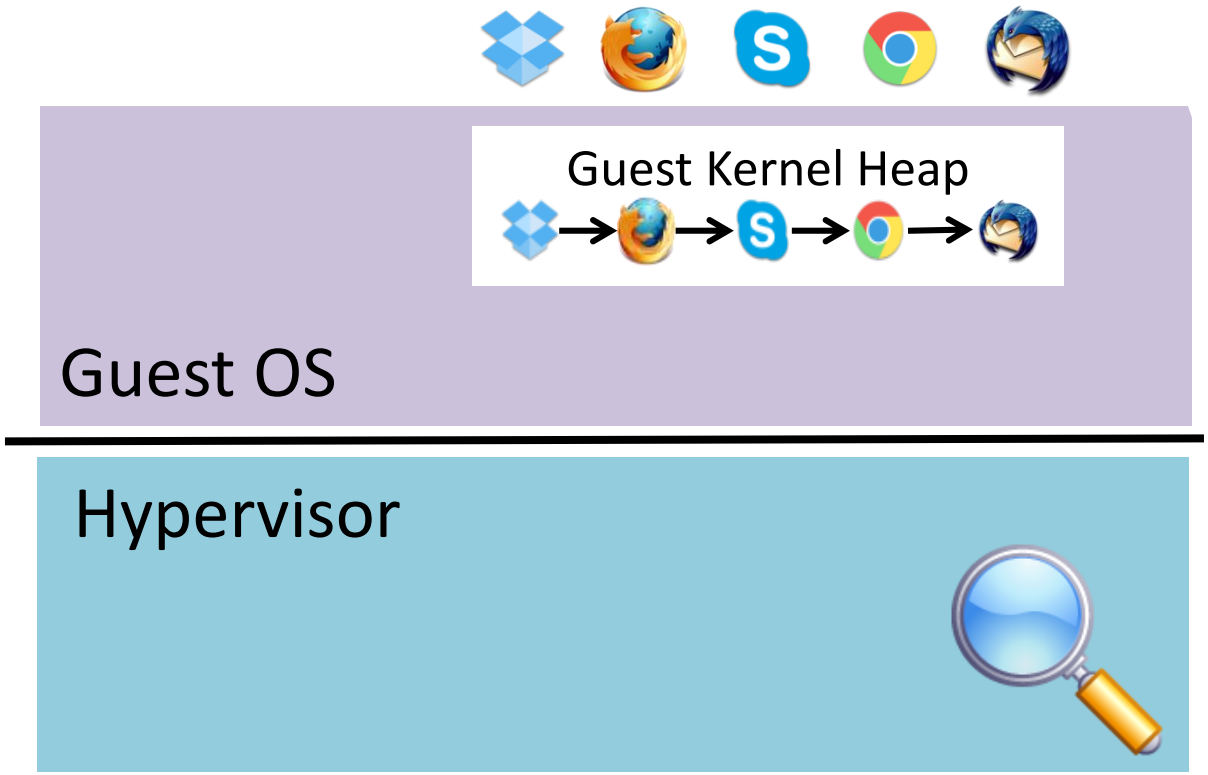
Hypervisor

Layered Security



Narrower Interface = Fewer exploitable vulnerabilities

Virtual Machine Introspection



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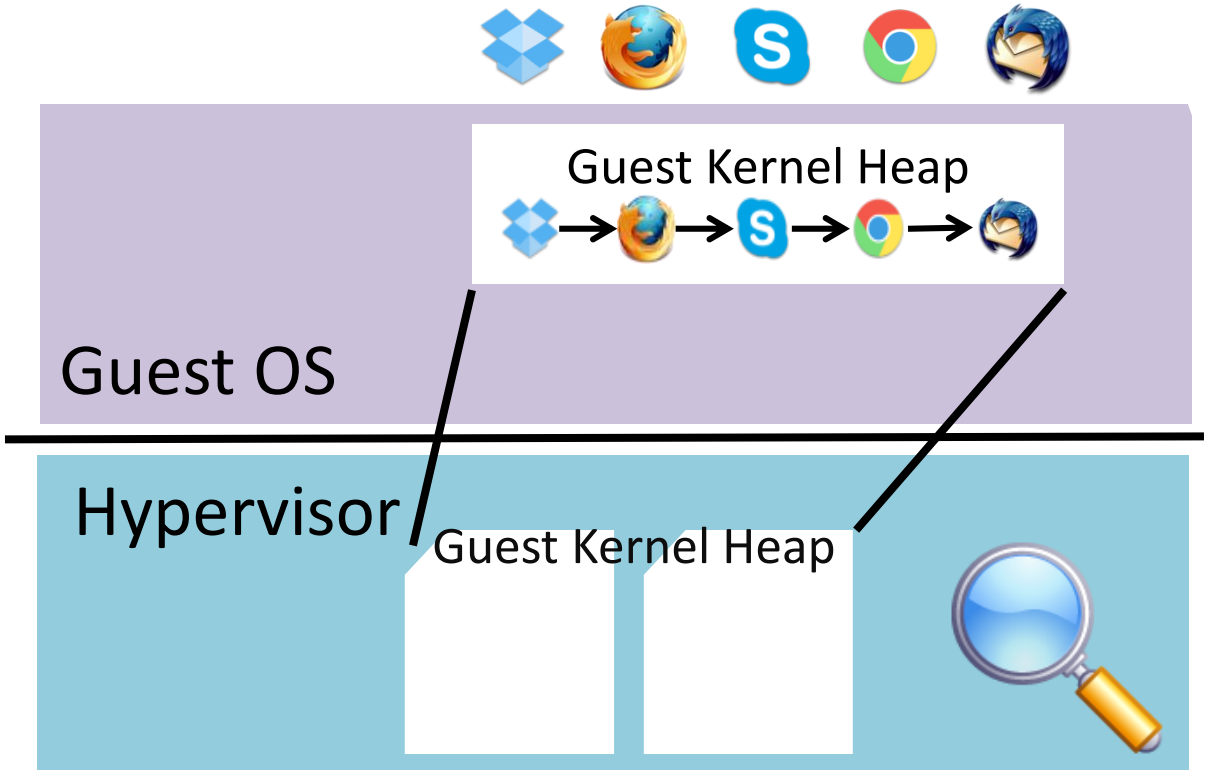

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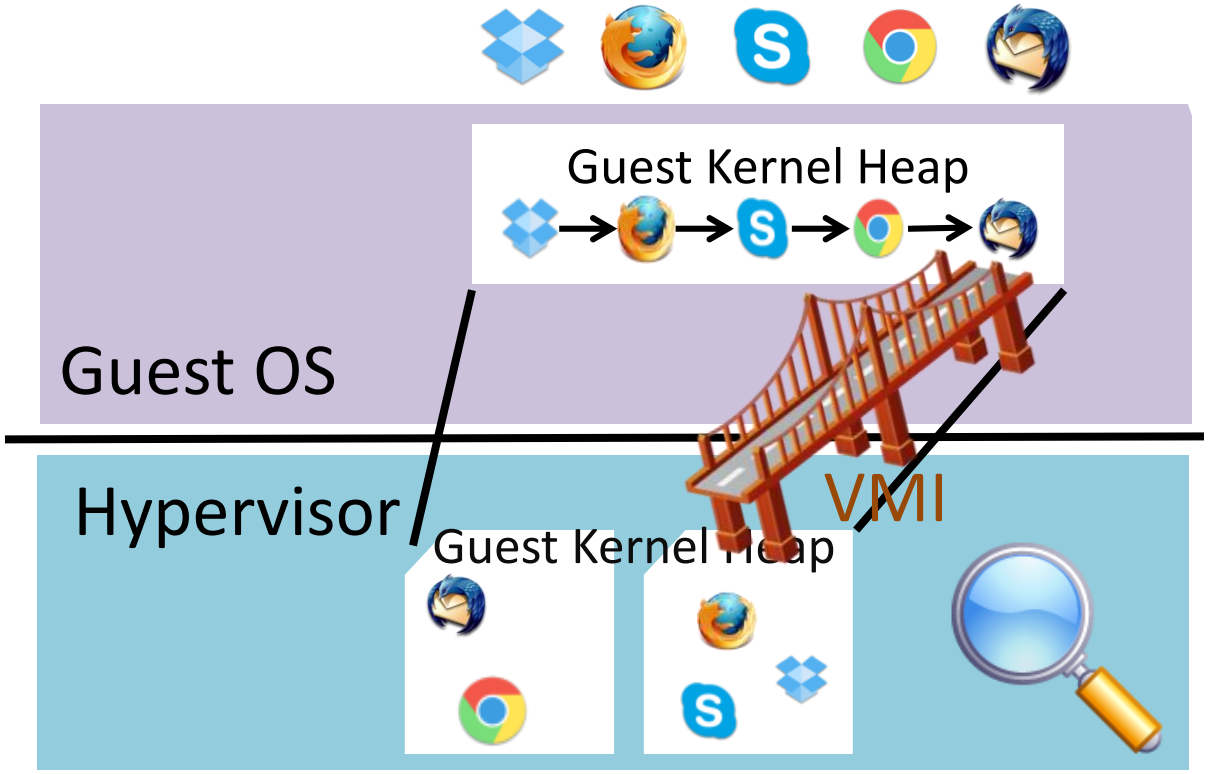

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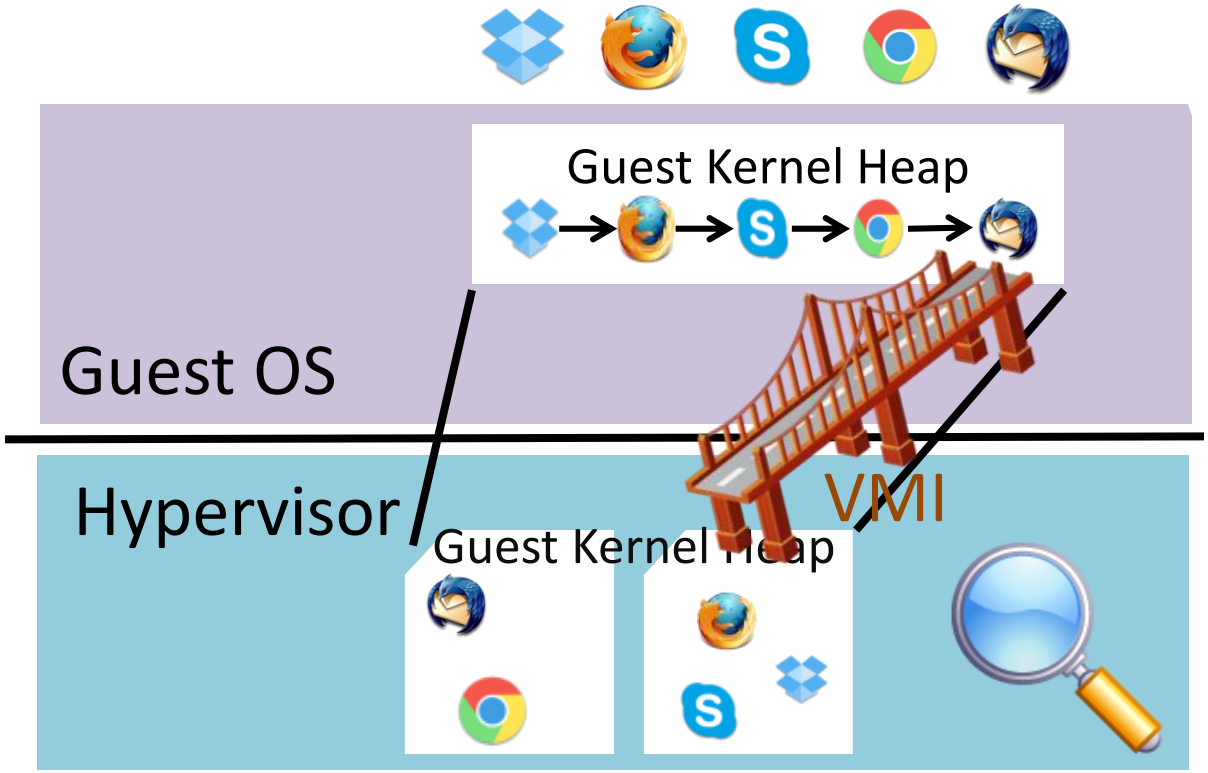

VMI: A technique to monitor the guest activities from VMM

Applications of VMI

- Introspect VM memory and CPU registers
  -
- Introspect disk contents
  -
- Network traffic
  -

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  - E.g., Intrusion Prevention Systems

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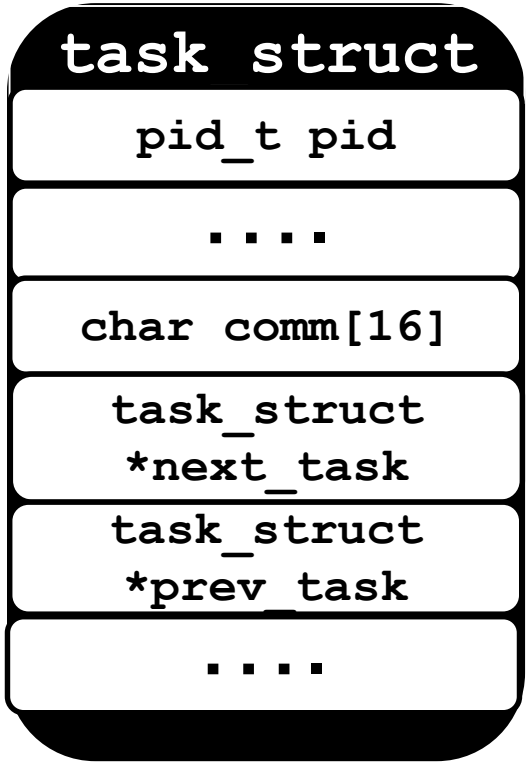
  - E.g., Differentiate VM data vs metadata
- Network traffic
  - E.g., Intrusion Prevention Systems

VMI is useful for more than just monitoring guest OS

VMI In Action



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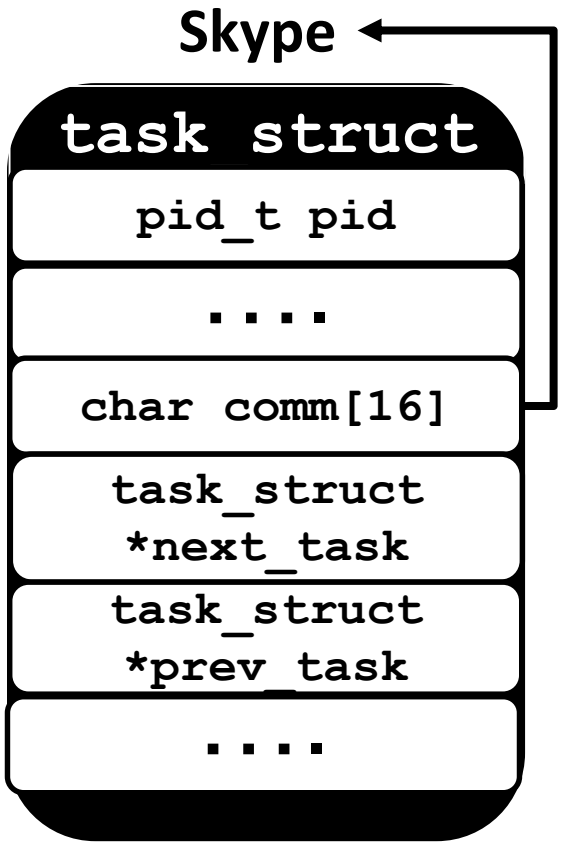

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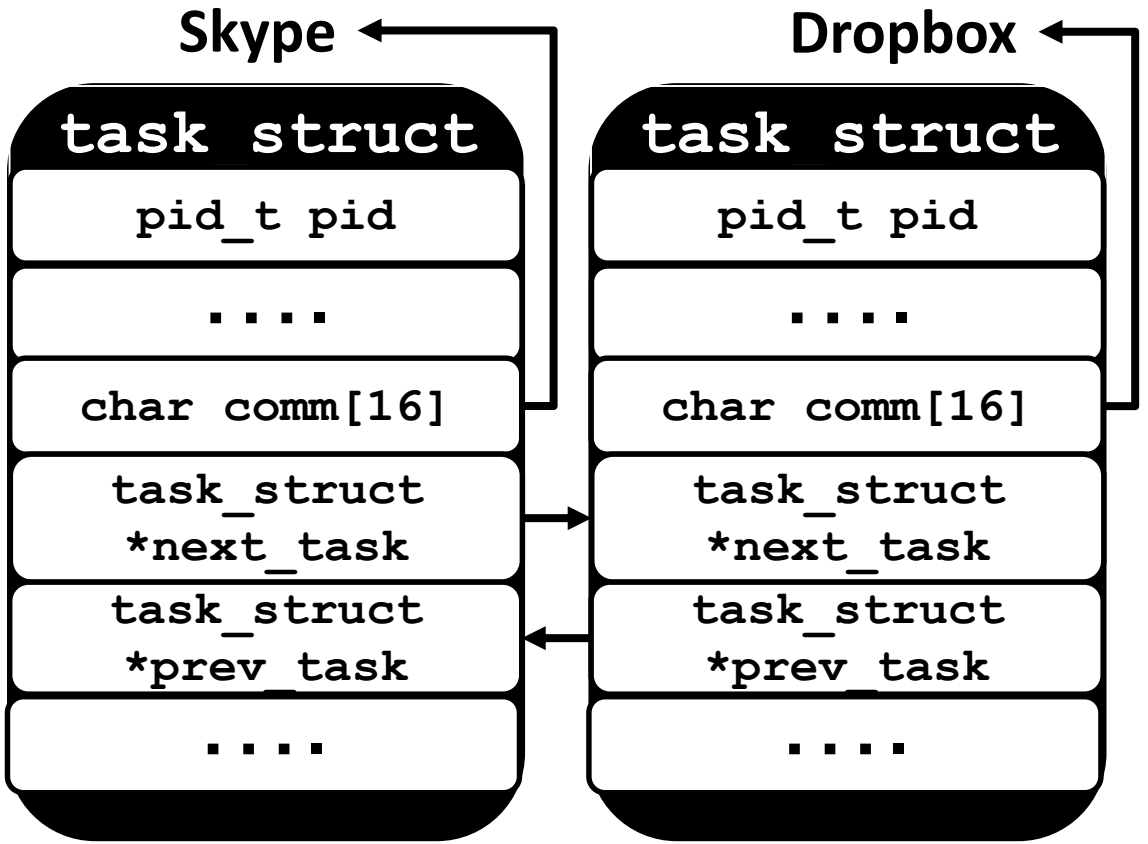
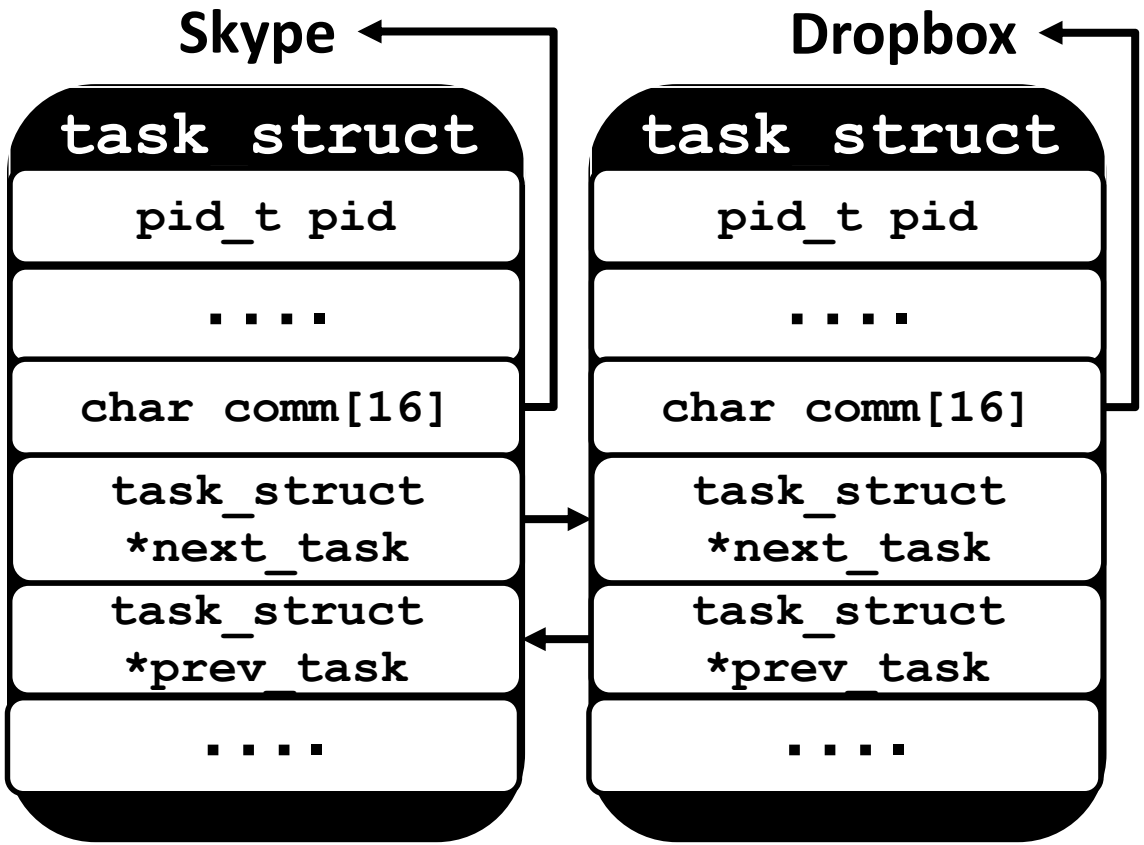


VMI In Action

`init_task`



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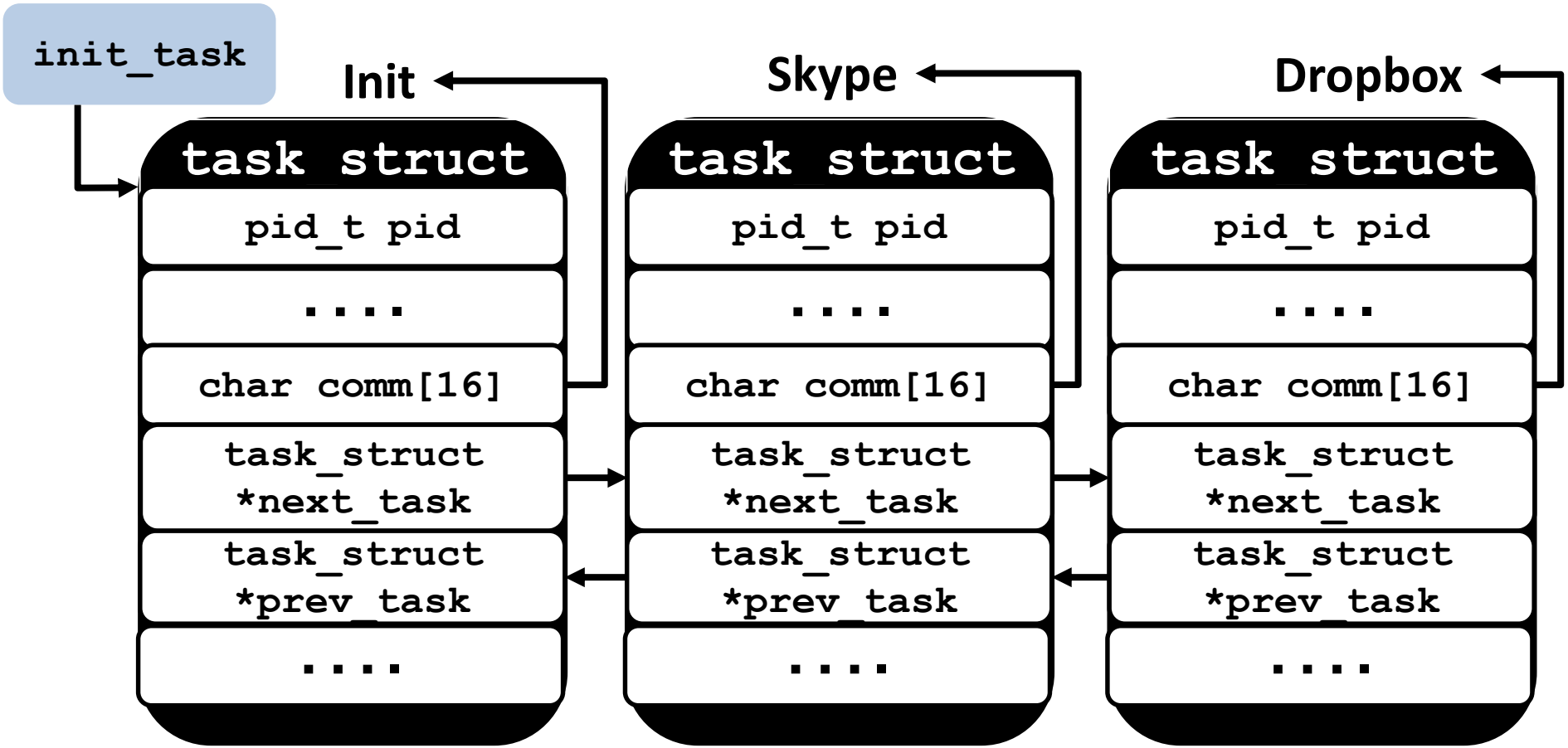

