SuperGlue: IDL-Based, System-Level Fault Tolerance for Embedded Systems

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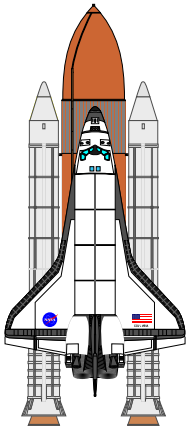
Presented by **Teodor Georgiev**

June 30, 2016

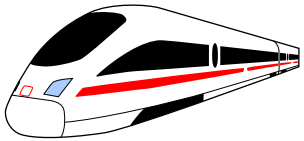
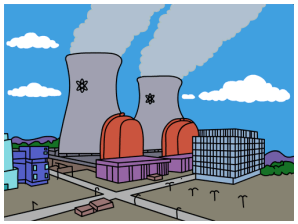
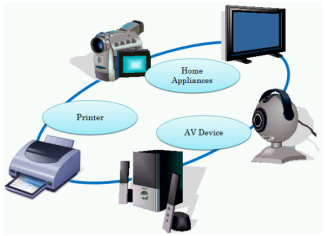
Computer Science Department
The George Washington University

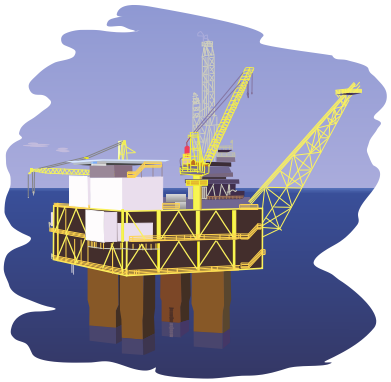
Outlines

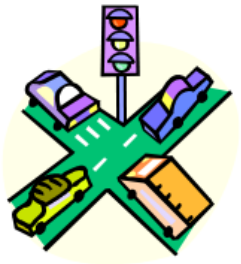
Real-Time and Embedded Systems



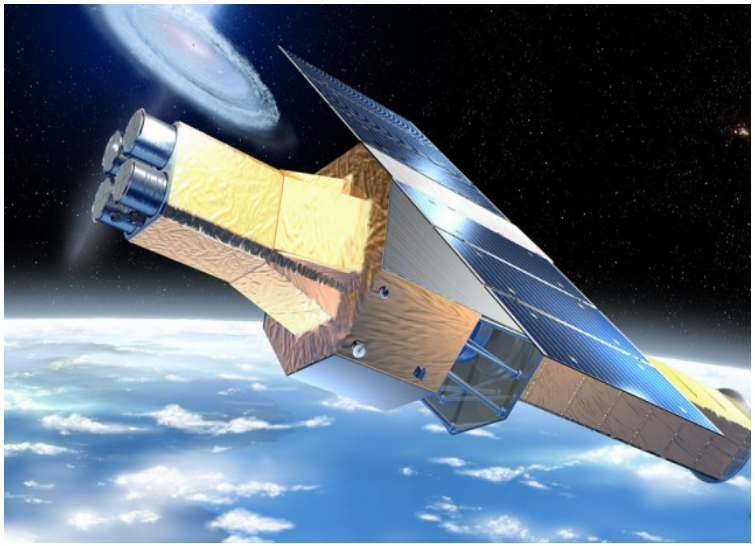