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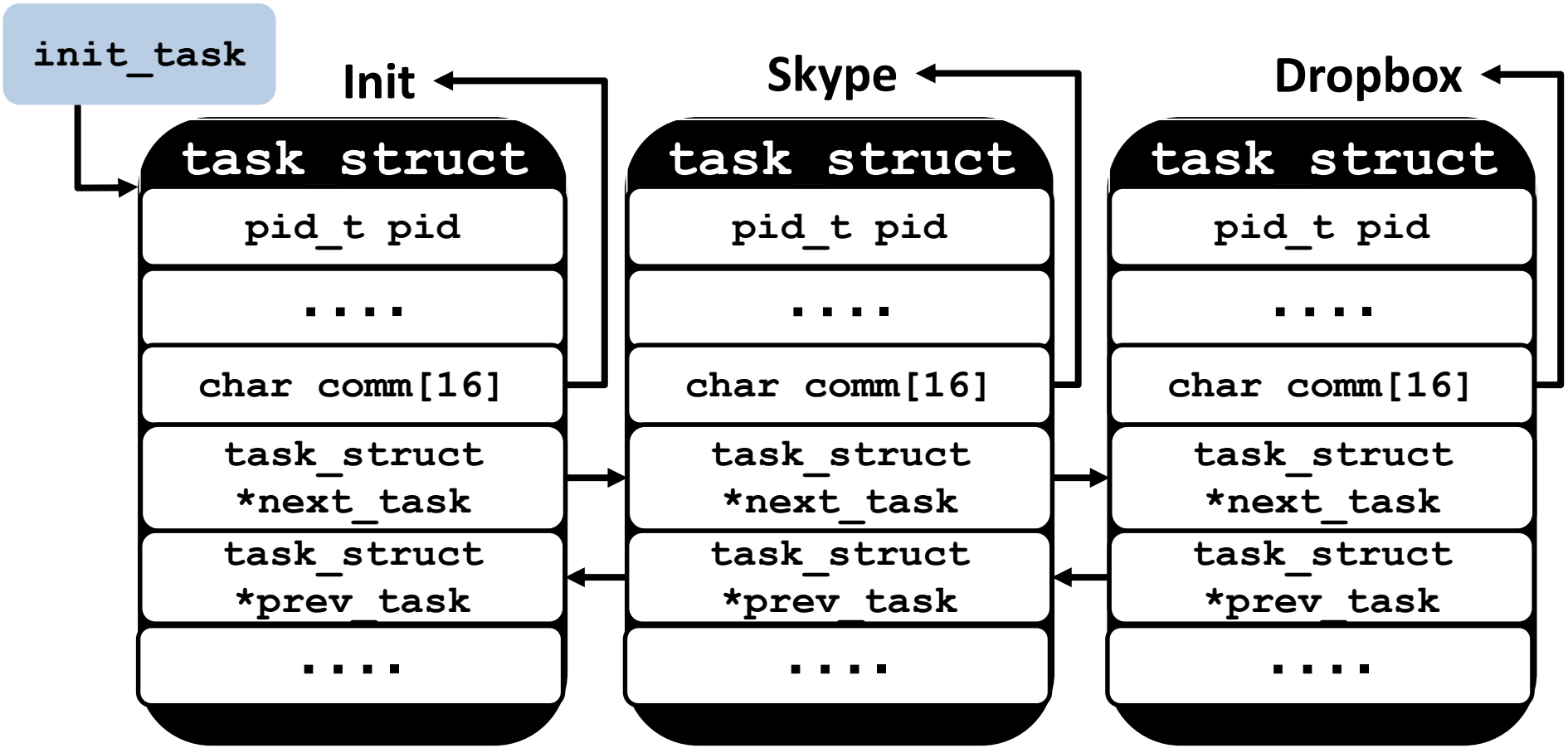
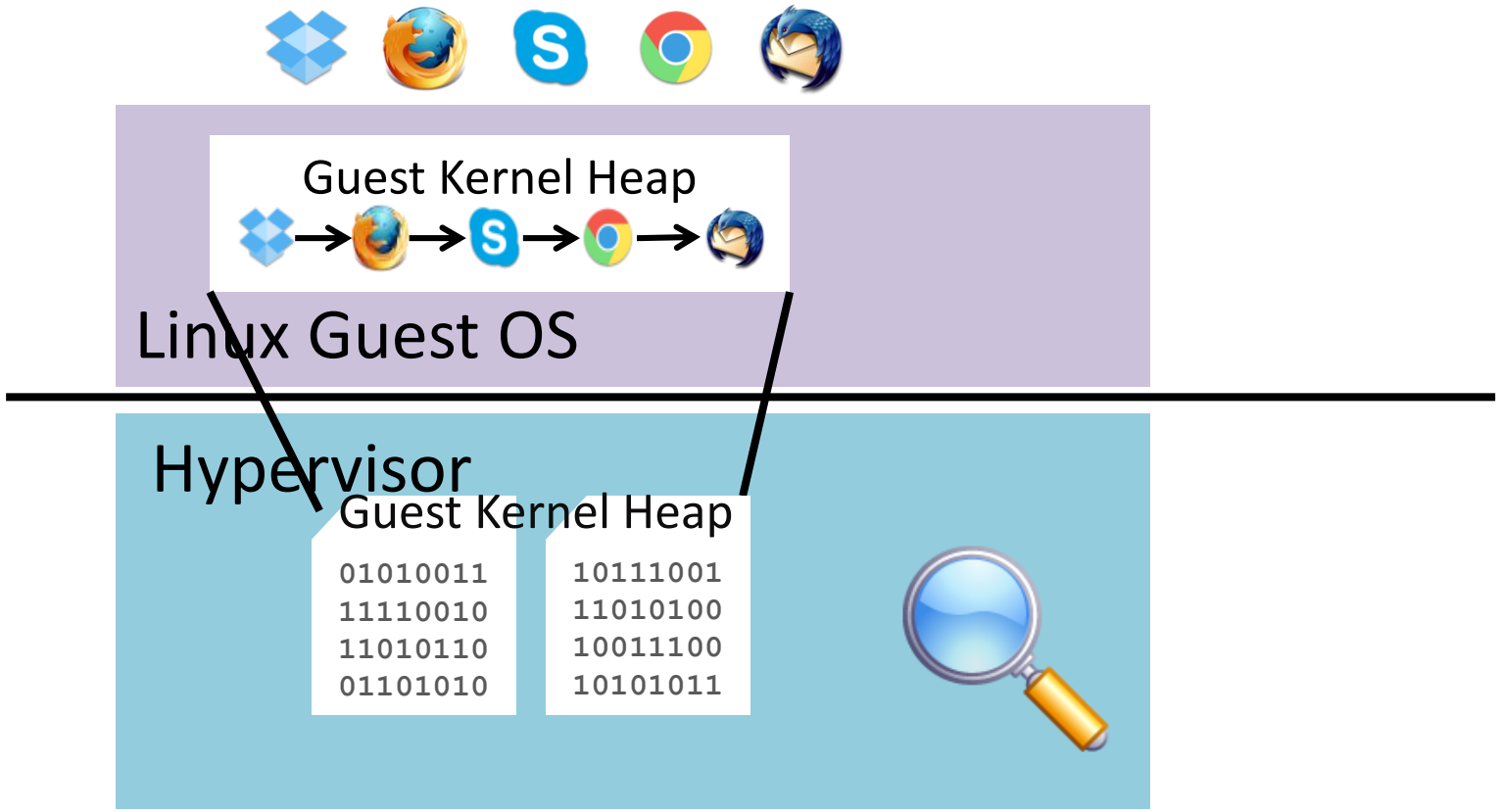


Typecast memory contents to structure definition

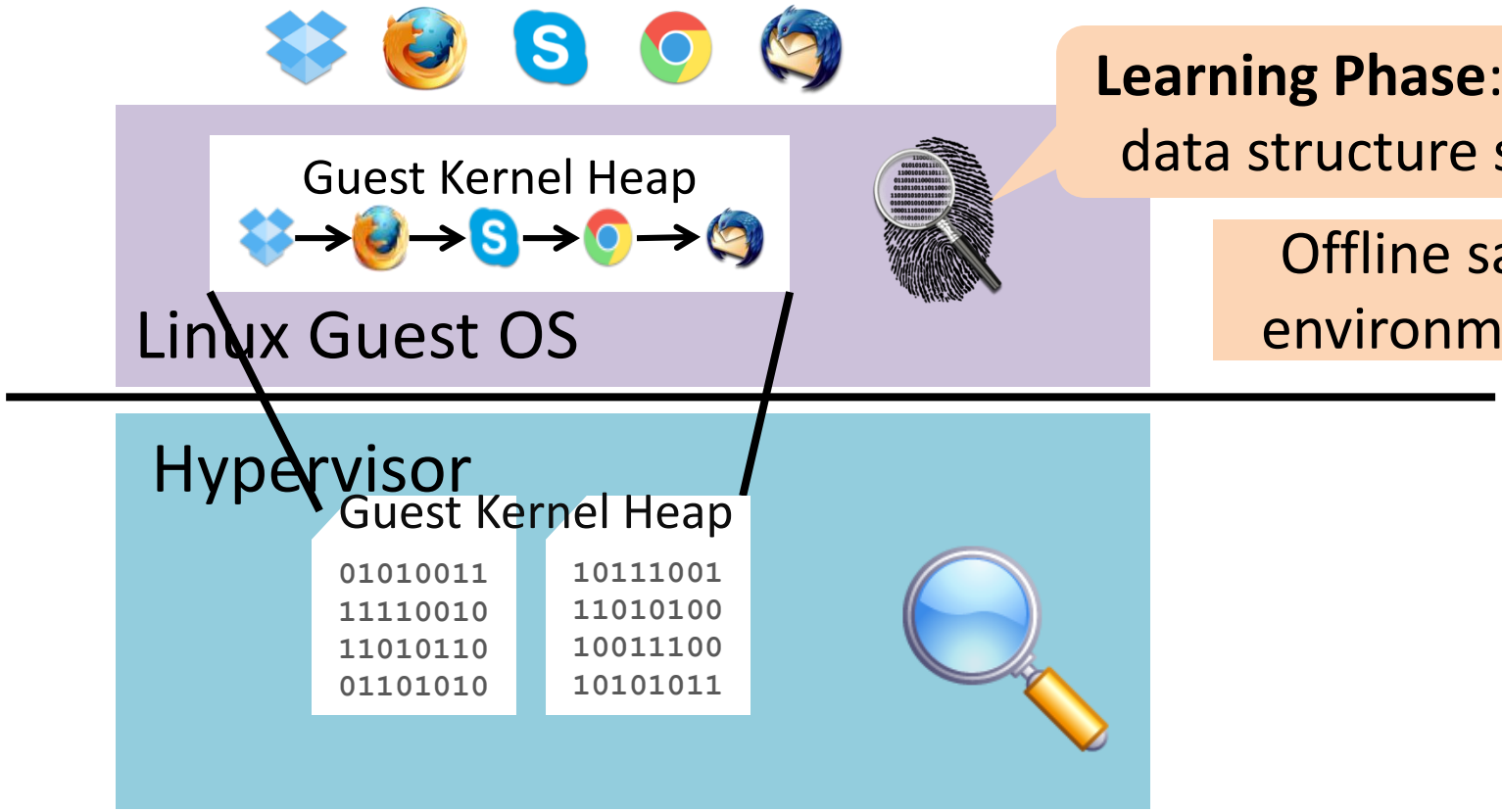
High-level VMI Techniques

- **Learning and Reconstruction**
  - Learn structure signature; Search object instances
- **Code Implanting**
  - Inject code in guest OS; VMM protects injected code
  - State of Art: SIM [1]
- **Data Outgrafting**
  - Reuse static kernel code; Input runtime heap & data
  - State of Art: VMST [2]

Learning and Reconstruction



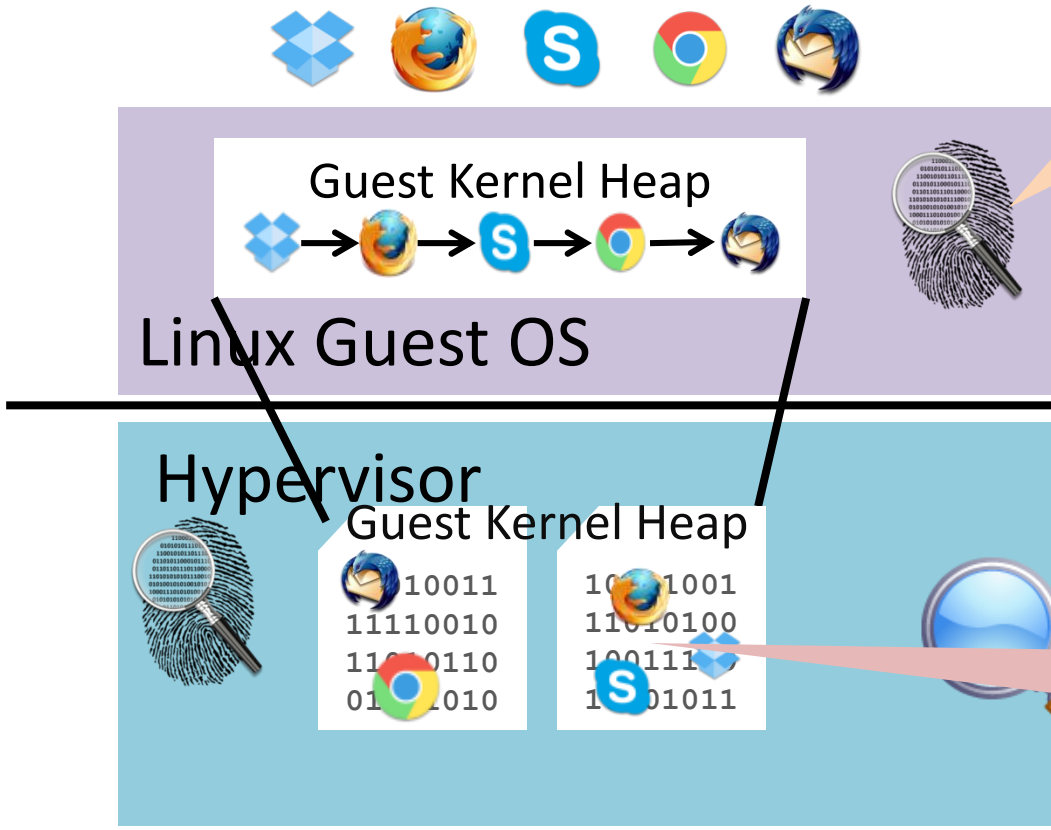
Learning and Reconstruction



Learning Phase: Generate data structure signature

Offline safe environment

Learning and Reconstruction



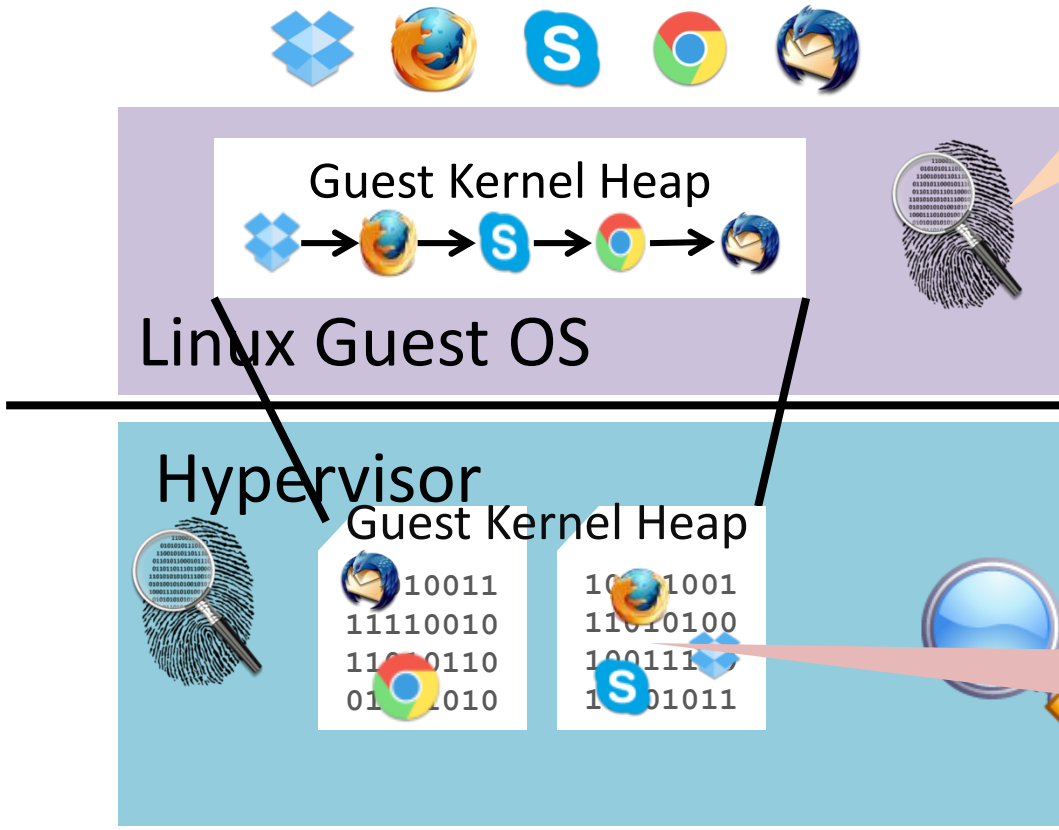
Learning Phase: Generate data structure signature

Offline safe environment

Continuous over guest lifespan

Searching Phase: Find data structure instances

Learning and Reconstruction



Learning Phase: Generate data structure signature

Offline safe environment

Continuous over guest lifespan

Searching Phase: Find data structure instances

Assumption: Same OS behavior in learning and monitoring

Approaches for L&R

- **Learning**: Extract data structure signature
  -
  -
  -
- **Searching**: Identify data structure instances
  -
  -
  -

Approaches for L&R

- **Learning**: Extract data structure signature
  - Hand-crafted data structure signatures
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- **Searching**: Identify data structure instances
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Approaches for L&R

- **Learning**: Extract data structure signature
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Approaches for L&R

- **Learning**: Extract data structure signature
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  - Traverse data structure pointers
  - Monitor object allocators

Learning Techniques

- Hand-crafted data structure signatures
  -
  -
- Source code analysis
  -
  -
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- Dynamic Learning
  -
  -

Learning Techniques

- Hand-crafted data structure signatures
  - Change to an OS kernel requires expert to update tools
  - State of Art: FACE/Ramparser [3], Volatility [4]
- Source code analysis
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- Source code analysis
  - Points-to analysis generates graph of kernel object types
  - Not all pointers in a data structure point to valid data
  - State of Art: MAS [5], SigGraph [6]
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  - Not all pointers in a data structure point to valid data
  - State of Art: MAS [5], SigGraph [6]
- Dynamic Learning
  - Supervised machine learning: train on a trusted OS
  - State of Art: RSFKDS [7]

Searching Techniques

- Linearly scan kernel memory

Guest Kernel Heap

```
01010011    10111001
11110010    11010100
11010110    10011100
01101010    10101011
```

- Traverse data structure pointers

Searching Techniques

- Linearly scan kernel memory

Guest Kernel Heap

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Searching Techniques

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Guest Kernel Heap

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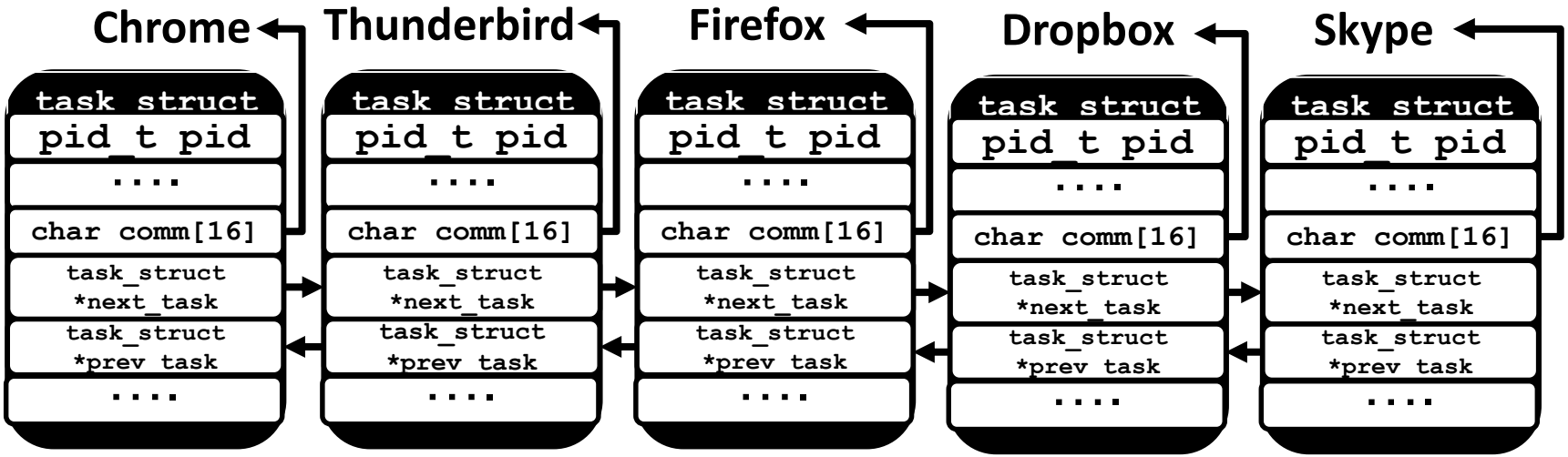

But L&R is too involved

- L&R builds tools to mine information
  - This is hard!!!
- Can we just cheat?
  - Reuse the static guest kernel code
  - Make runtime kernel data and heap available to it

Just reuse the guest code to interpret kernel heap

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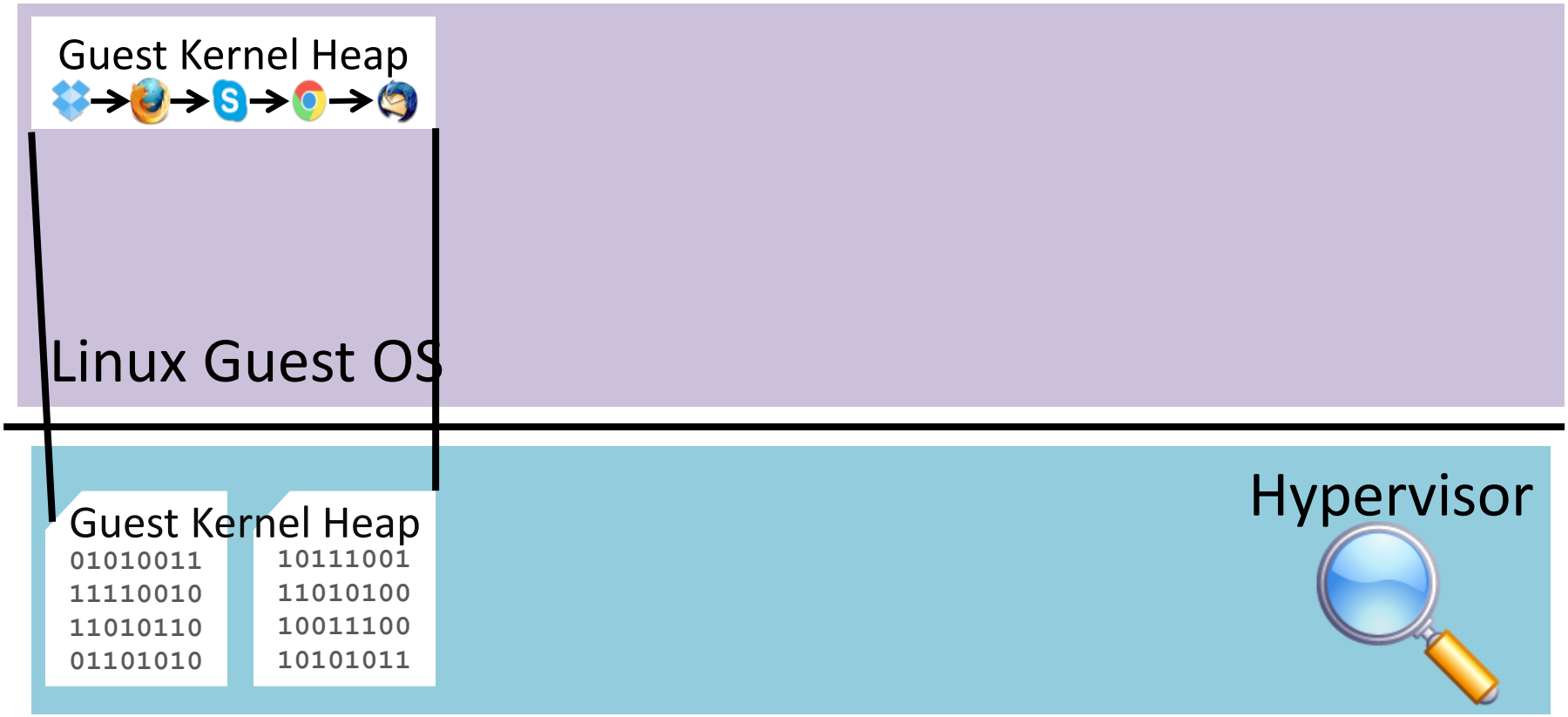
Code Implanting



Code Implanting

Guest Kernel Heap

```
struct task_struct *task;
for_each_process(task)
    call_home("%s\n",task->comm);
return 0;
```

Linux Guest OS

Guest Kernel Heap

```
01010011  10111001
11110010  11010100
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01101010  10101011
```

Hypervisor

Code Implanting

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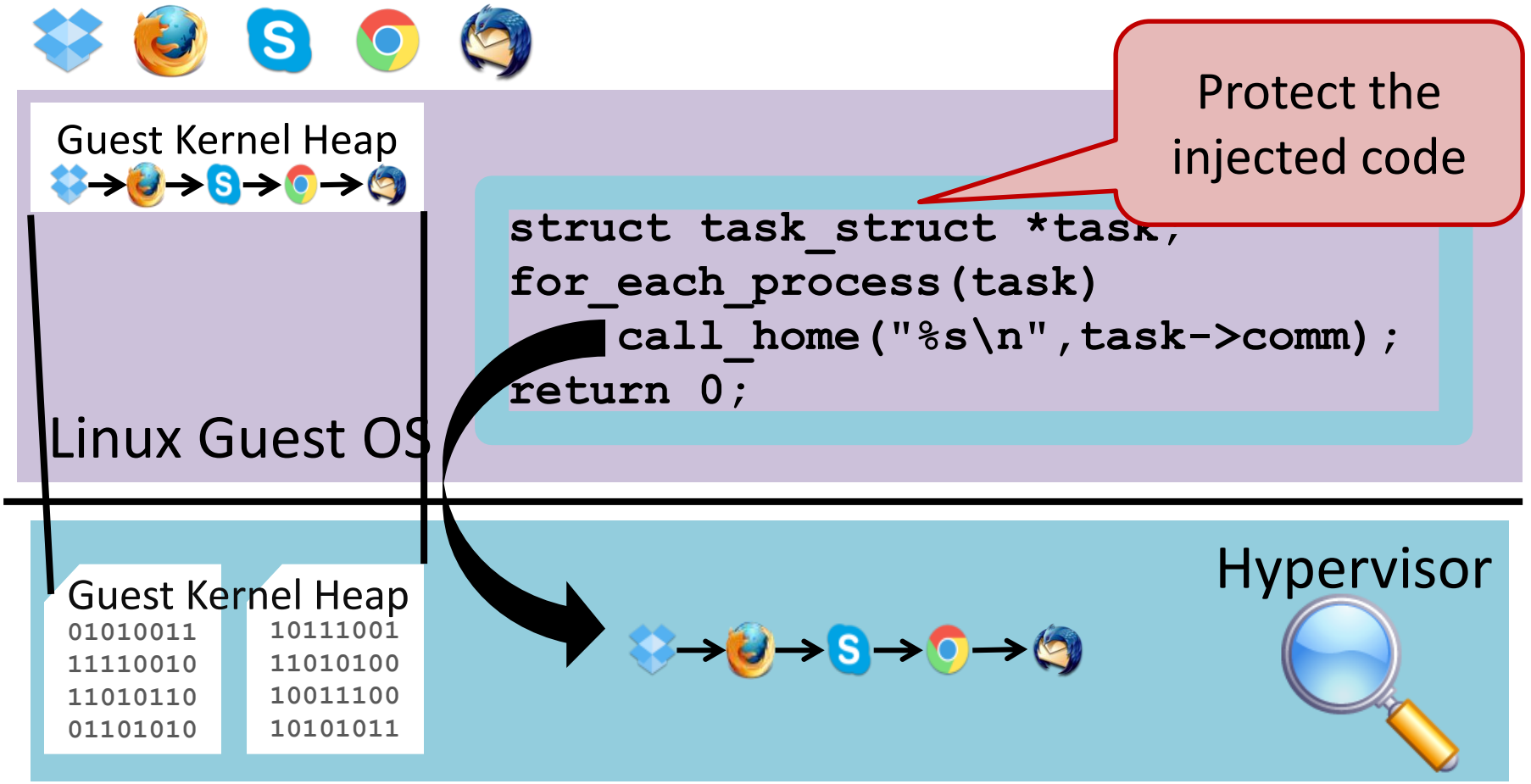

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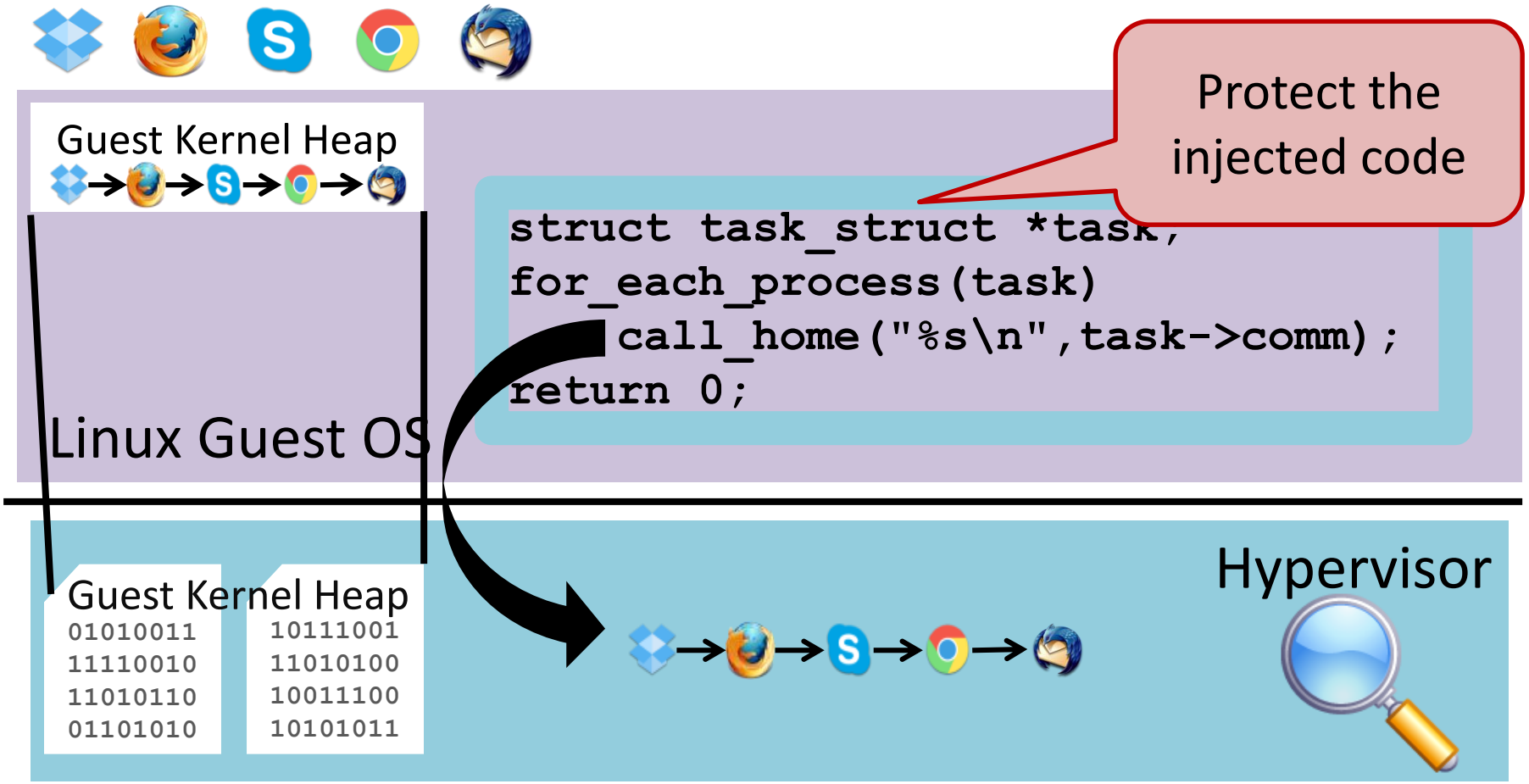

Inject code in guest OS; Difficult to protect

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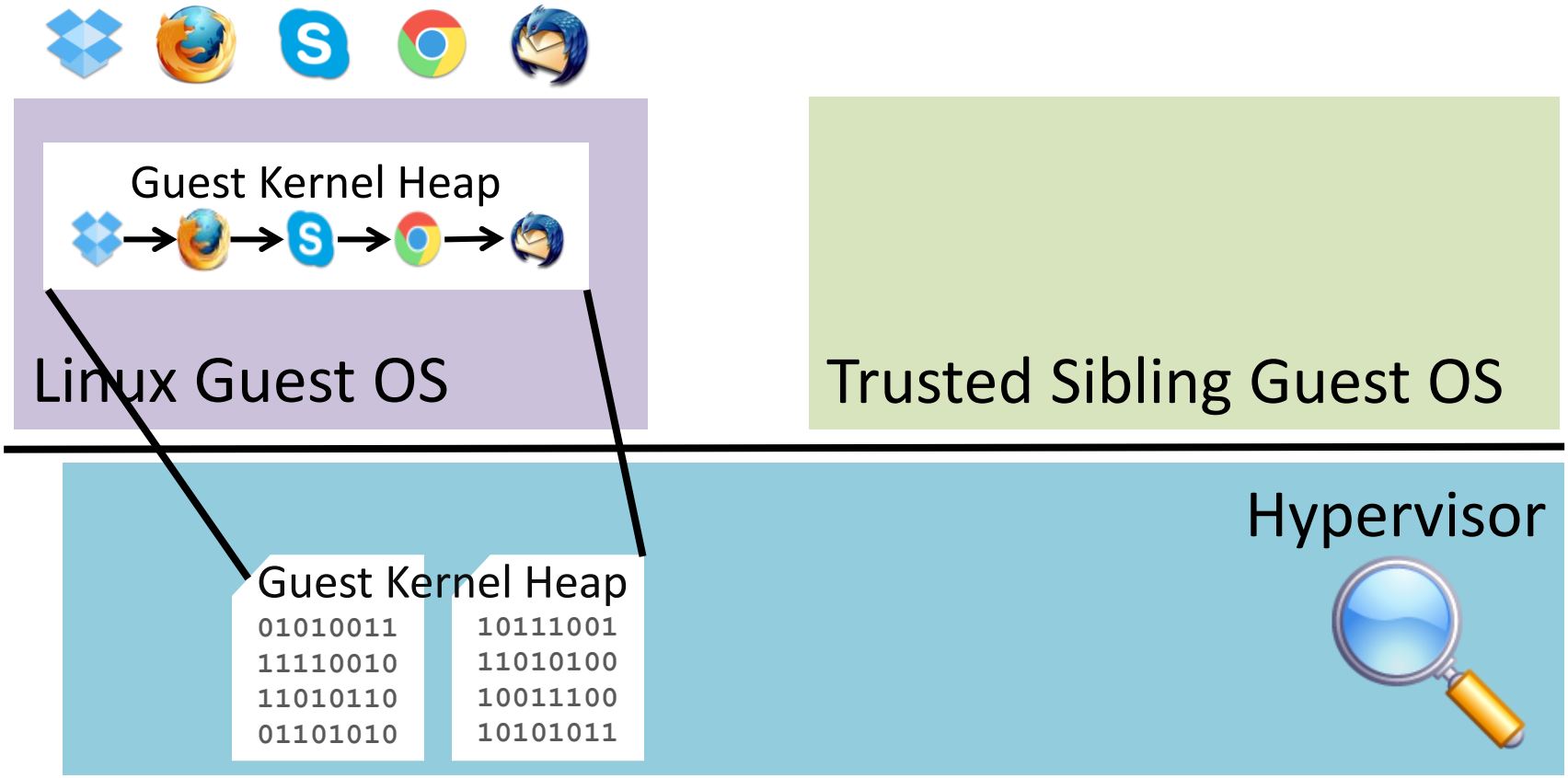
Data Outgrafting



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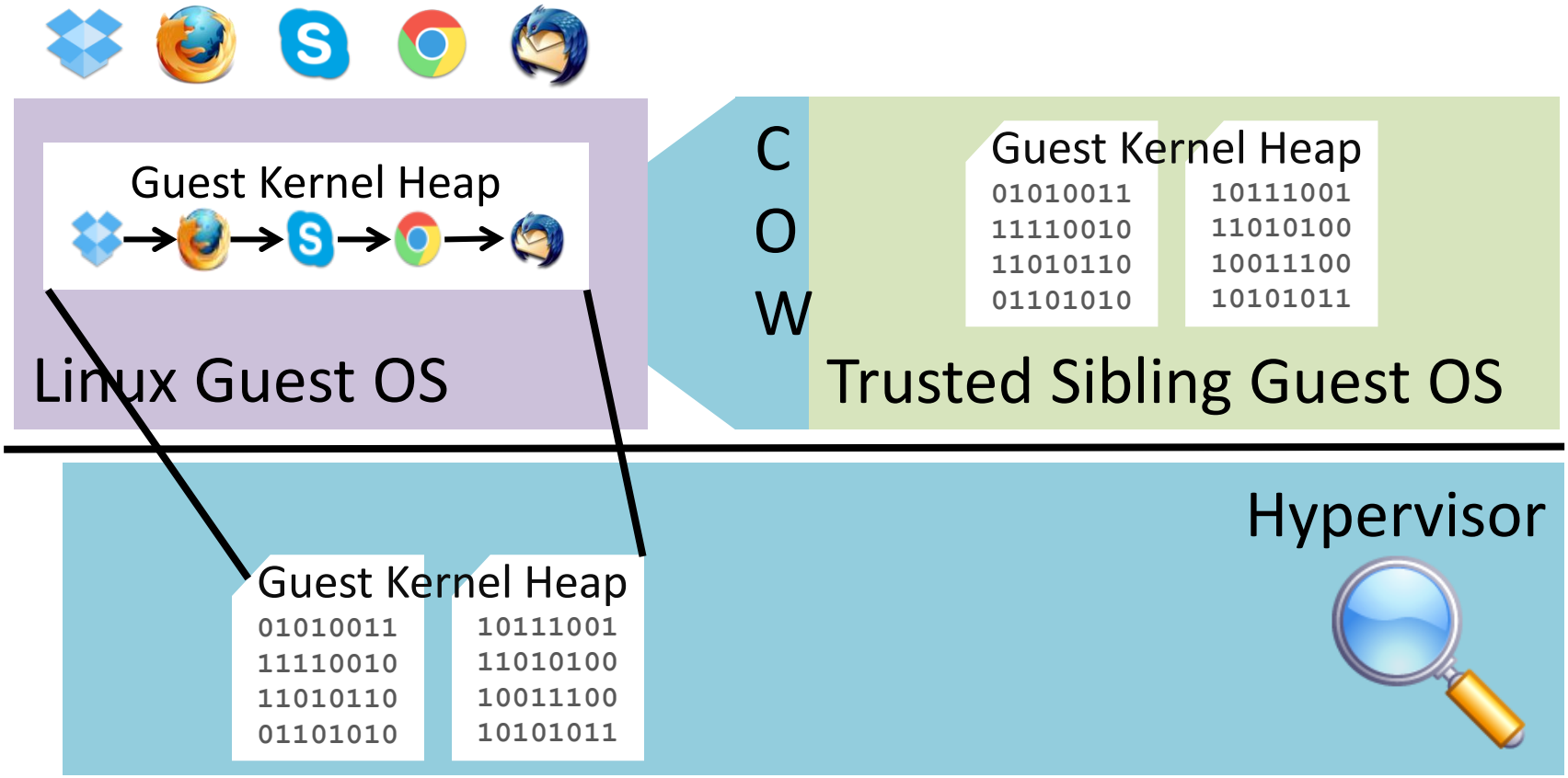

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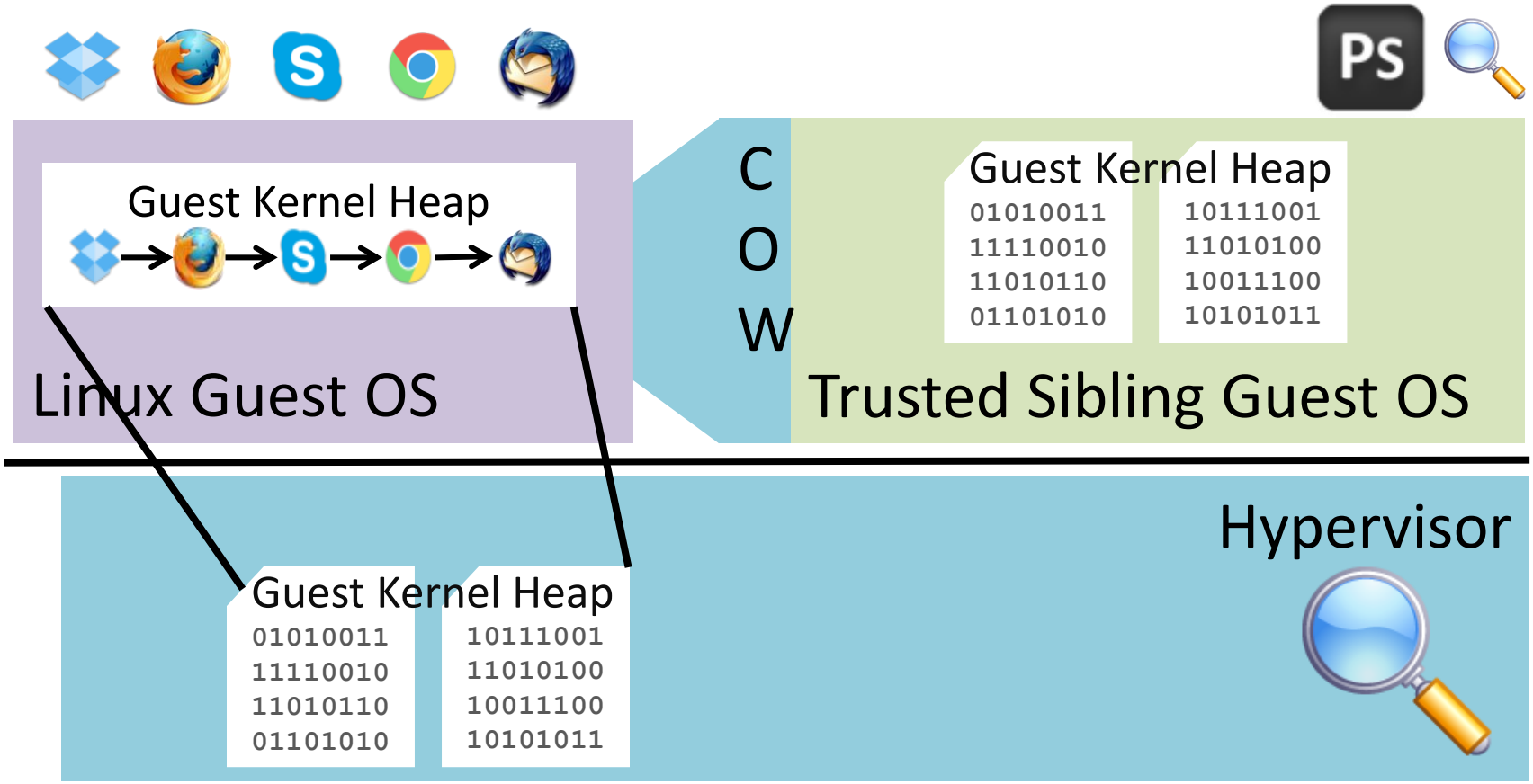

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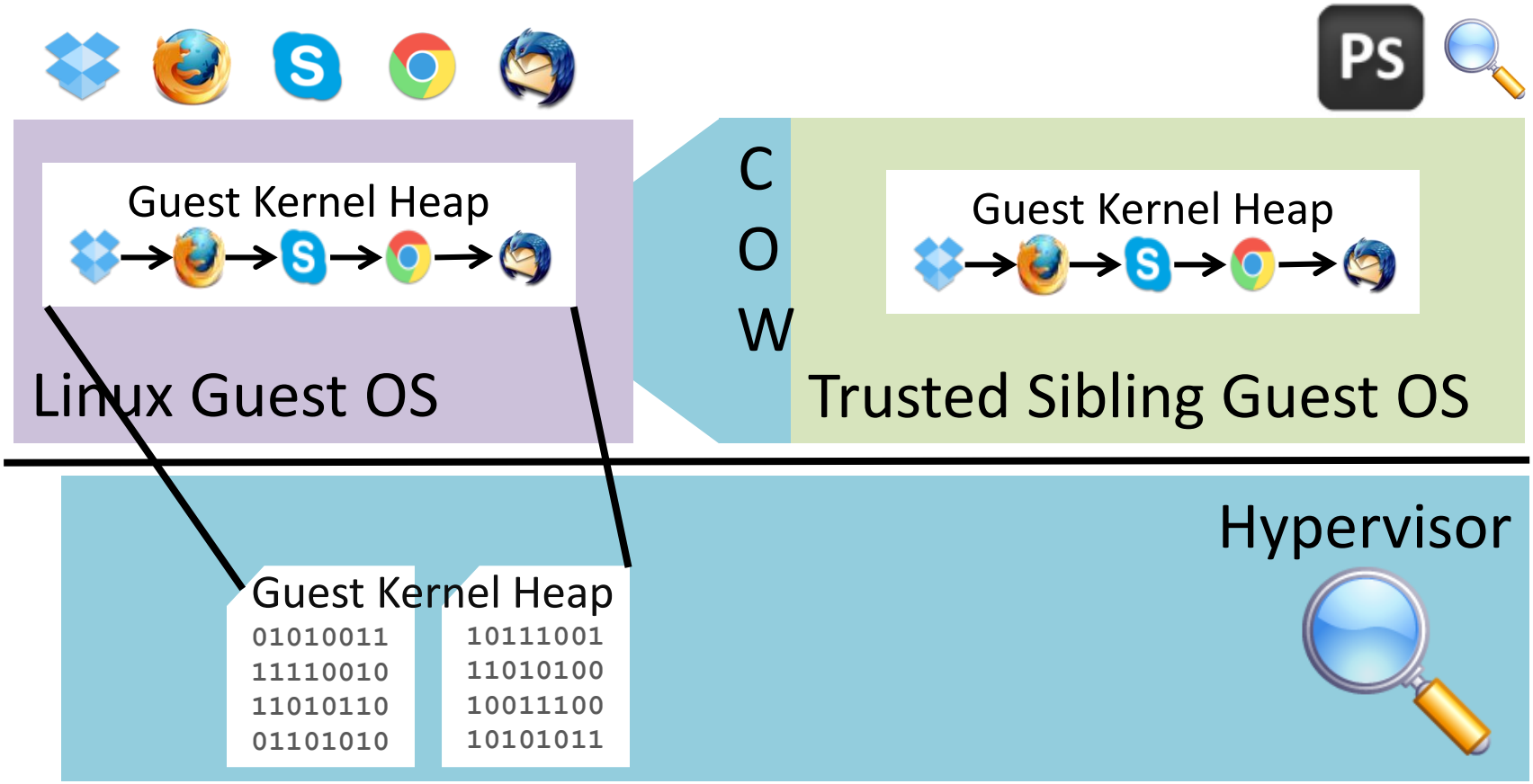

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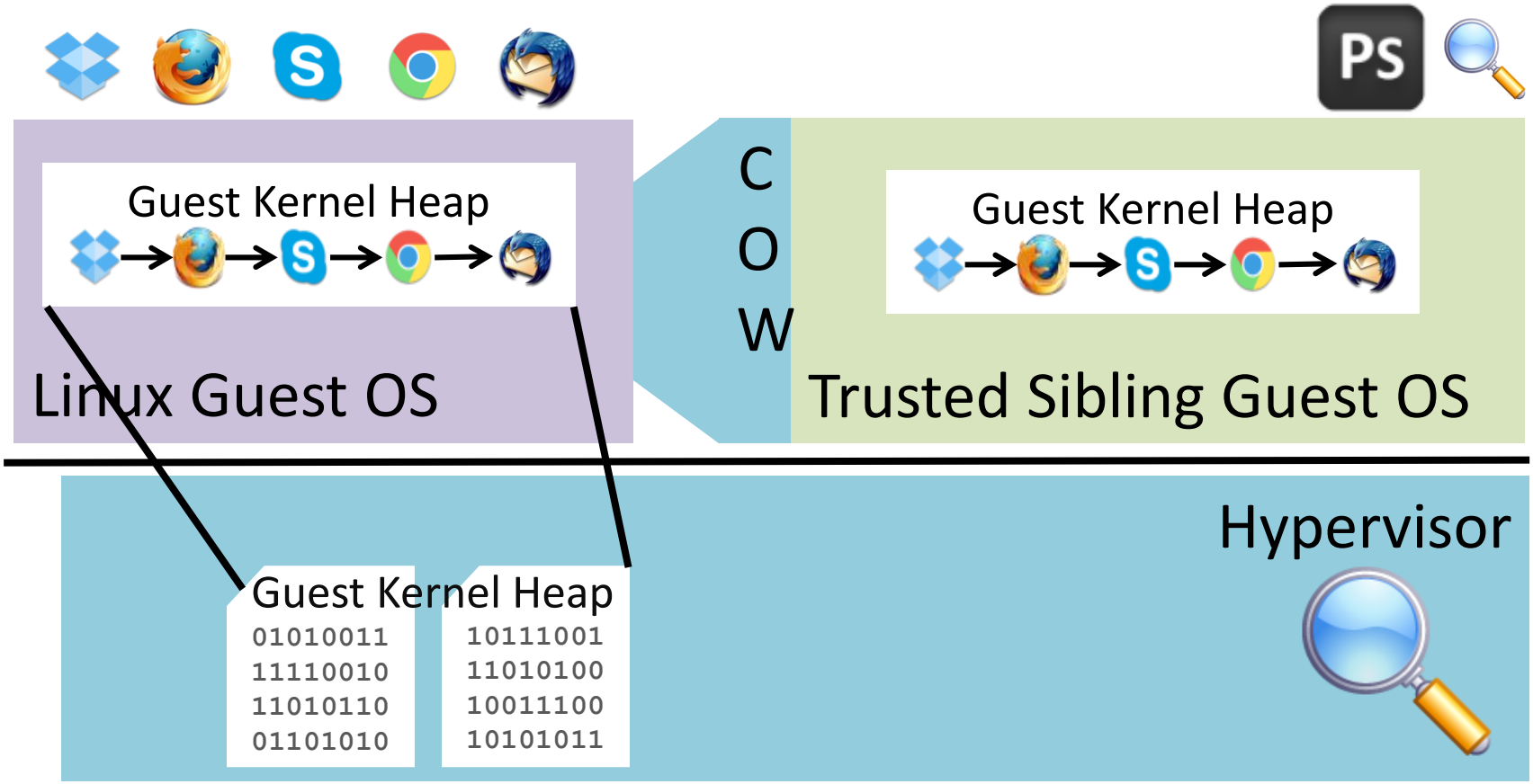
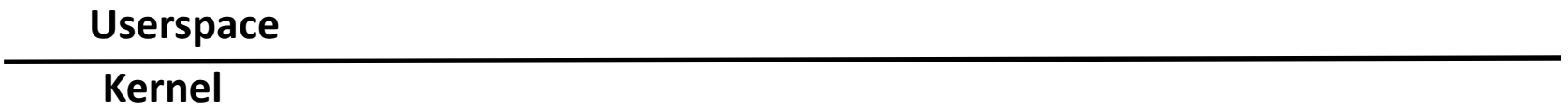


Reuse static trusted kernel code; Input runtime heap & data

Listing all the running processes



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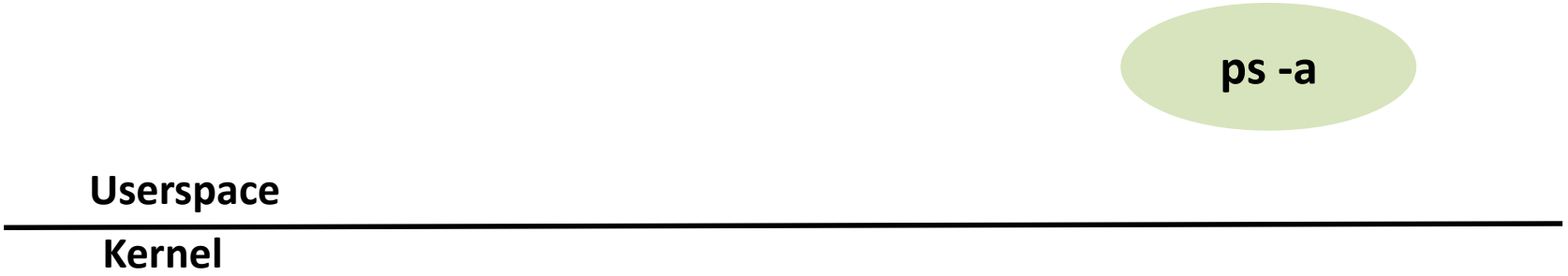

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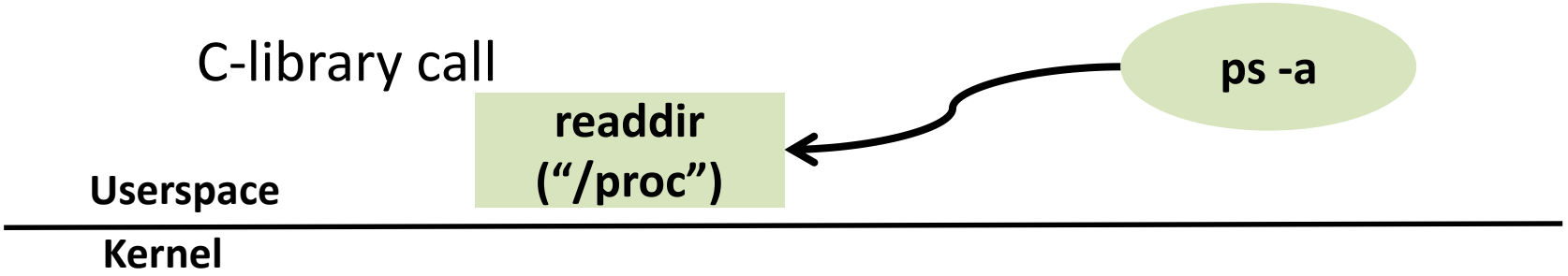

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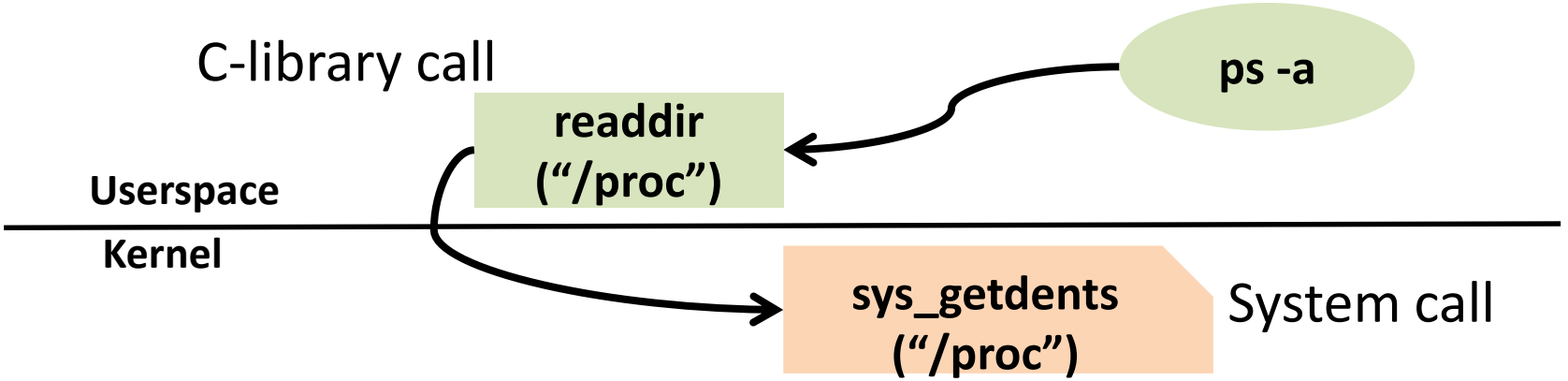

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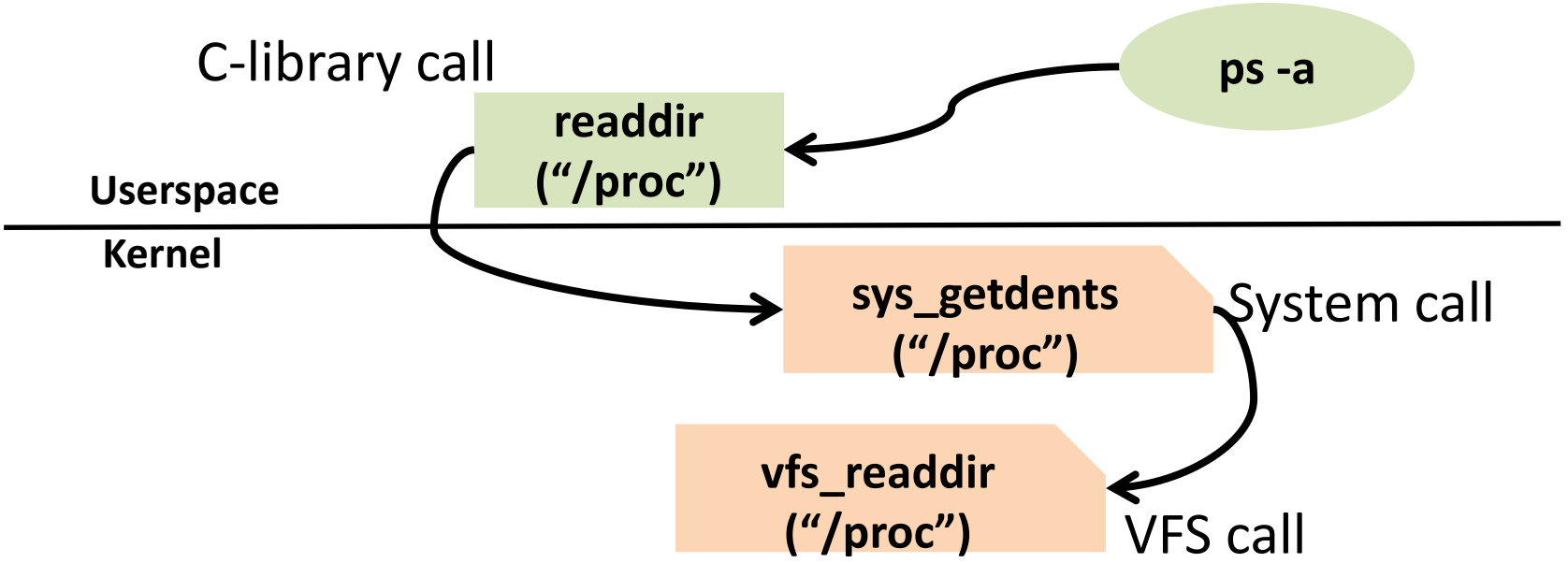

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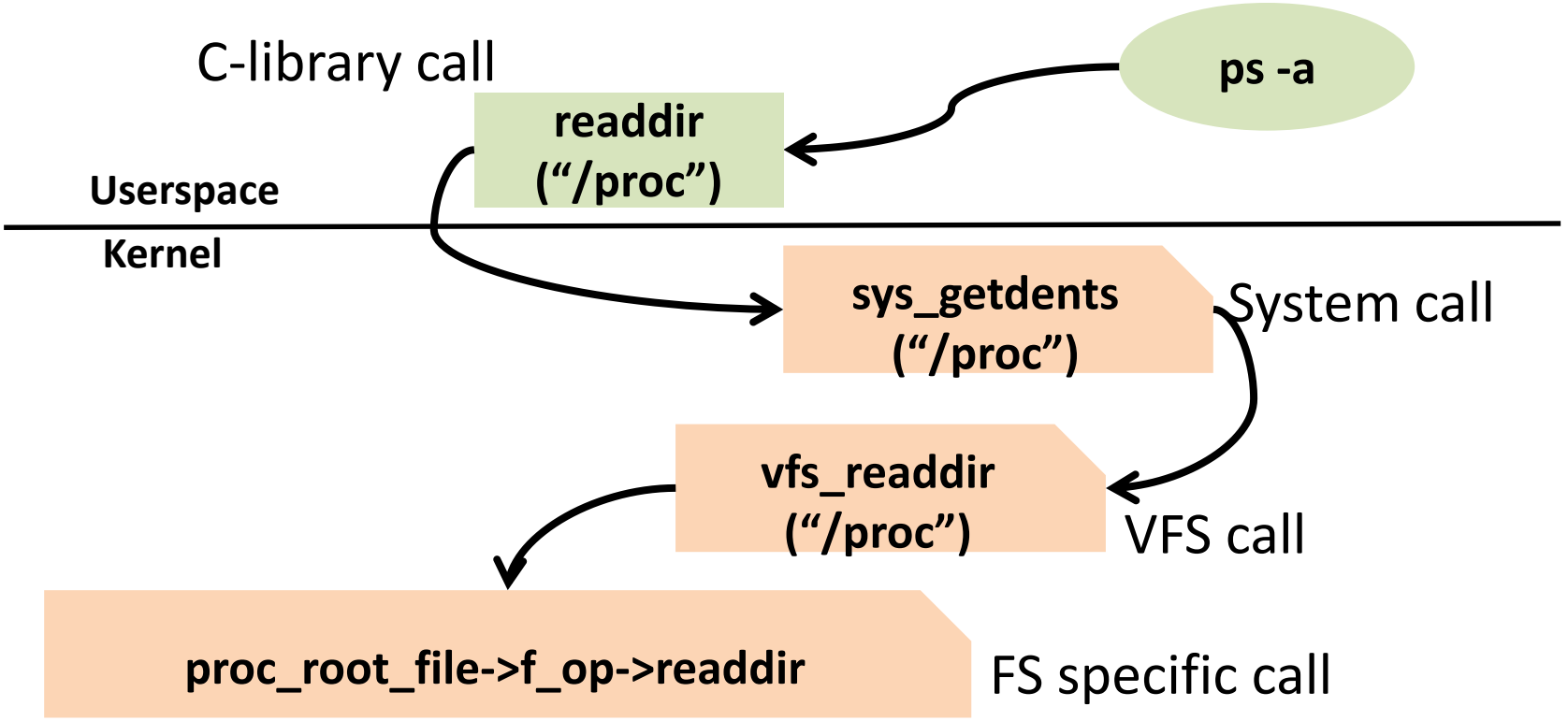

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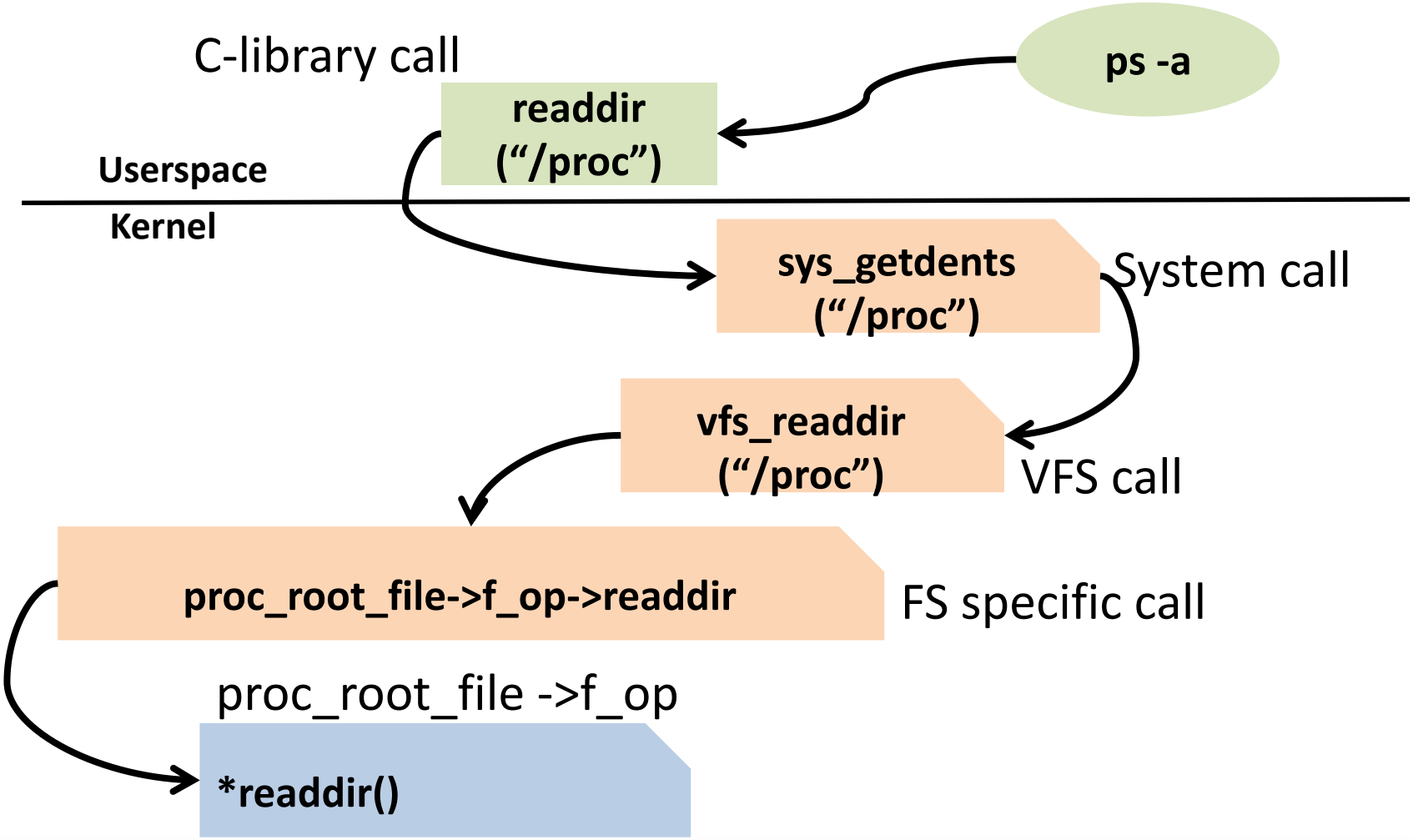
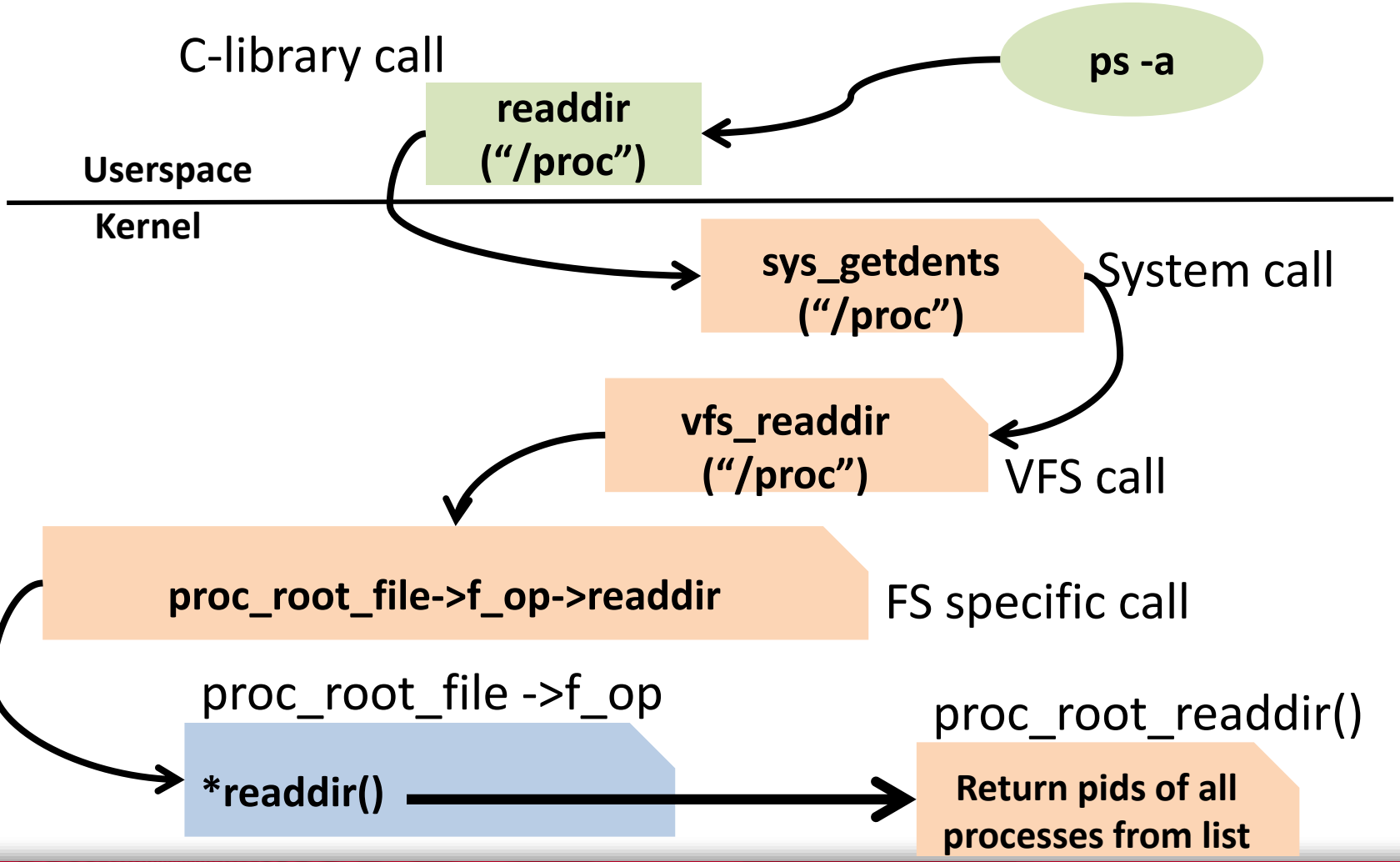


Listing all the running processes

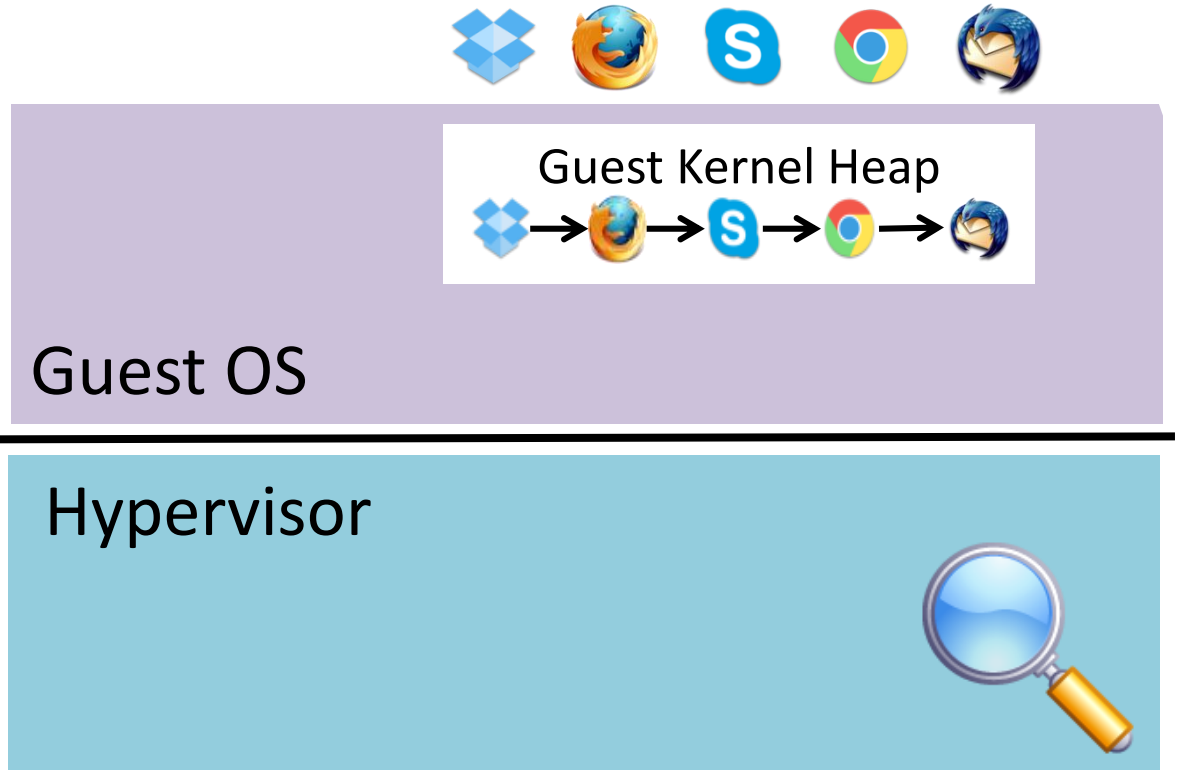


Trusted Guest Pervasive in VMI

Technique	Approach	Trust Guest That
Learn & Reconstruct	Learn template then search	➢Same OS behavior in learning and monitoring phases
Code Implanting	Monitoring inside guest OS	➢Guest OS reports correct information
Data Outgrafting	Use sibling VM; share memory	➢Identical guest OS behavior in monitored and trusted sibling VM

Current VMI techniques built on some level of trust in guest

Semantic Gap



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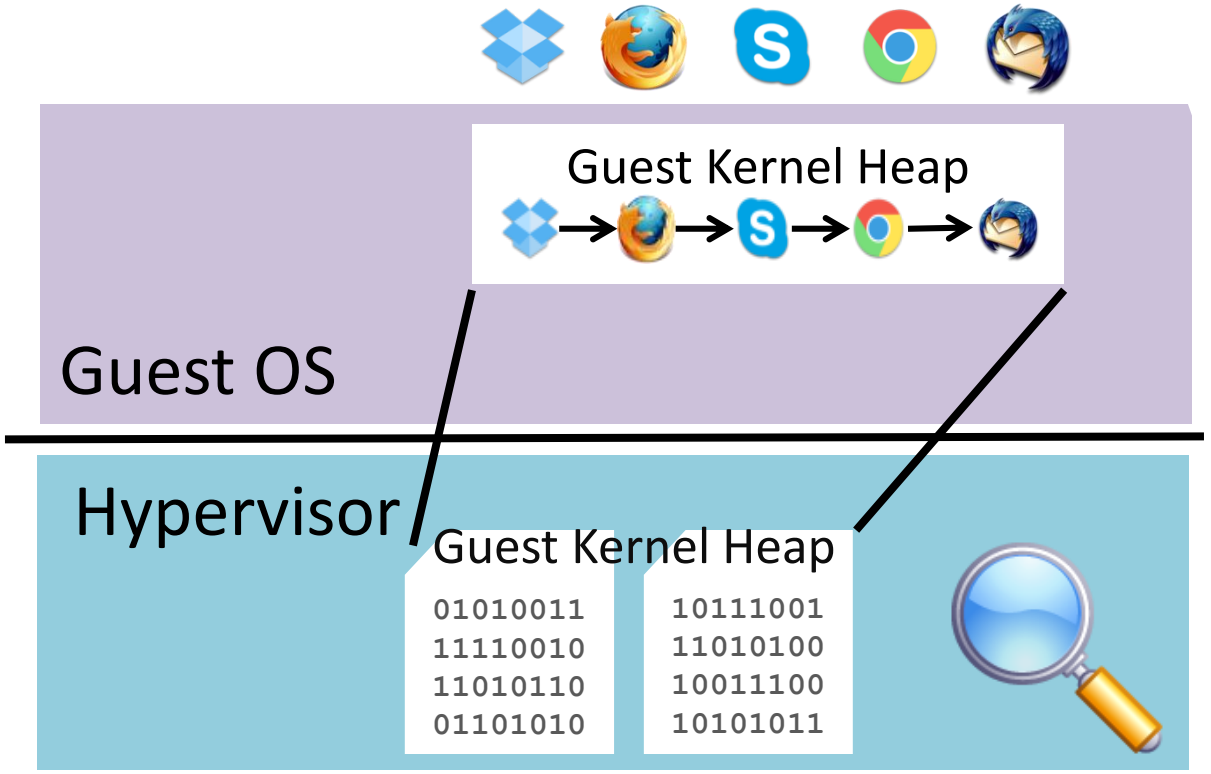

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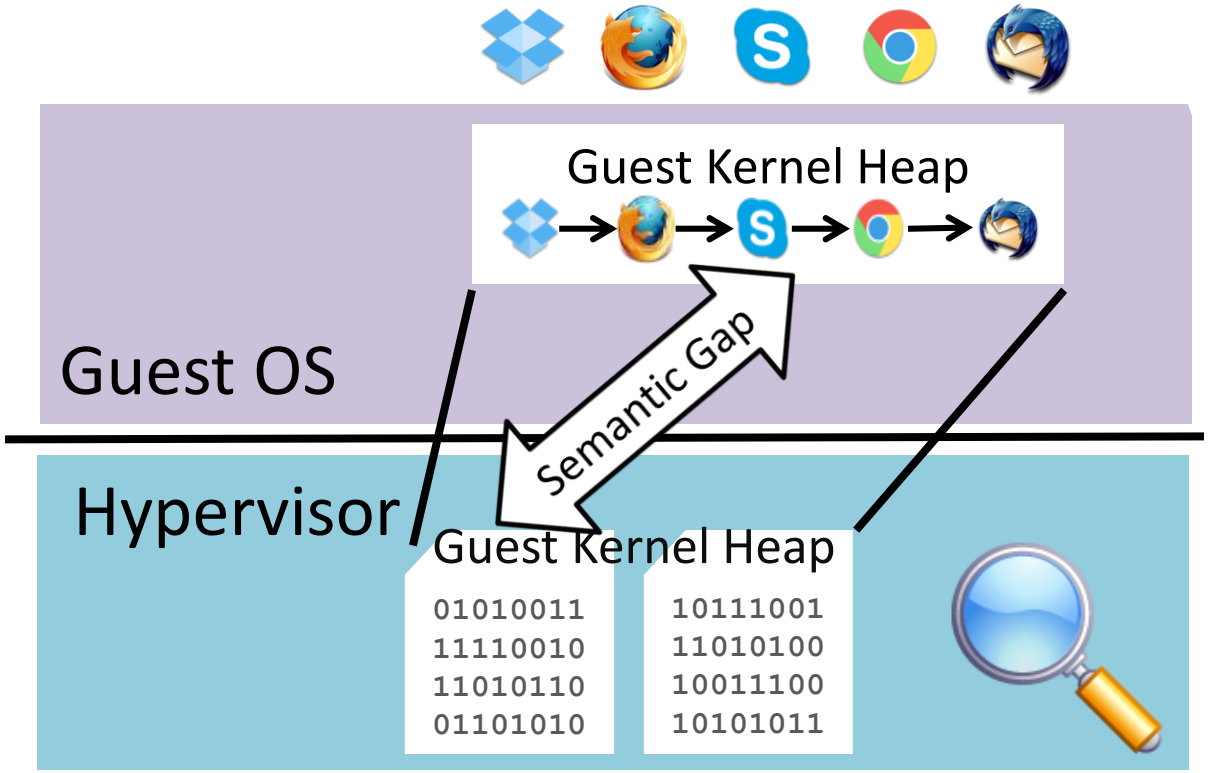

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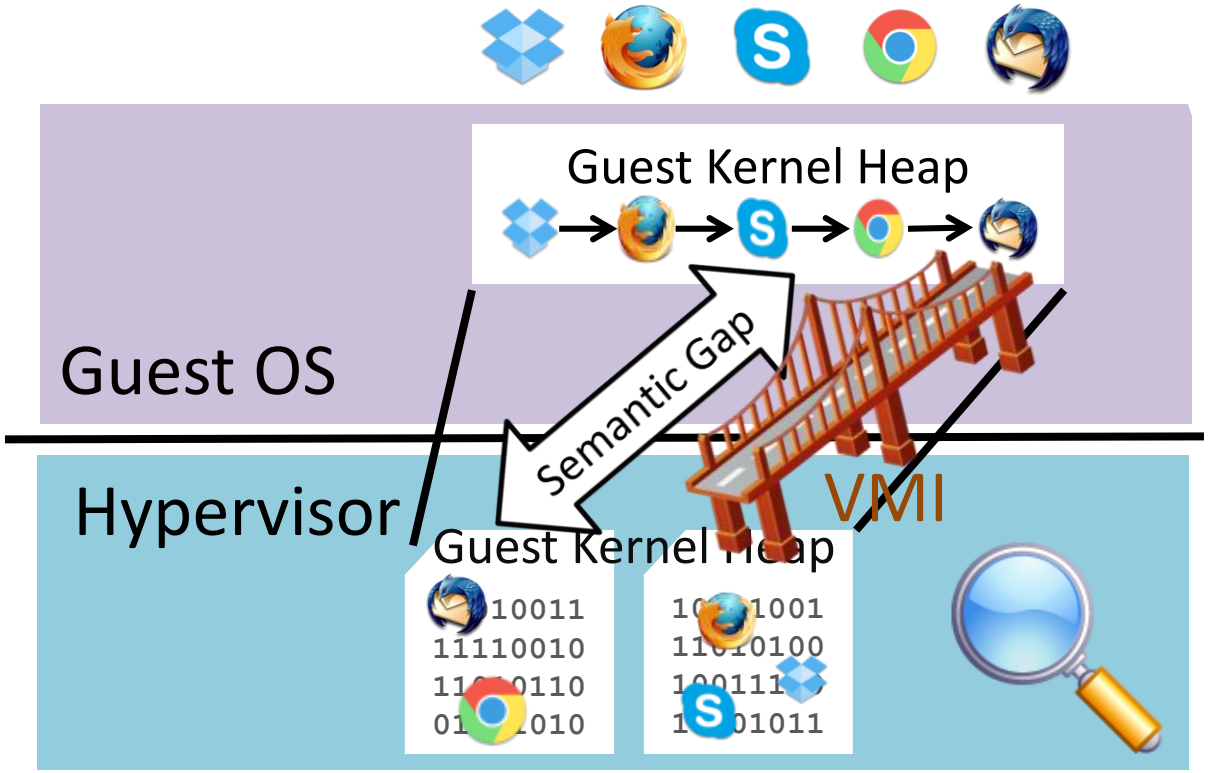

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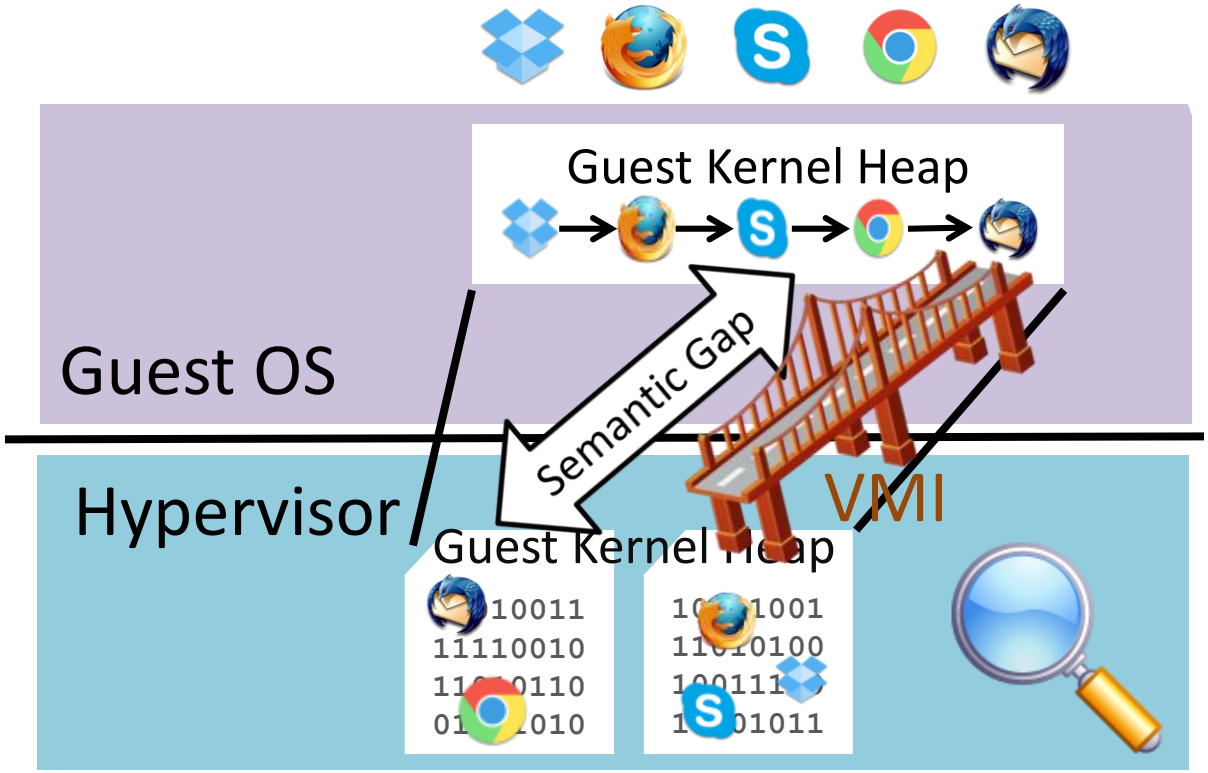

Need high level information; Available low level information

Semantic Gap: Details

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Hypervisor can observe	Monitor wants to observe
	Variable values

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CPU Registers	Variable values

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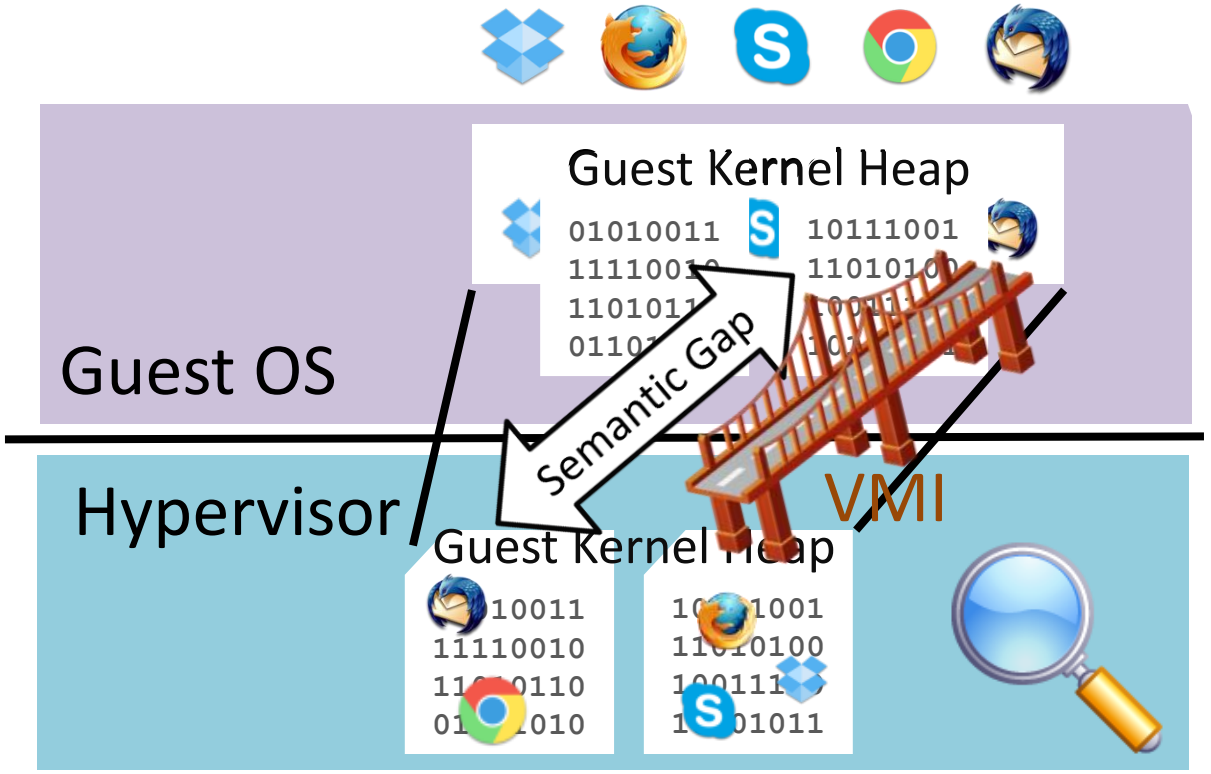
Semantic Gap: A challenge for VMI



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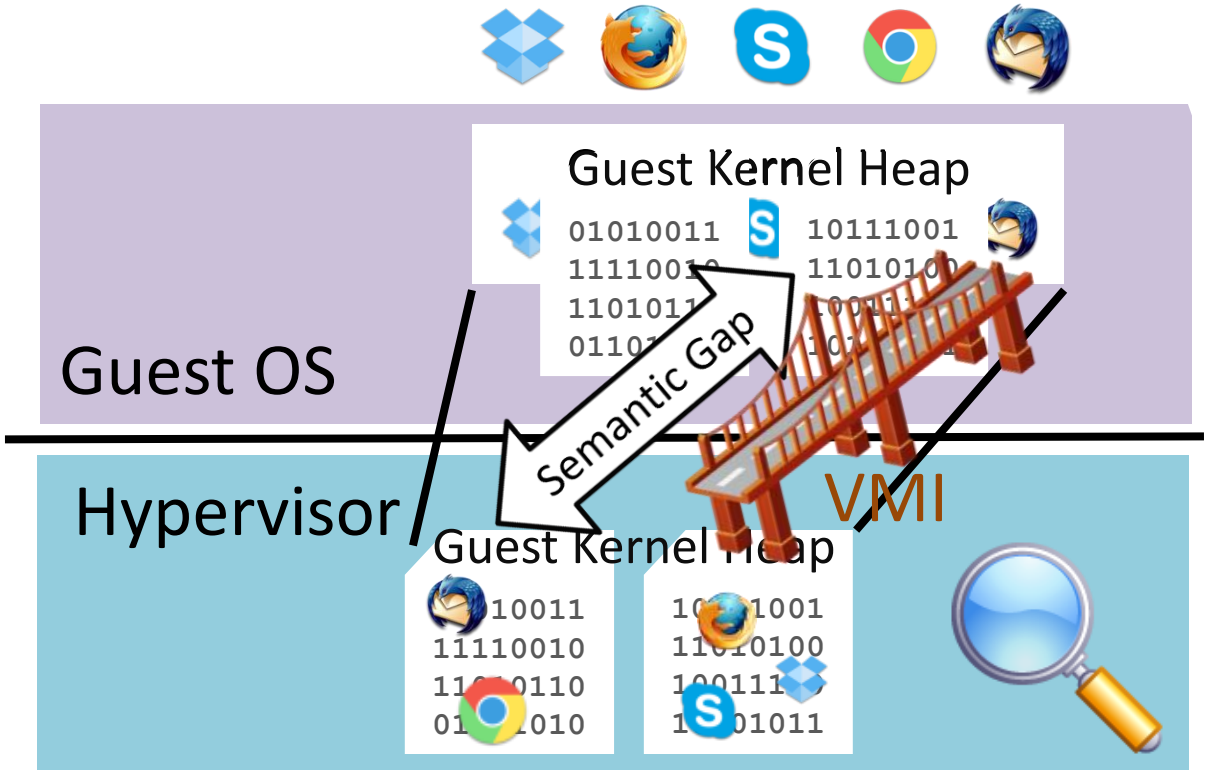
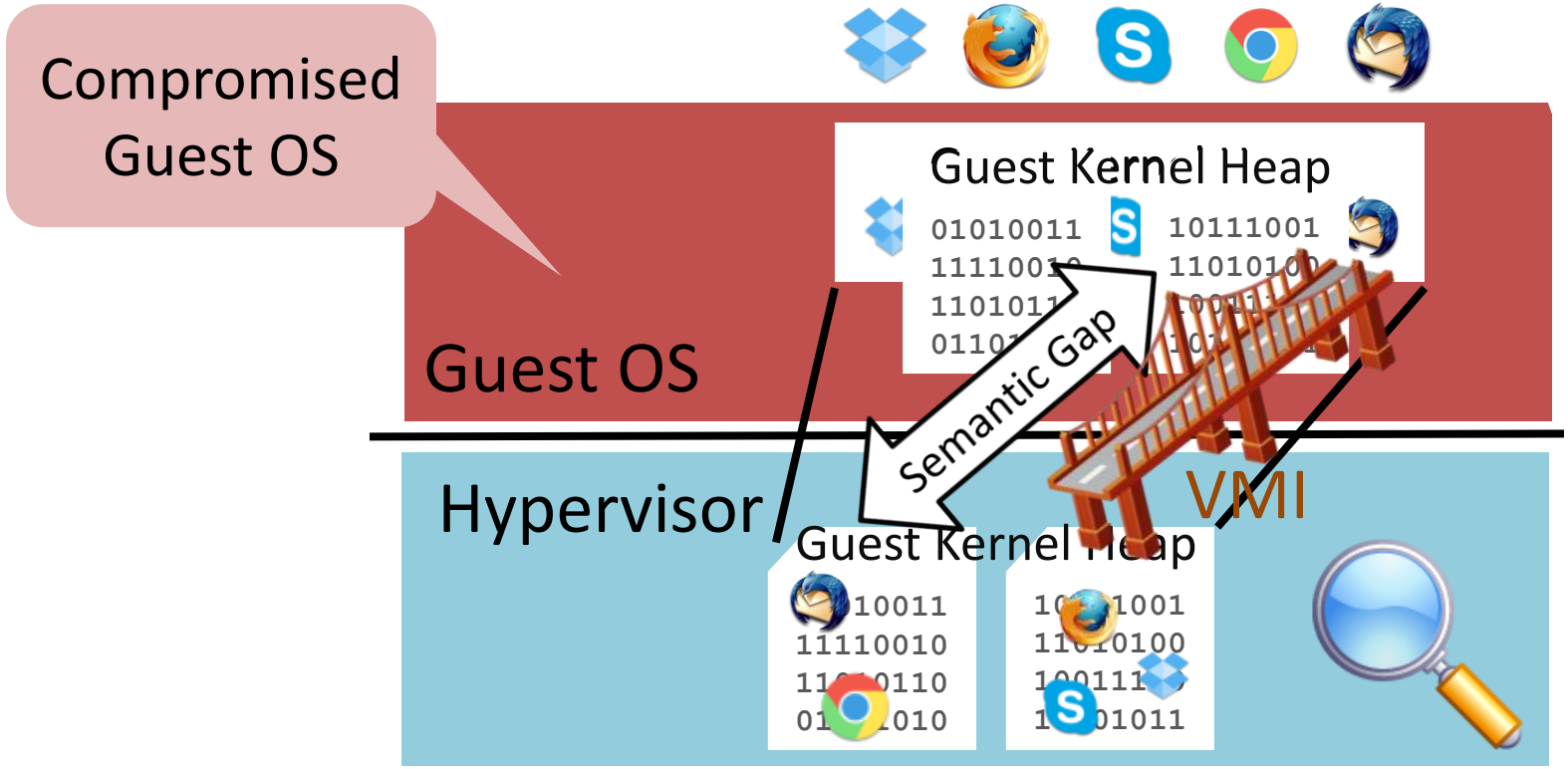


VMI Challenge : Bridge the semantic gap

Semantic Gap: A challenge for VMI



VMI Challenge : Bridge the semantic gap even for compromised guest

VMI: Rootkit Detection Technique

- VMI is building block for layered security
  - Trusted hypervisor monitors less trusted guest
- **Common VMI goal**:
  - List processes in guest and identify malicious ones
- **Rootkit goal**:
  - Confuse VMI & hide malicious process

Rootkit Attack Techniques

- **Write text Segment**
  - .
- Kernel Object Hooking (KOH)
- Direct Kernel Object Manipulation (DKOM)
- Dynamic Kernel Structure Manipulation (DKSM)

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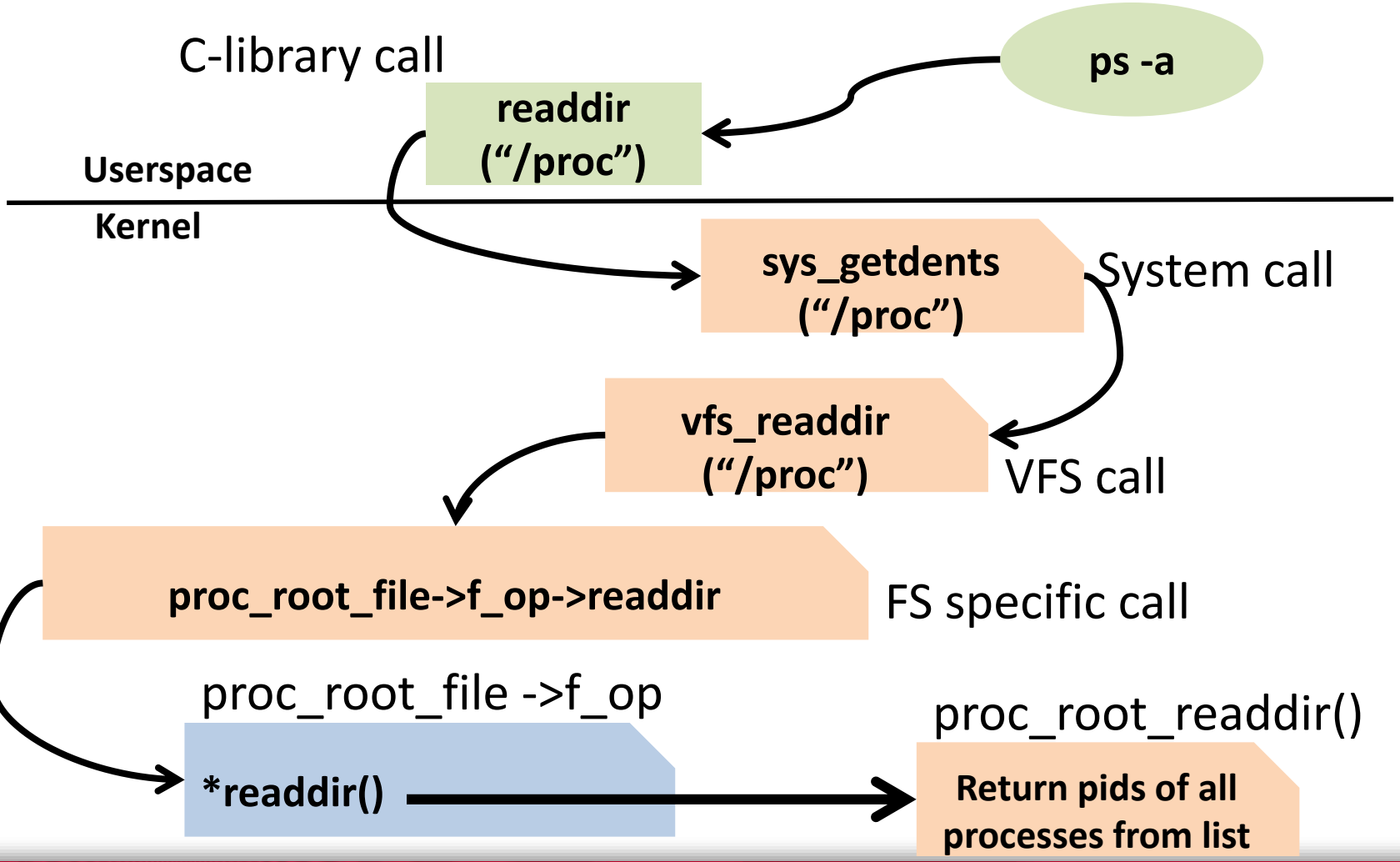

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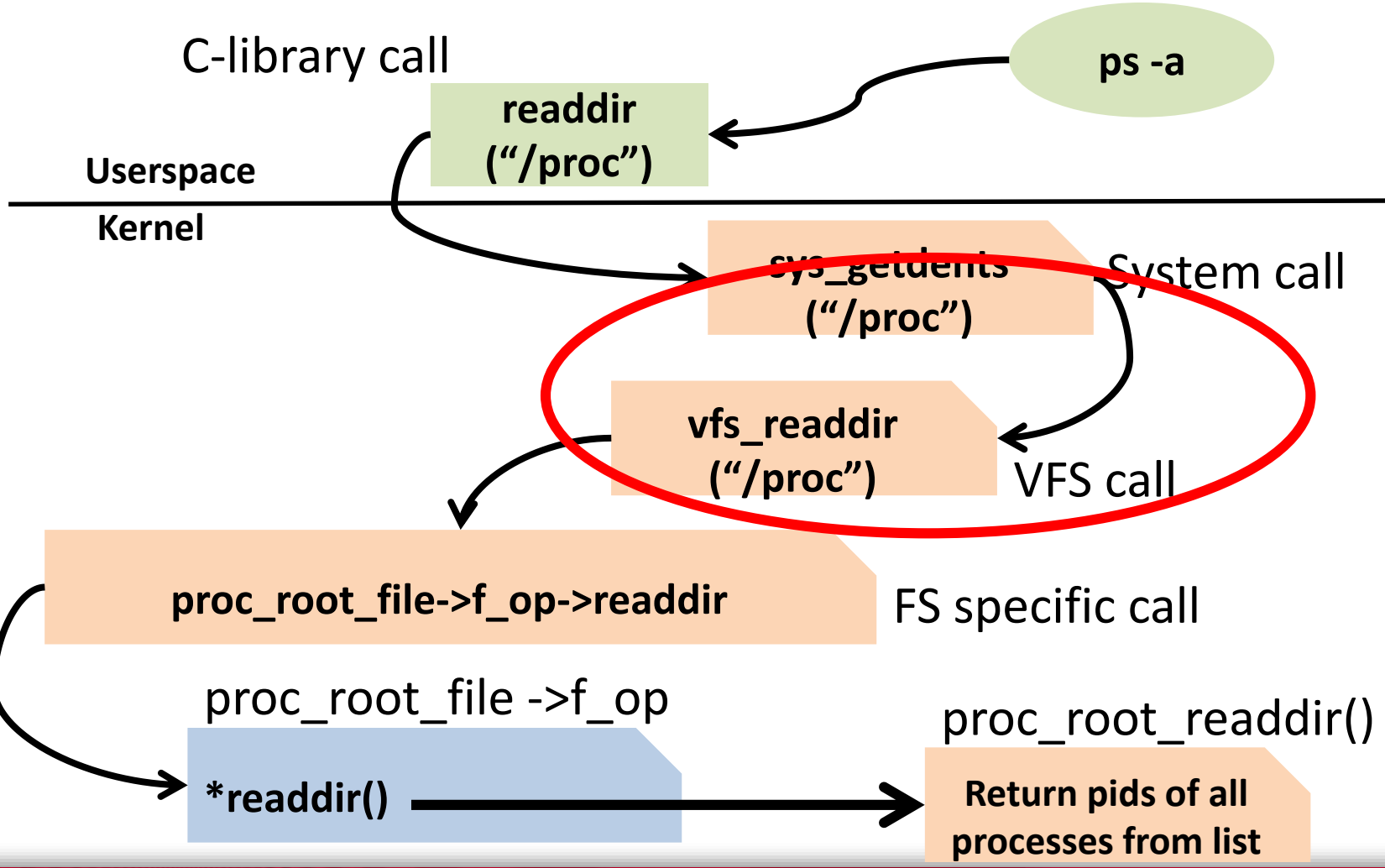

Change Text Section (1/2)

```
vfs_readdir()
{
        …
}

sys_getdents()
{
        …
        CALL vfs_readdir;
        …
}
```

Change Text Section (1/2)

```
vfs_readdir()
{
        …
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{
        …
        CALL mal_readdir;
        …
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```
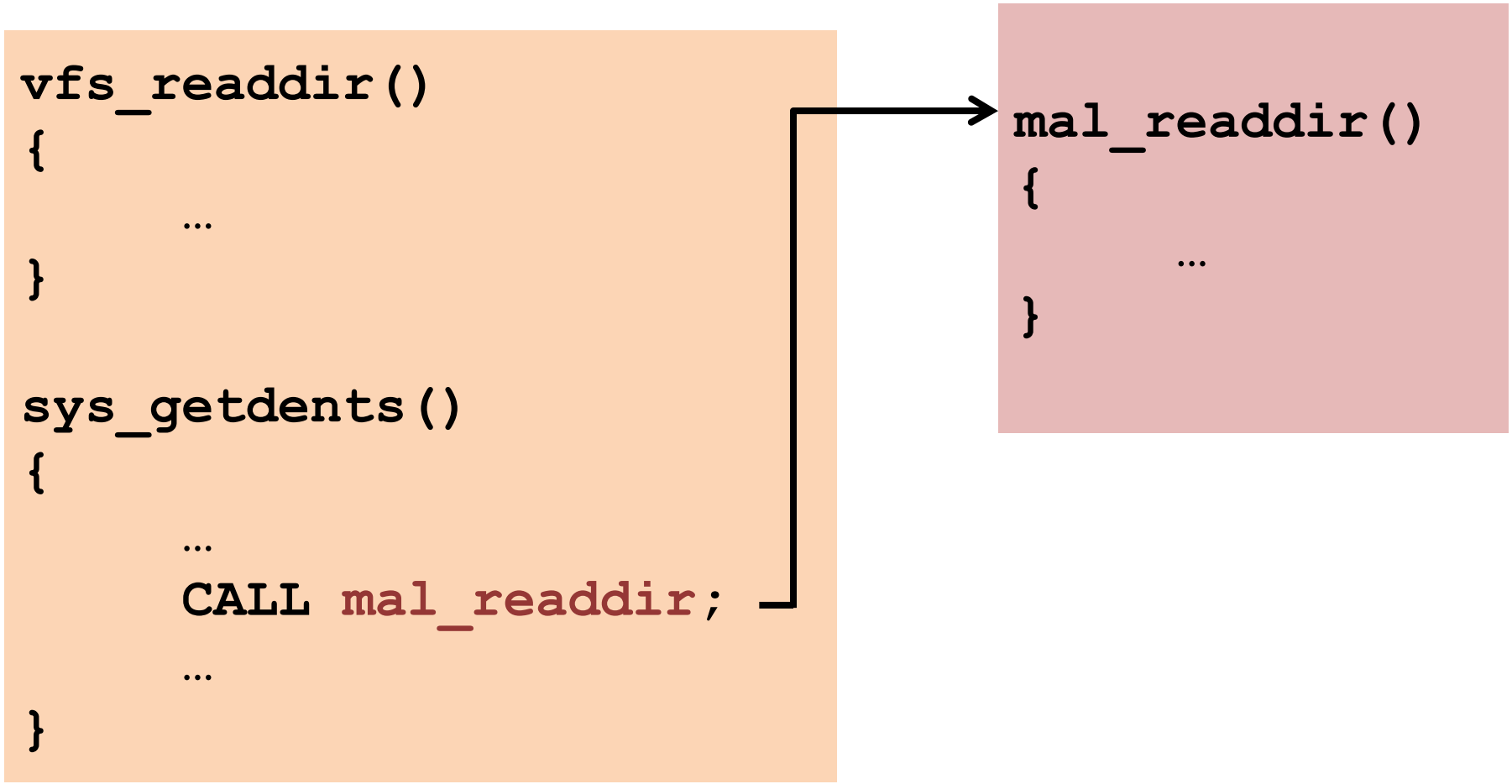

Change Text Section (1/2)



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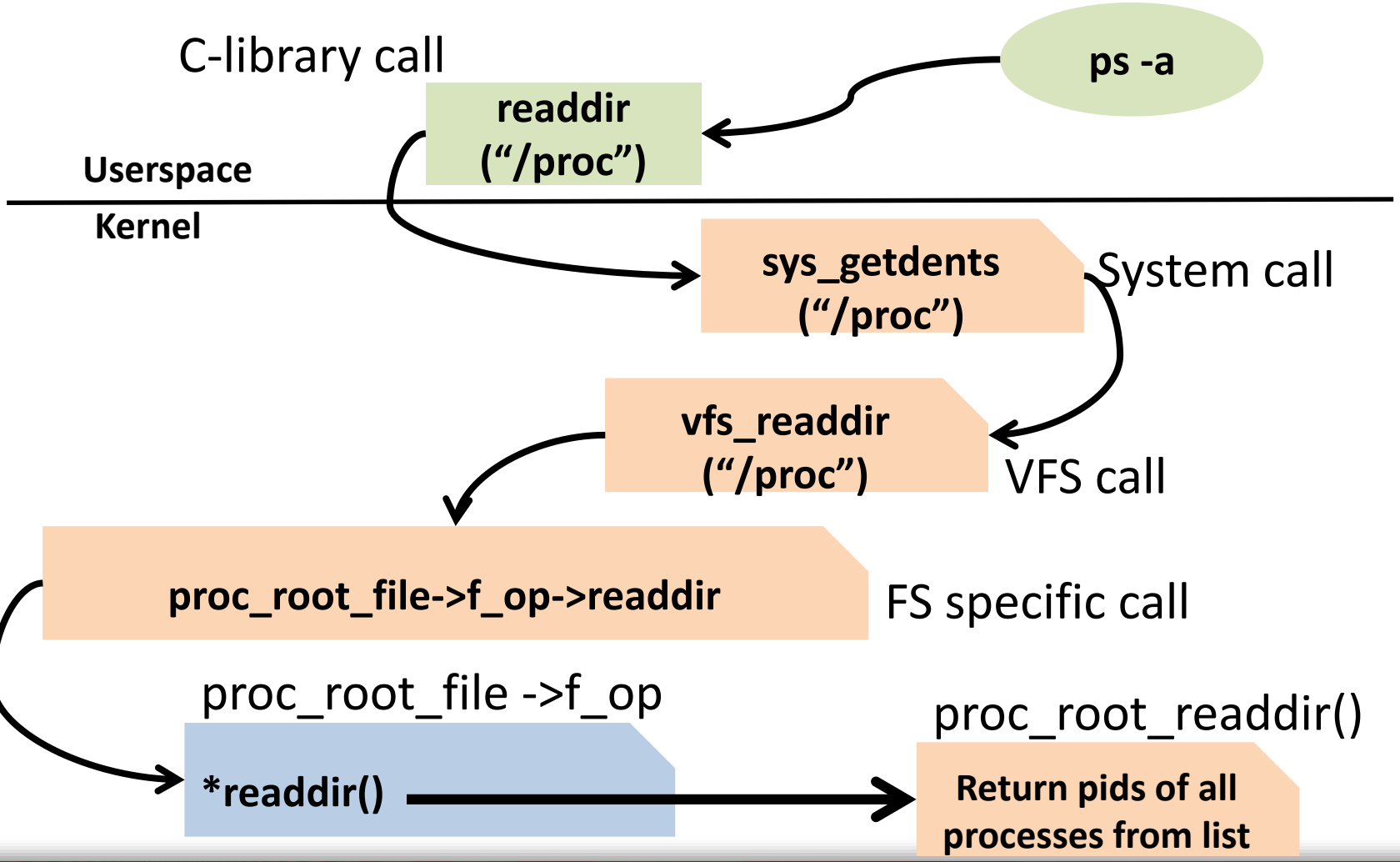

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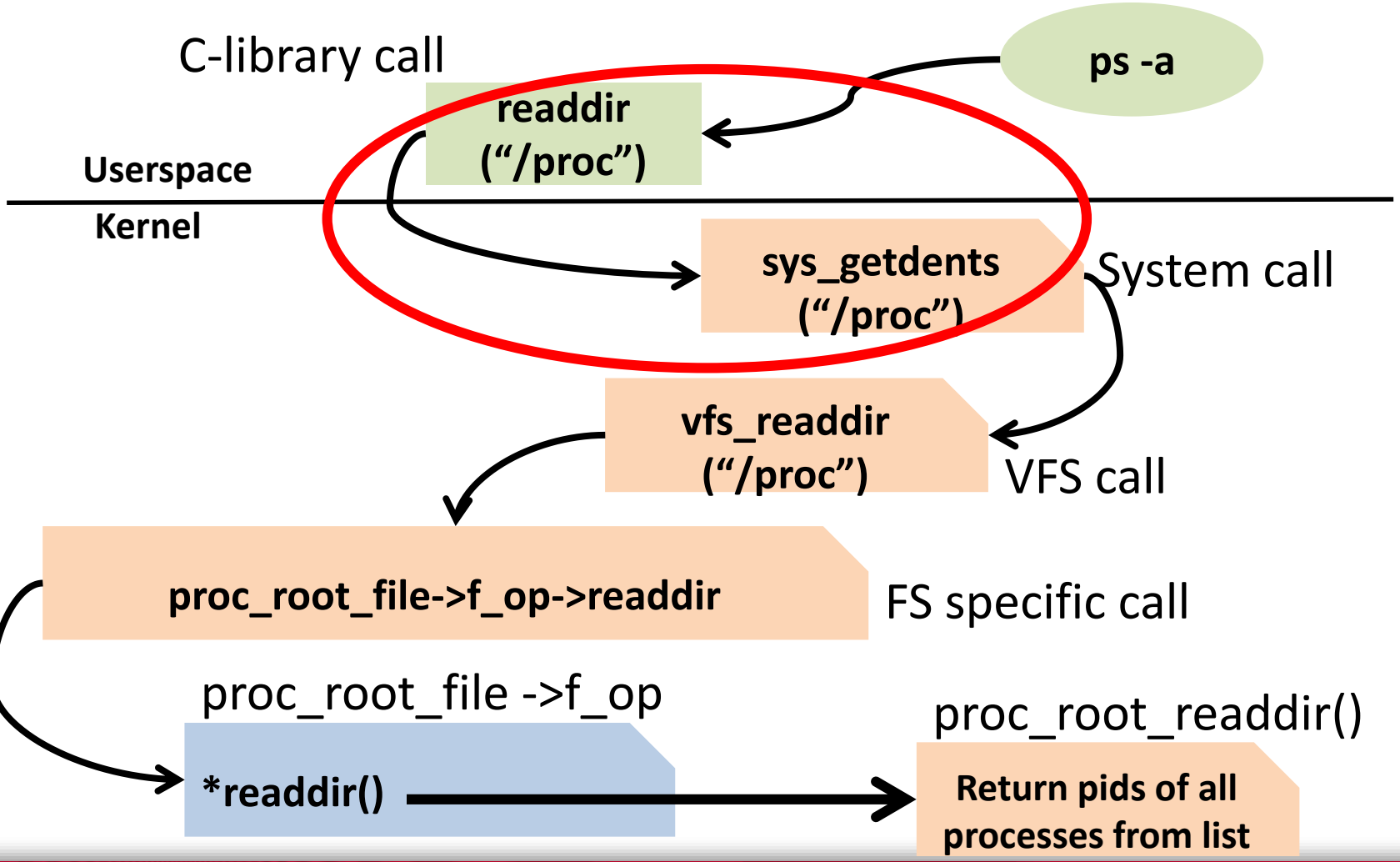
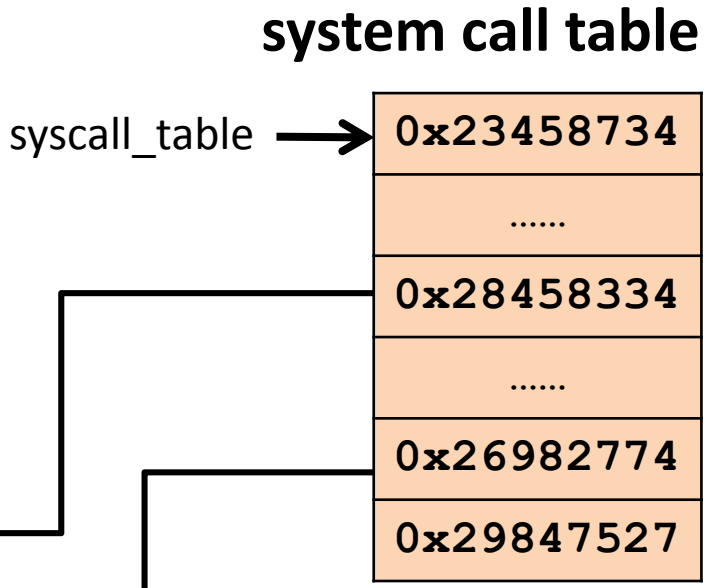


Change Text Section (2/2)

```
syscall_nr_getdents = 141
syscall_nr_open = 5
getdents:
CALL syscall_table[syscall_nr_getdents-1];
open:
CALL syscall_table[syscall_nr_open-1];
```

```
sys_open()
{
   …
}
```

```
sys_getdents()
{
   …
}
```



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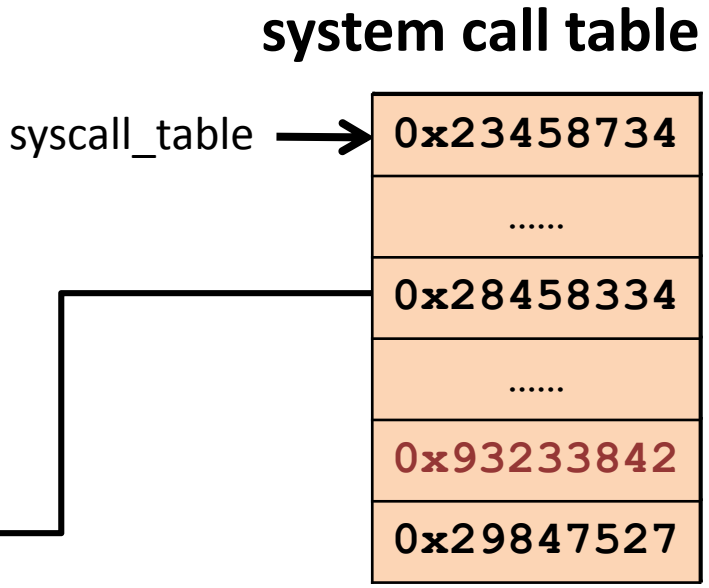

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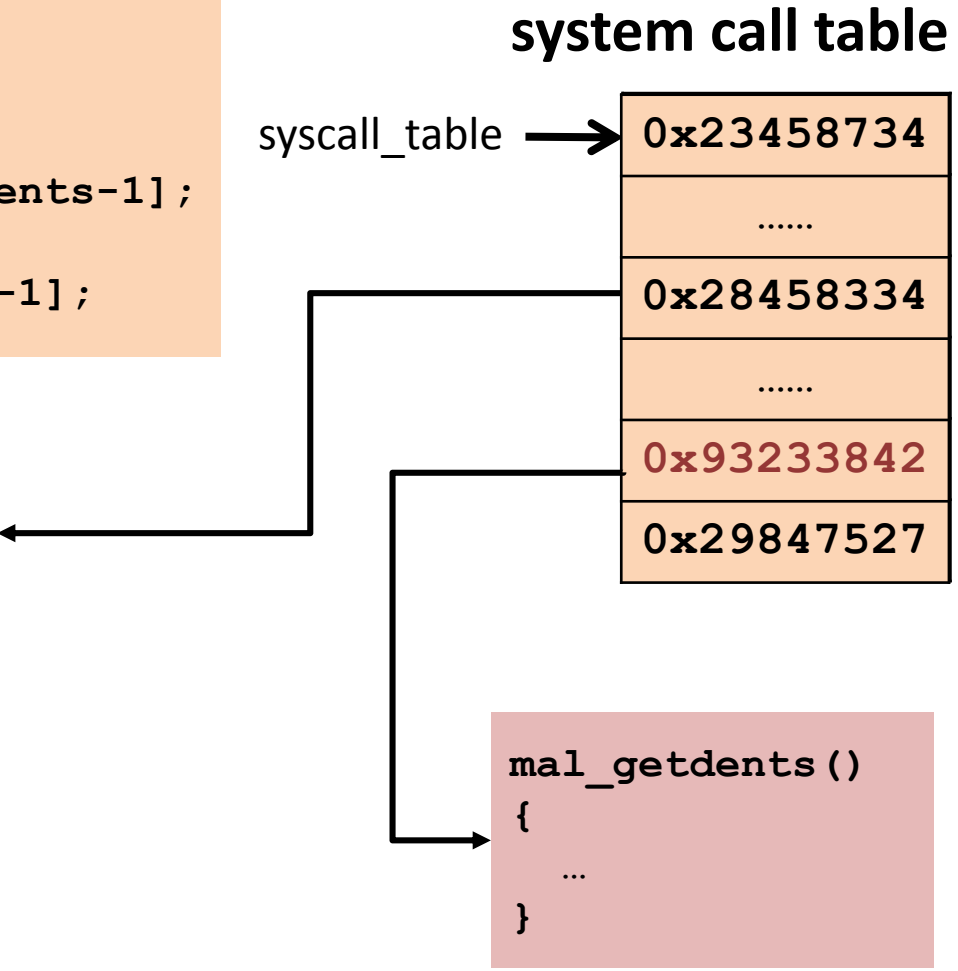

Write Text Segment Trust

- **Attack**: Change control flow by writing text segment
  -
-
  -
  -
  -
-

Write Text Segment Trust

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-
  -
  -
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  - Prevent guest from overwriting executable code pages
  - State of Art: SecVisor[8]
-

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Cannot prevent attacks on control data in data segment

Rootkit Attack Techniques

- **Write text Segment**
  - Change `call` instruction argument
- **Kernel Object Hooking (KOH)**
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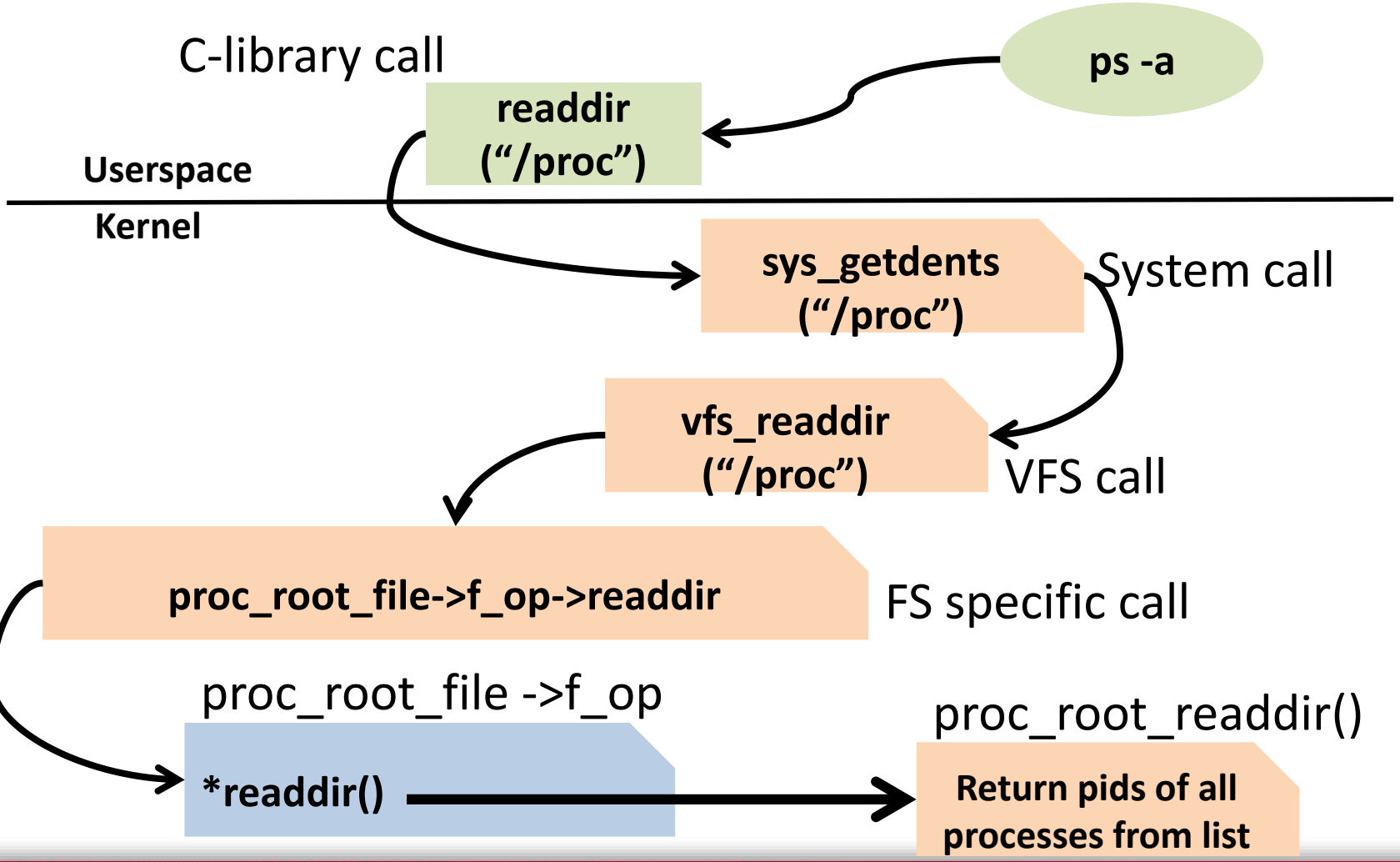

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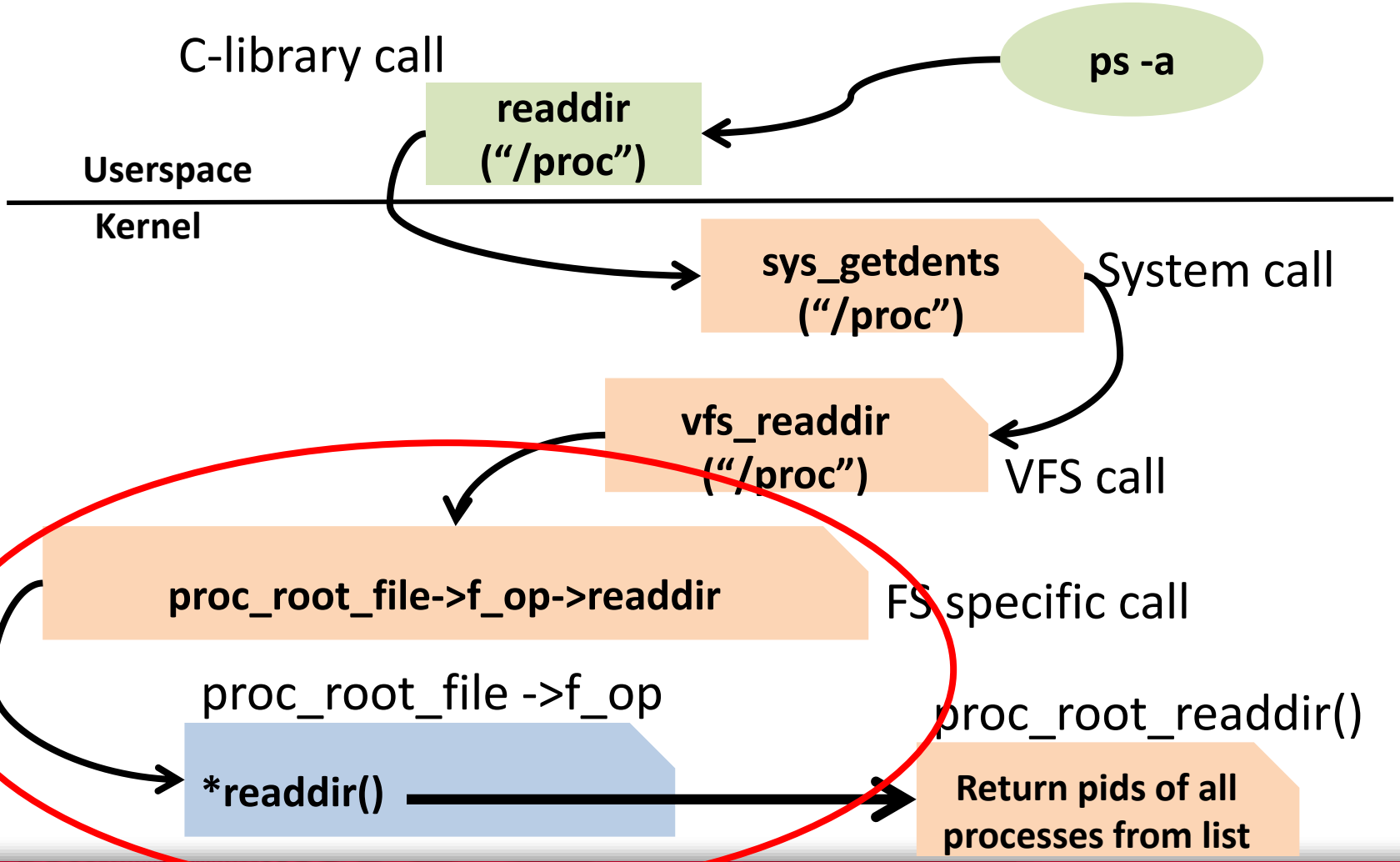

Kernel Object Hooking (KOH)

```
struct file{
   …
   struct path f_path;
   const struct file_operations
        *f_op;
   struct fown_struct f_owner;
   void *f_security;
   fmode_t f_mode;
   off_t f_pos;
   …
}
```

file struct object for /proc

```
struct file_operations{
   …
   int (*open) (struct inode
*, struct file *);
   ssize_t (*read) (struct
file *, char __user *,
size_t, loff_t *);
   int (*readdir) (struct
file *, void *, filldir_t);
   …
}
```

file_operations object for /proc

```
proc_root_readdir(){
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```

readdir code for proc filesystem

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file_operations object for /proc

```
proc_root_readdir(){
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}
```

readdir code for proc filesystem

```
mal_readdir(){
   …
}
```

KOH Defense Trust Assumptions

- **Attack**: Change function pointers in objects
- **Defense**: Protect initialized function pointers
  - Redirect hooks to write protected memory
  - State of Art: HookSafe[9]
- **Trust Assumption**: Pristine initial OS copy
  - Administrator can white-list safe modules
  - All hooks are learned during dynamic analysis

Cannot protect data fields in heap section

Rootkit Attack Techniques

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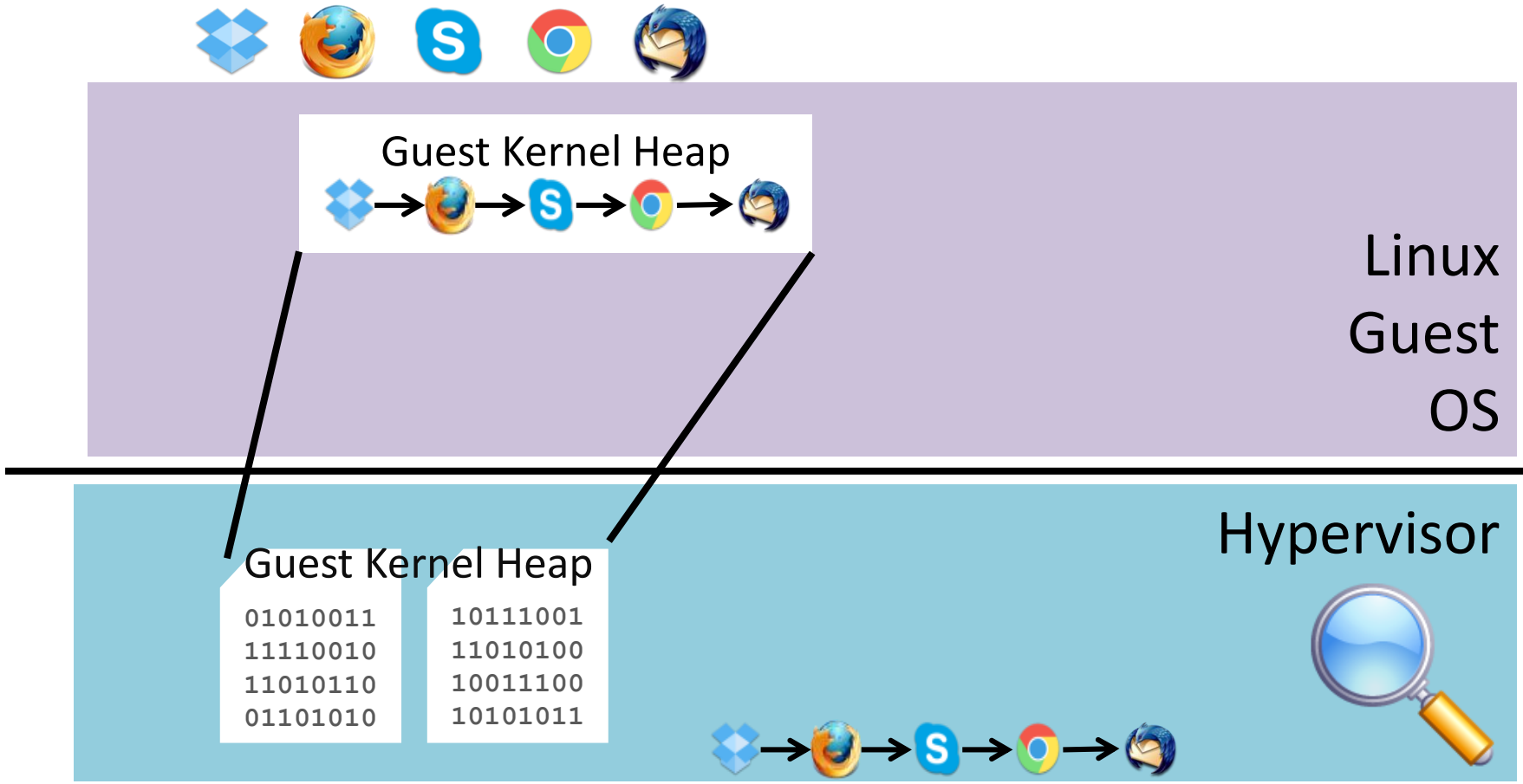

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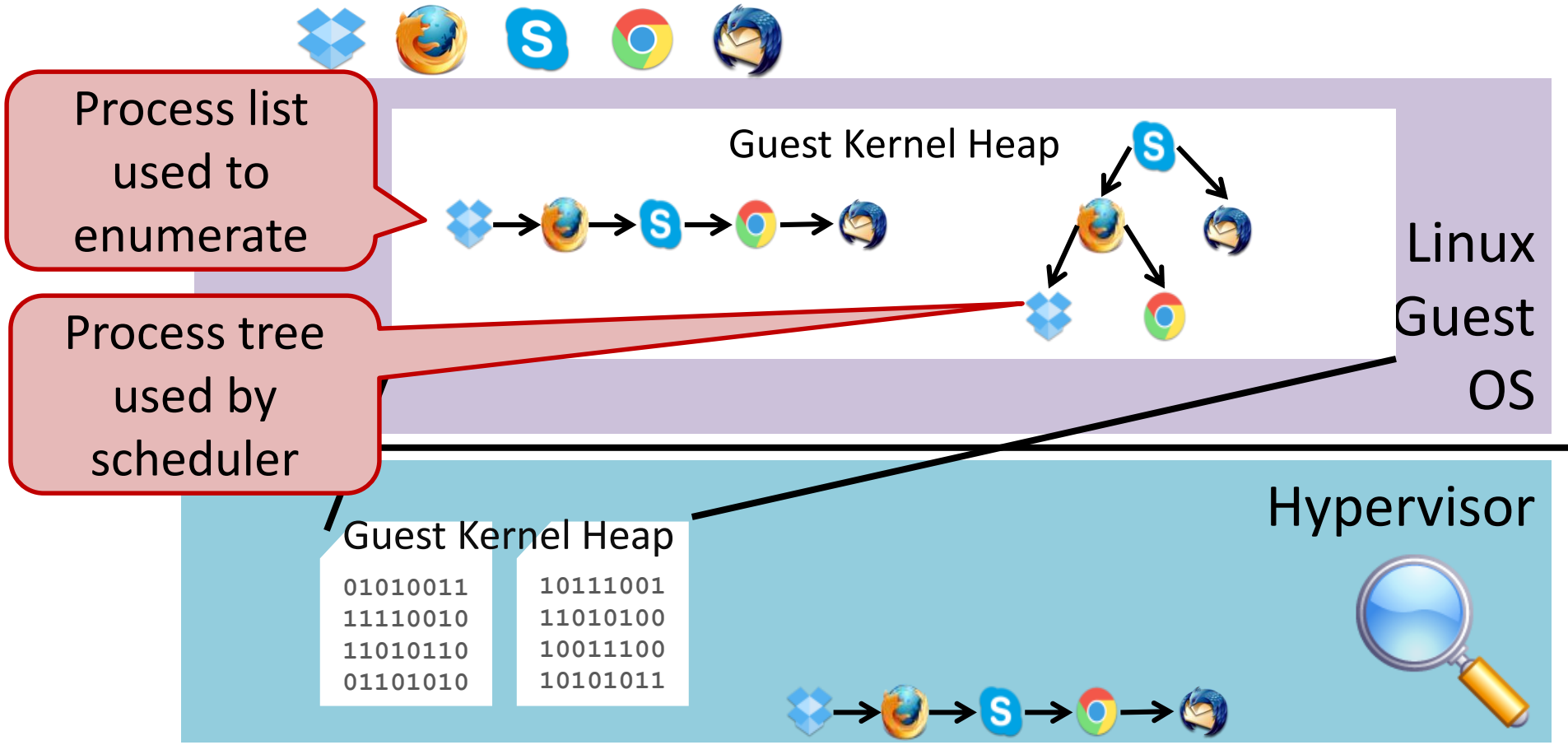

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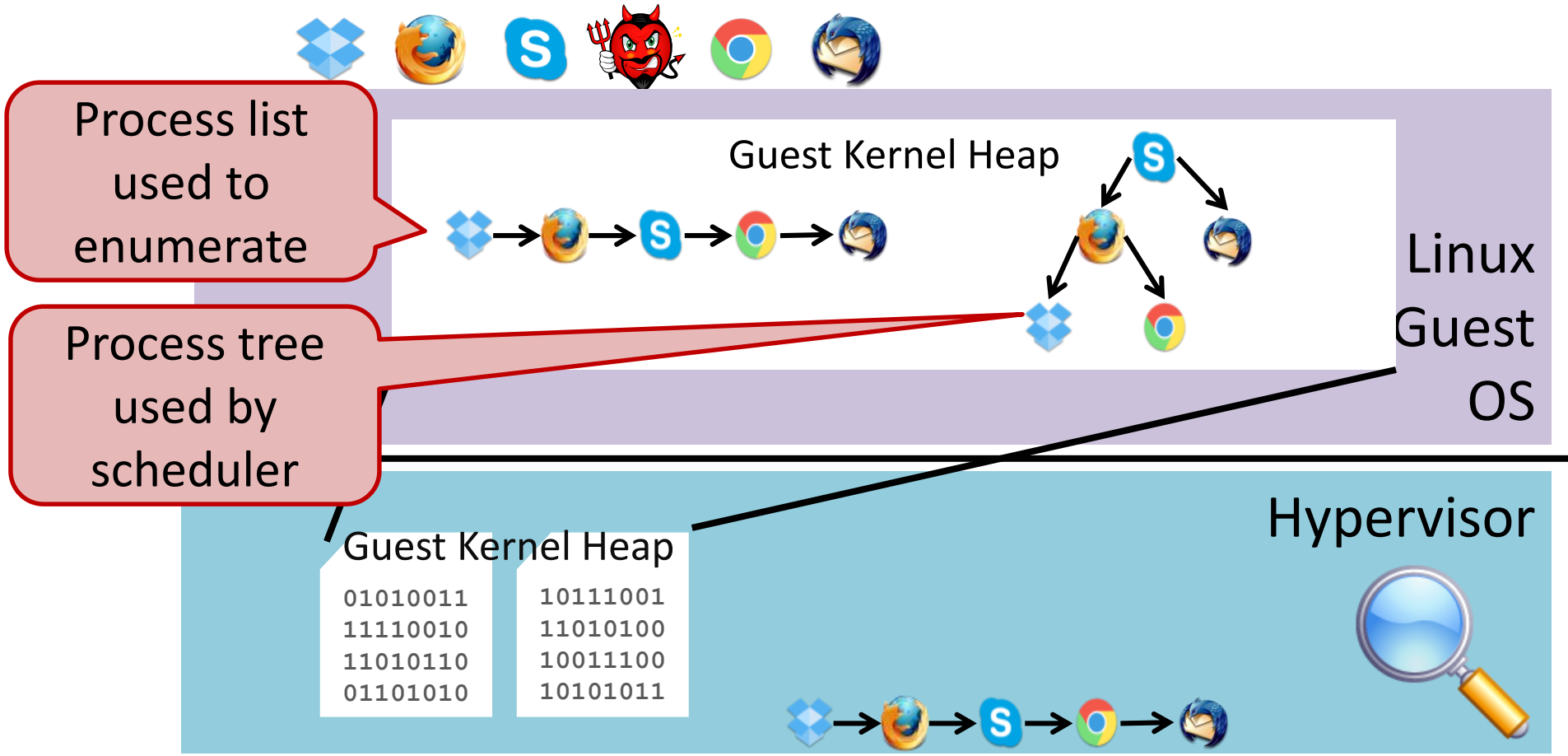

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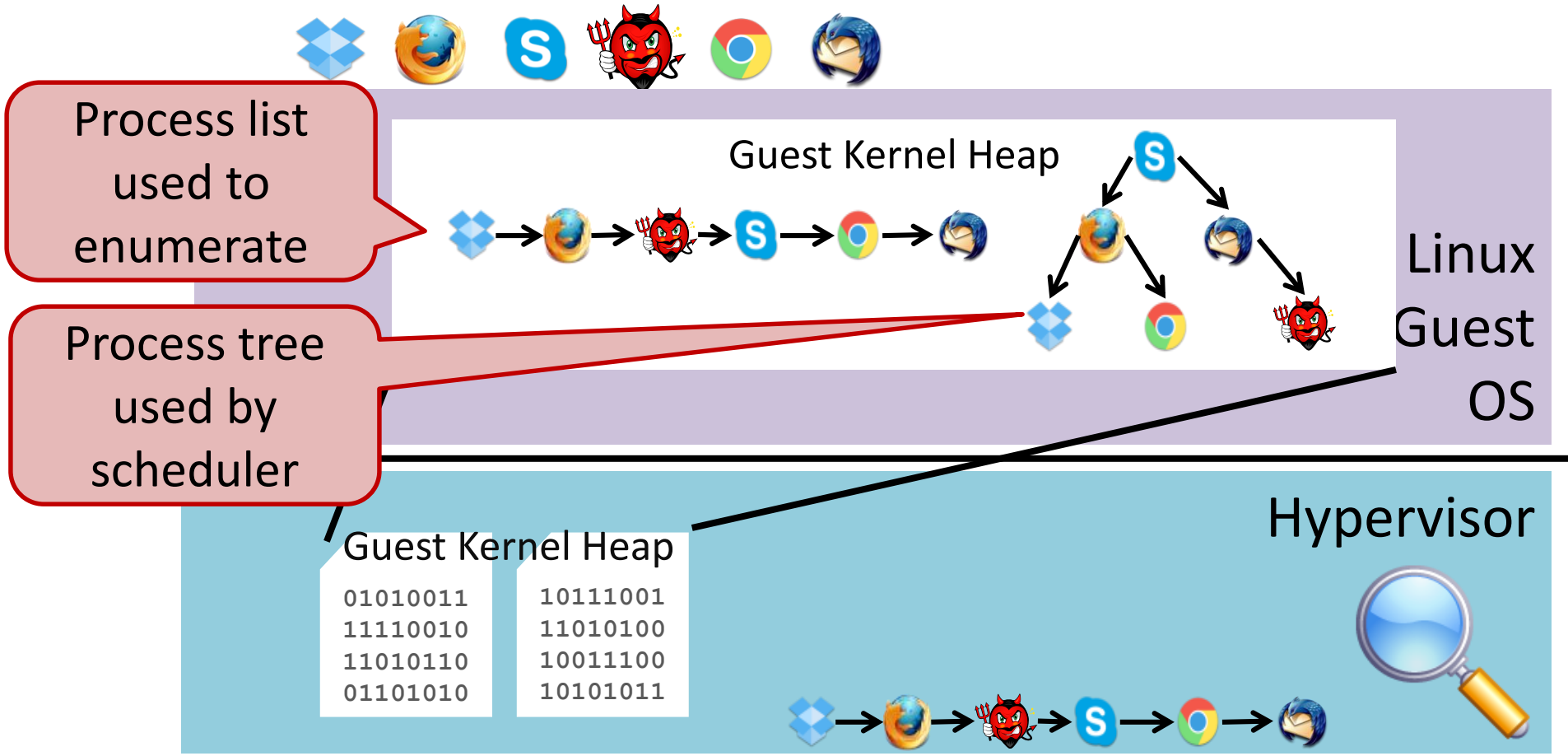

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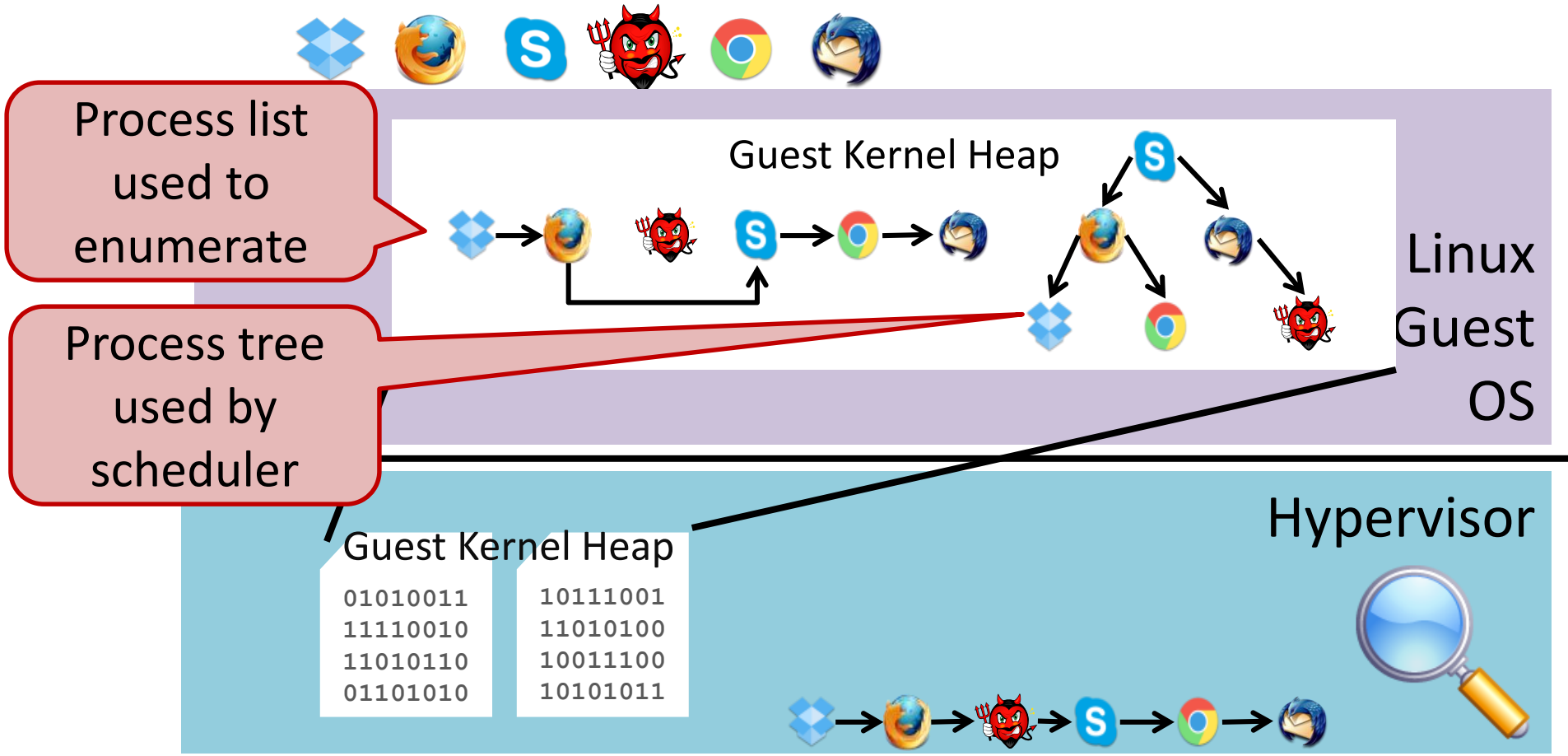

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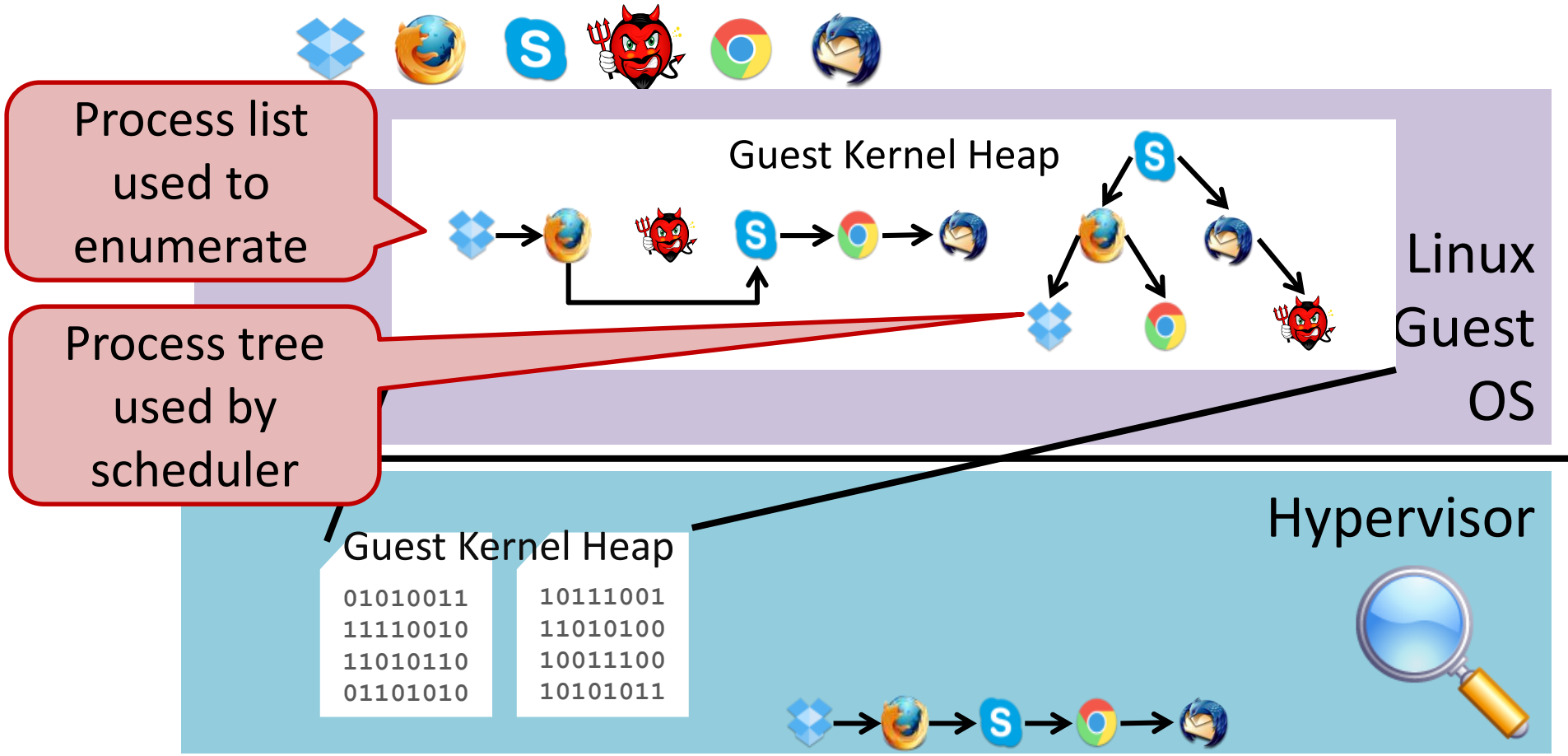

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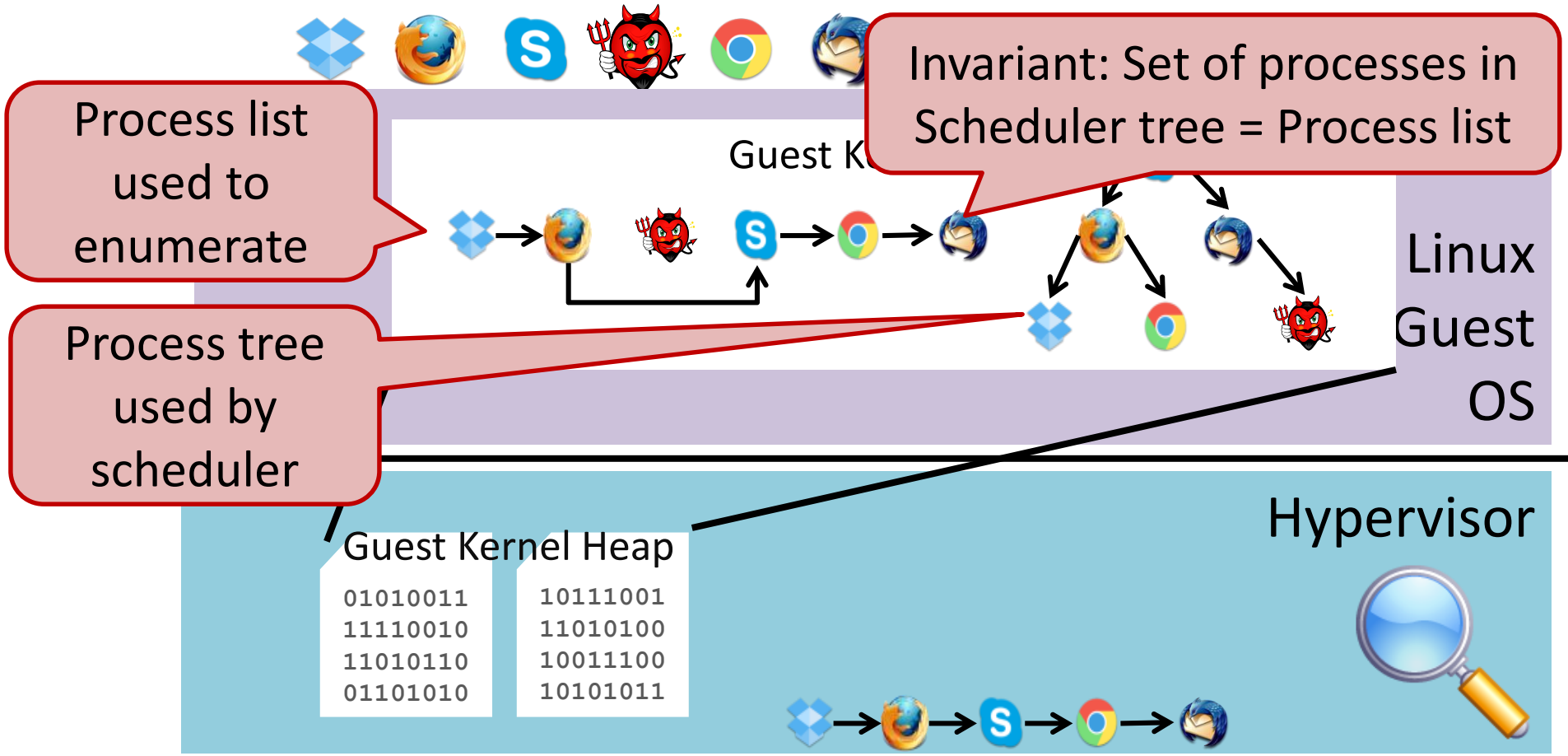

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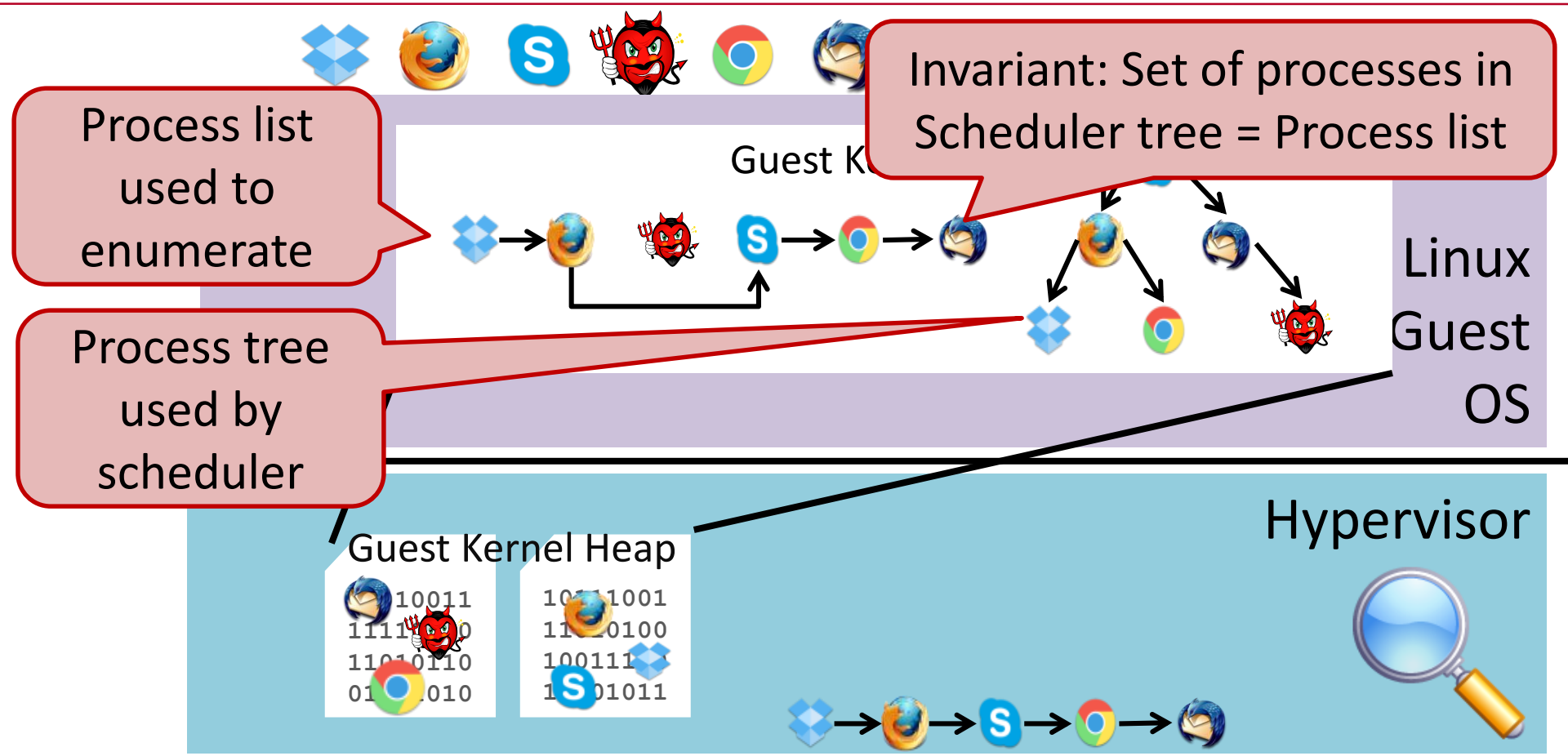

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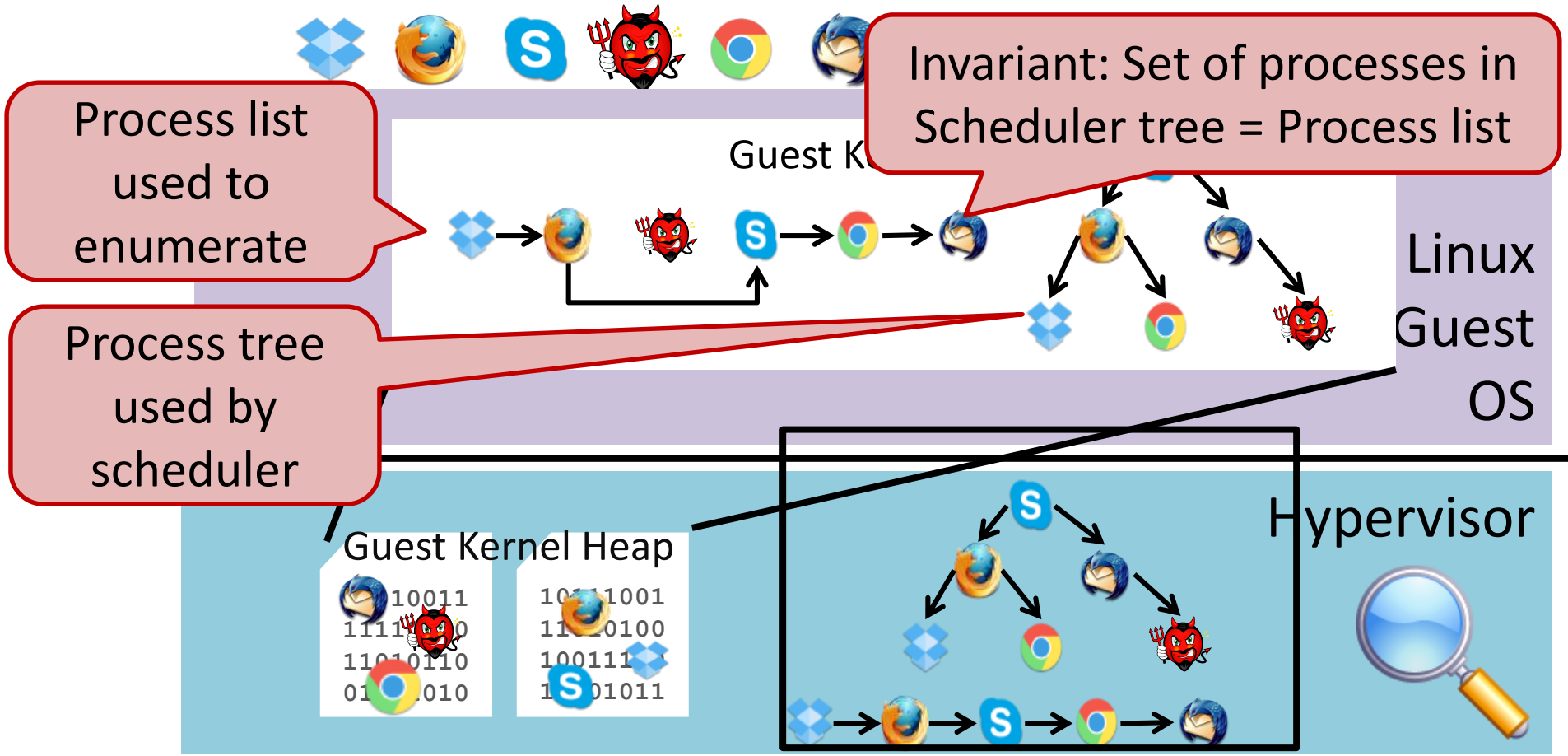

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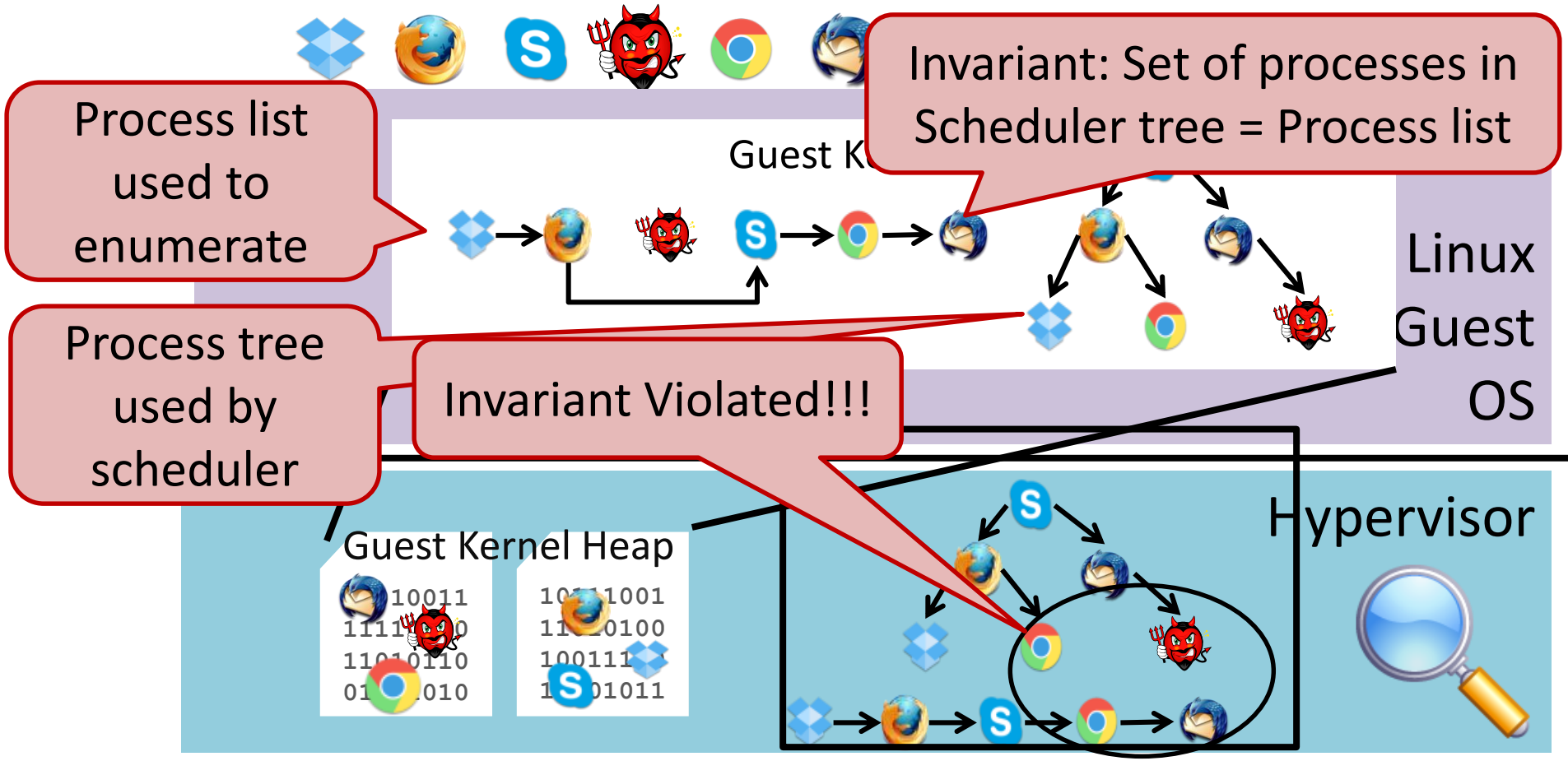

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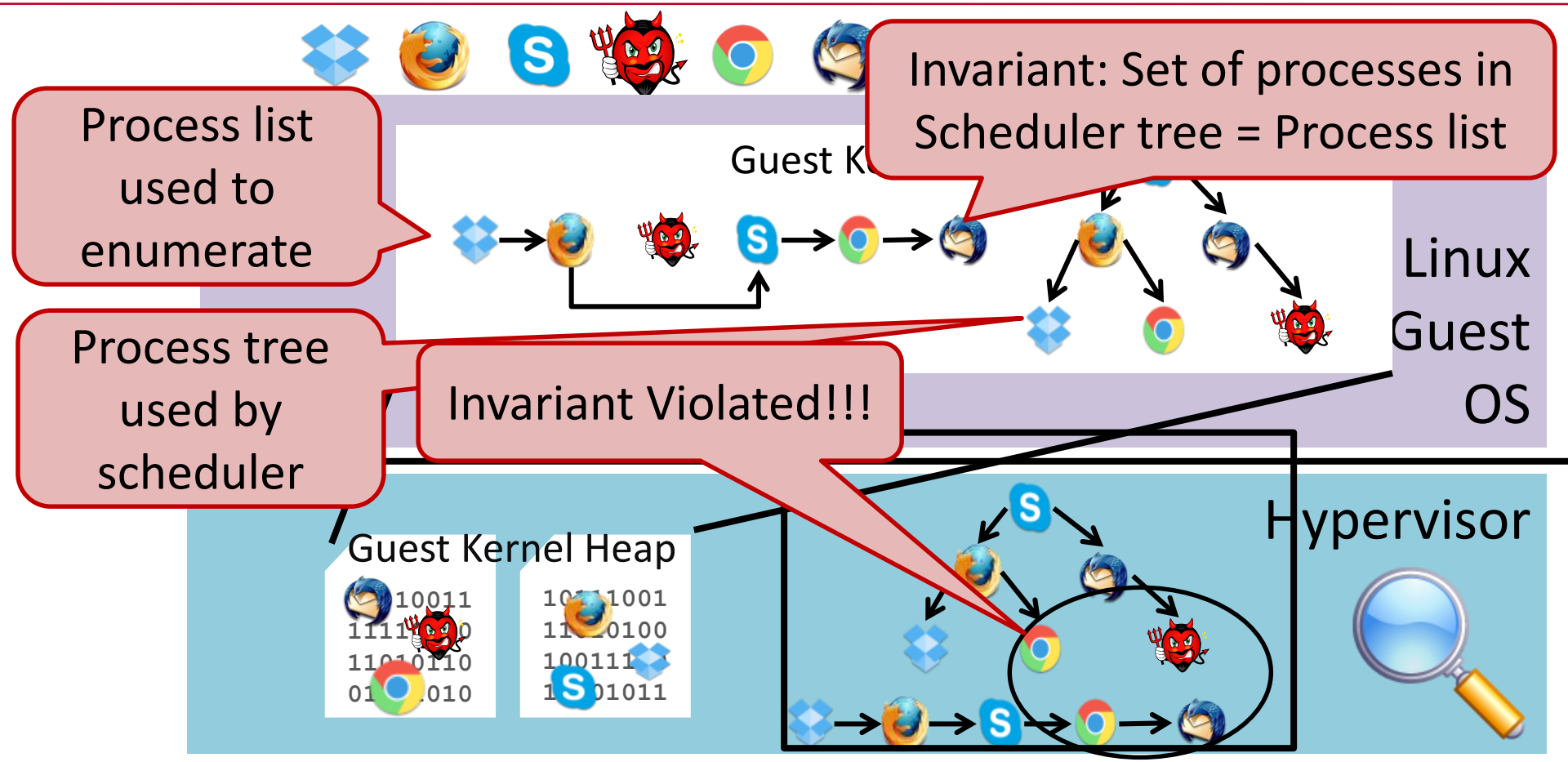

Assume attacker can't win race with asynchronous checking

DKOM Defense Trust Assumptions

- **Attack**: Modify the kernel objects in heap
- **Defense**: Asynchronously check invariants
  - State of Art: OSck[10]
- **Trust Assumption**:
  - All security invariants can be learned
  - Invariants can be checked in single search
  - Attackers cannot win races with the monitor
  - Availability of other integrity defenses

Cannot prevent attacks or detect transient attacks

Rootkit Attack Techniques

- **Write text Segment**
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  - Change function pointers (data segment)
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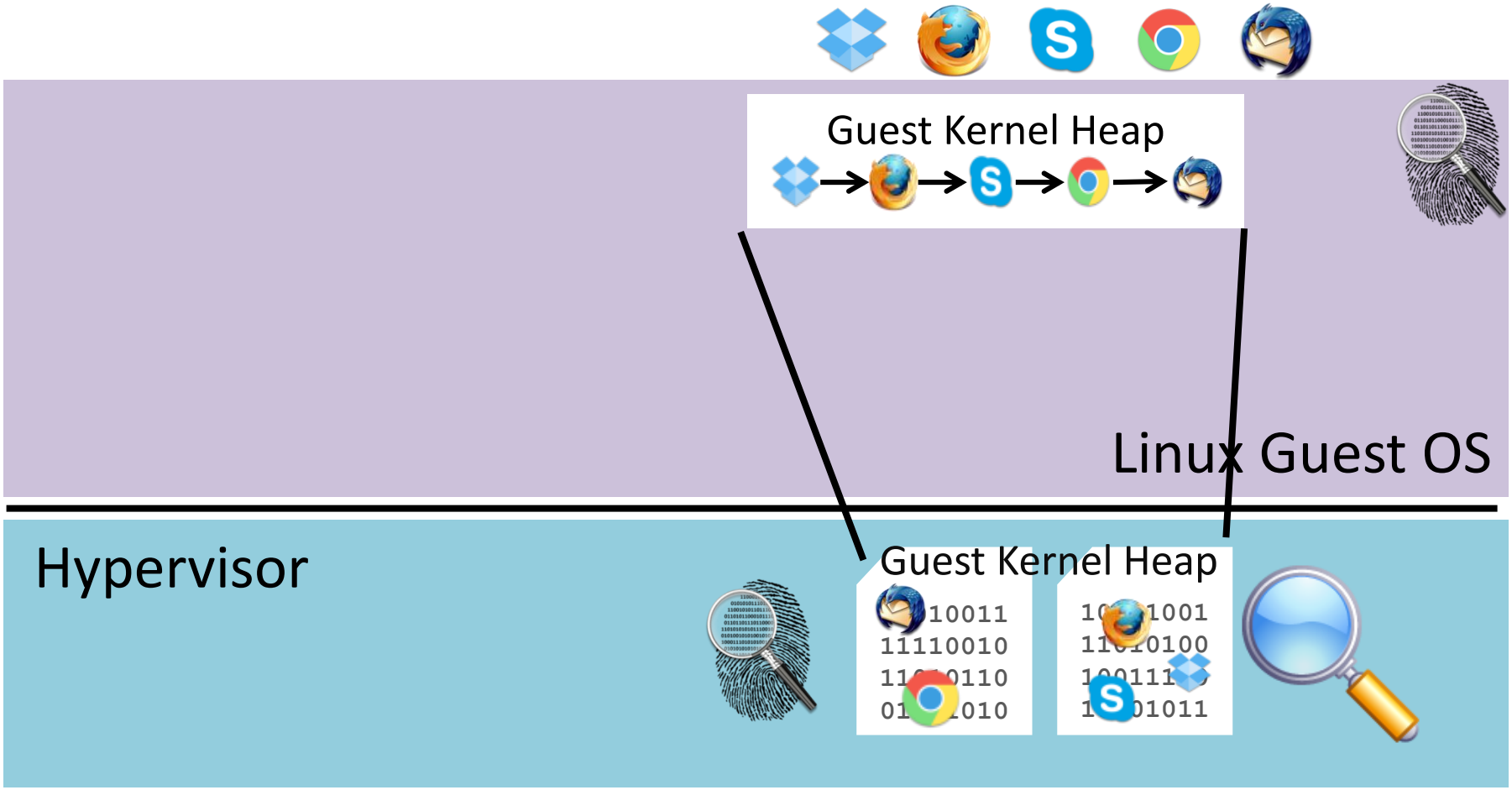
  - Change data structure interpretation

Data Structure Manipulation Attack



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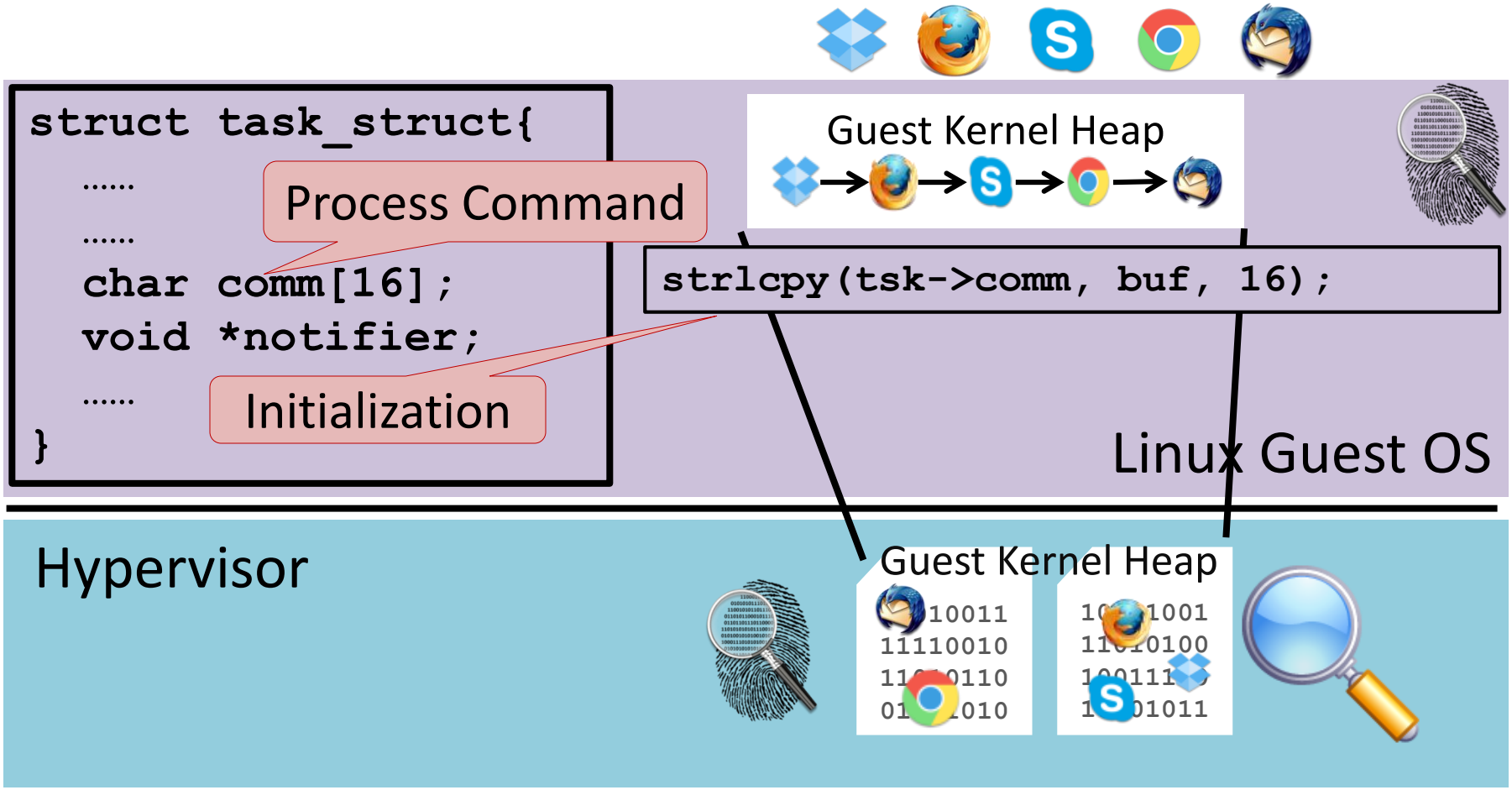

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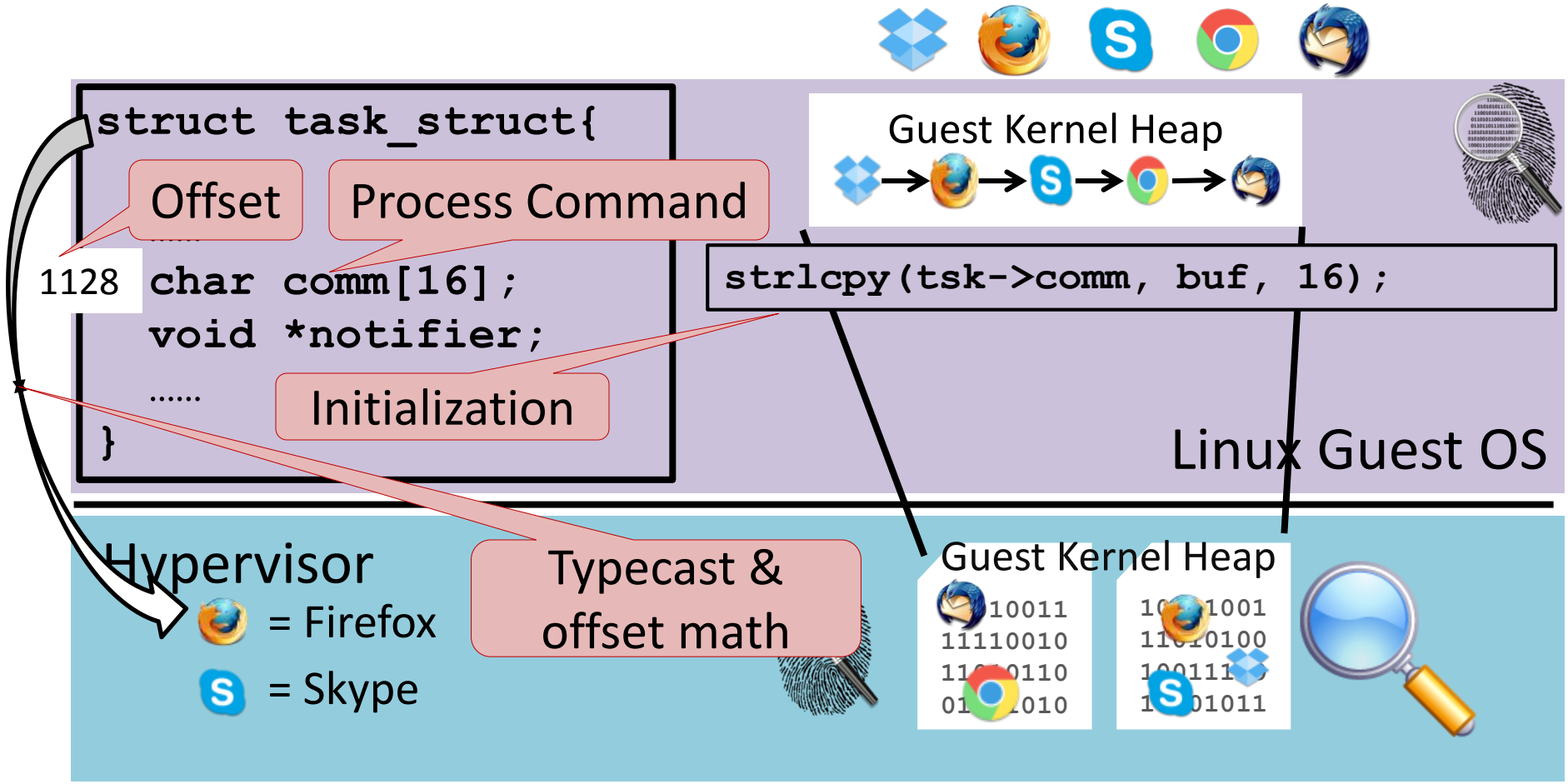

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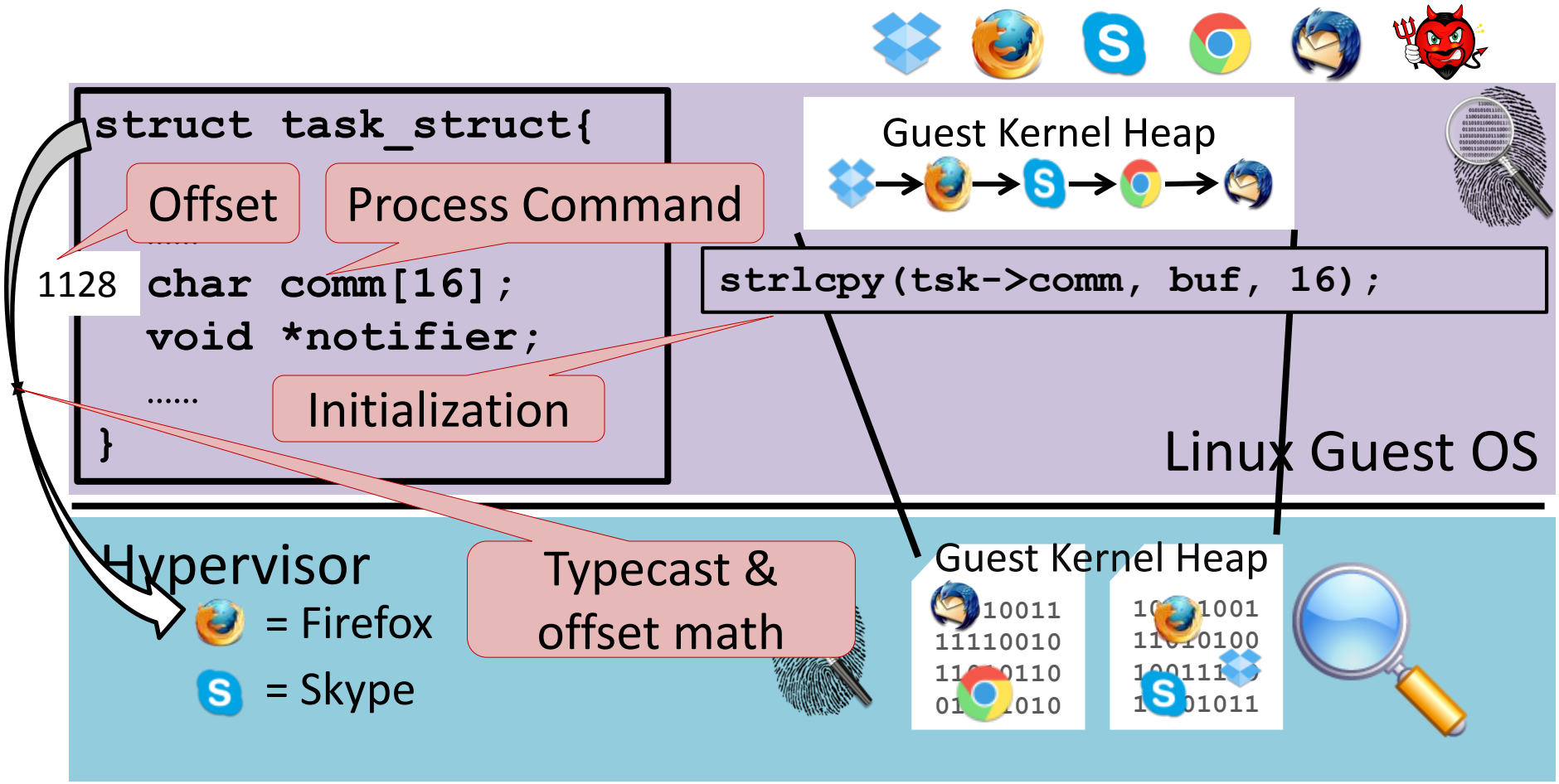

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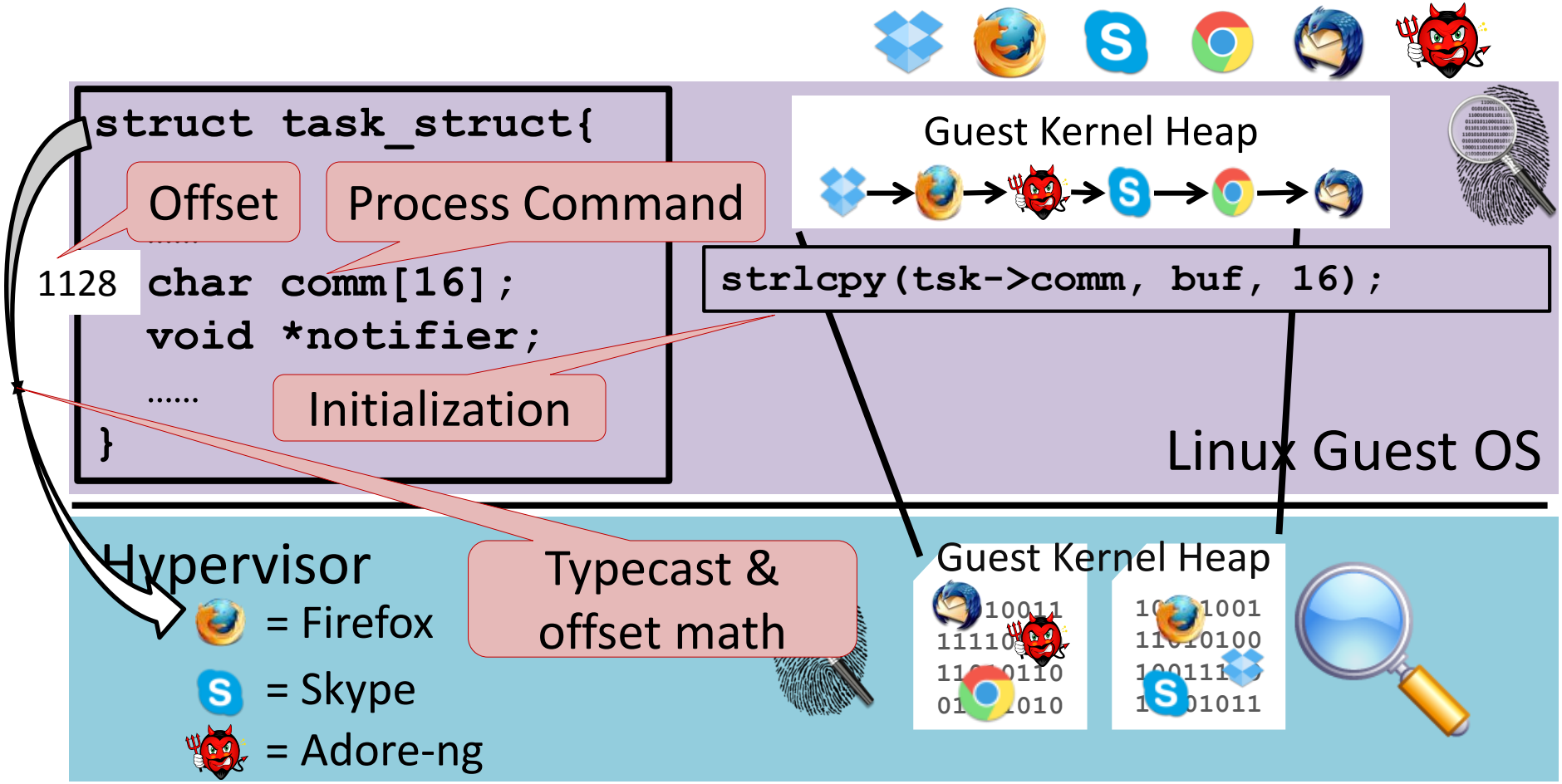
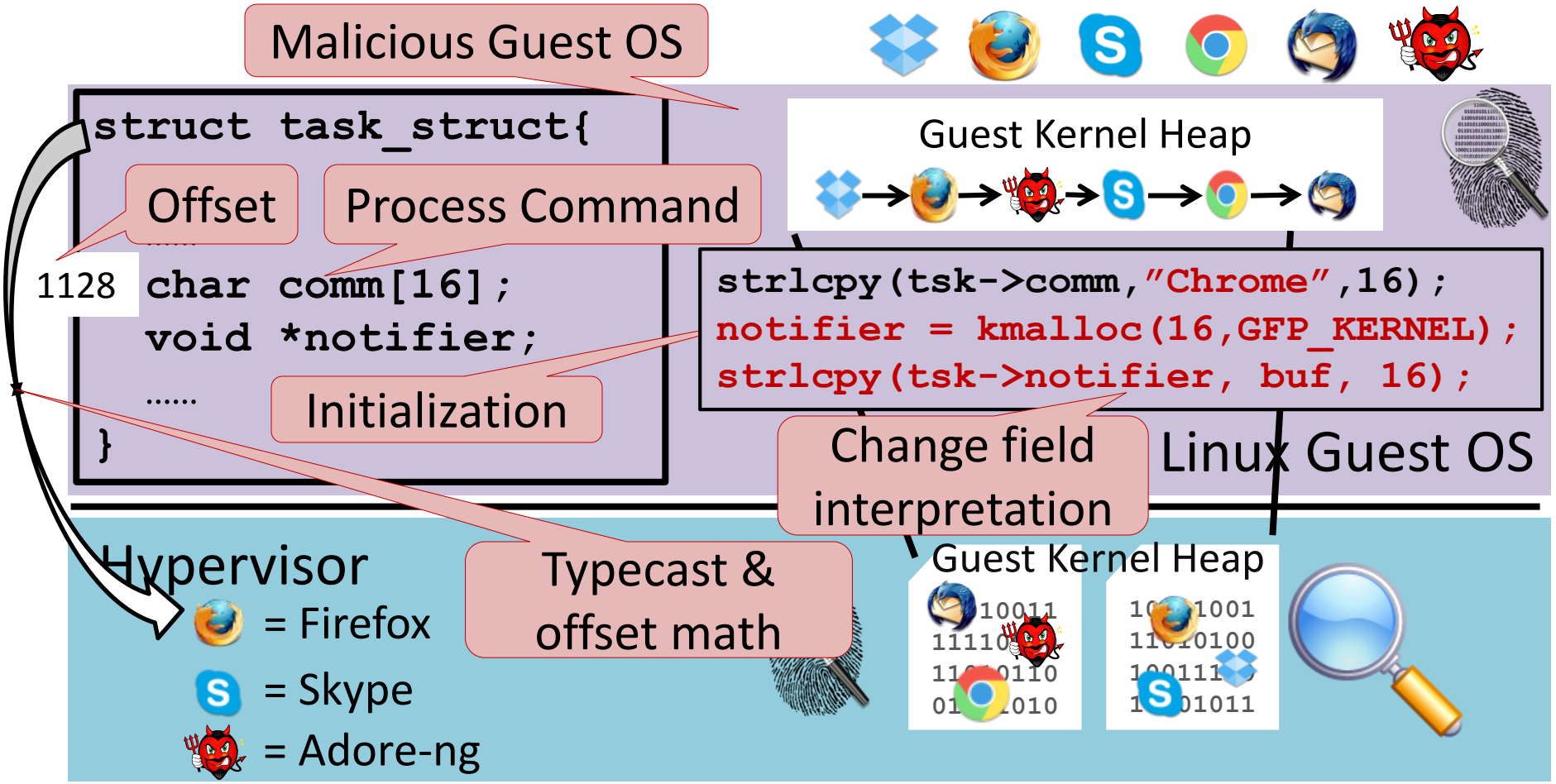
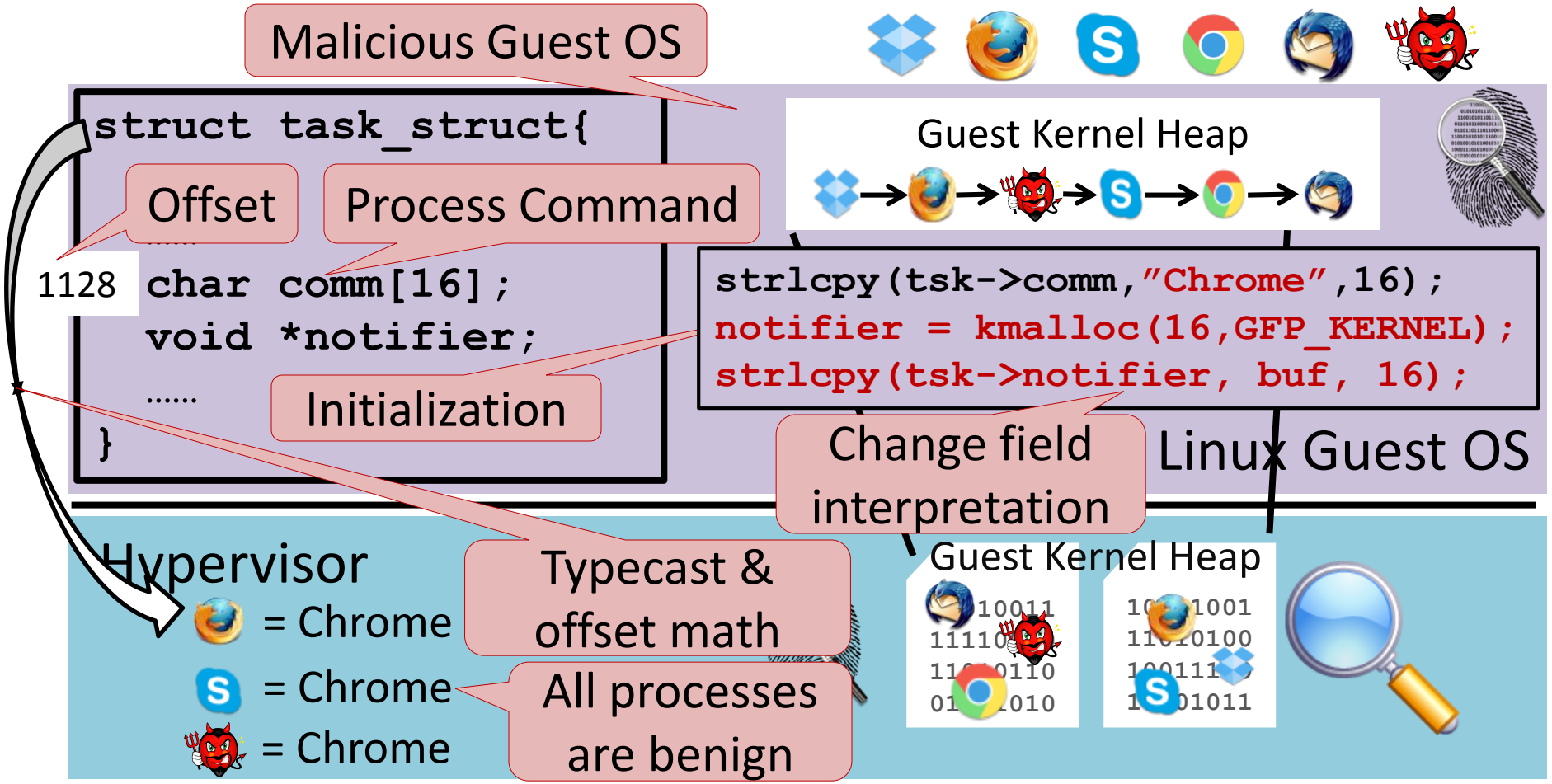


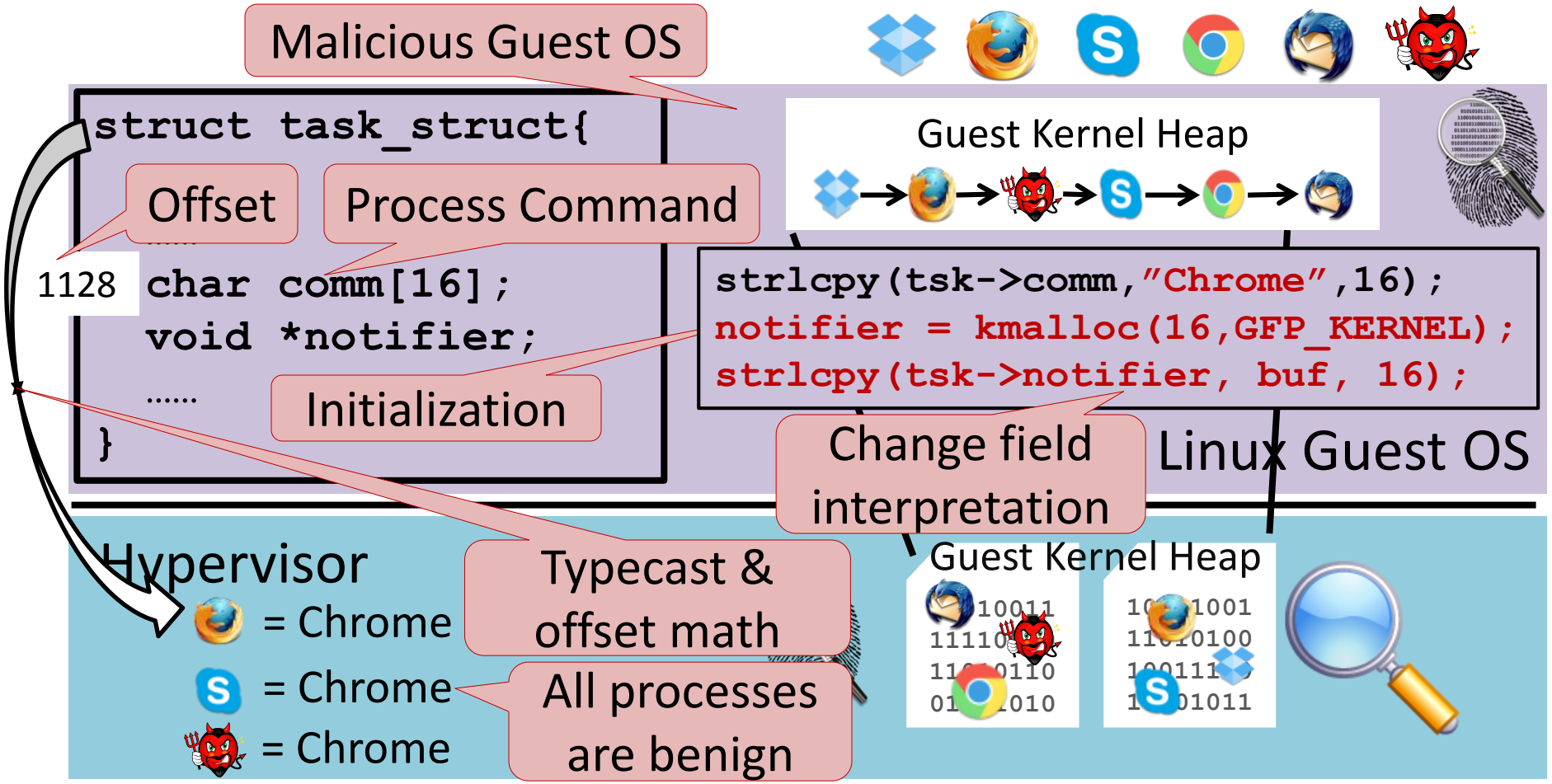
Data Structure Manipulation Attack



Data Structure Manipulation Attack



Data Structure Manipulation Attack



Malicious or Compromised OS can violate VMI assumptions

DKSM Trust Assumptions

- **Assumption:** Consistent structure interpretation
- **Attack**: Change interpretation of a data structure
  - Mislead VMI tools by presenting false system state
- **Defense**: No existing defense
  - CFI on benign kernel may help prevent bootstrapping
  - Attack obviated by generous threat models
  - Trust guest OS to be uncompromised and benign

Structure manipulation: Realistic but outside threat model

Recap

- **Weak Semantic Gap**: **Solved**
  - An engineering challenge
  - Assume guest OS respects data structure templates
- **Strong Semantic Gap**: **Open problem**
  - Malicious or Compromised OS
  - Exploit fragile assumptions to confuse VMI designs

Problem worth working: Strong Semantic Gap

Scalability

- Many VMI designs are fairly expensive
  - Some run sibling VM on dedicated core for analysis
- VMI can be useful in a cloud or multi-VM system
  - Manage overhead & scalability with increase in VMs
- Some VMI systems trade risk to reduce overhead
  - Identify techniques to minimize both overheads & risk

One consideration for VMI systems: Scalabilty

Privacy

- VMI can create new side-channels in cloud
  - Scan period or sibling VM activities using cache timing
- Shouldn't force choice of integrity or privacy risks.
- VMI should evaluate risks of new side channels.
  - Take into account compliance regulation

Another consideration for VMI systems: Privacy

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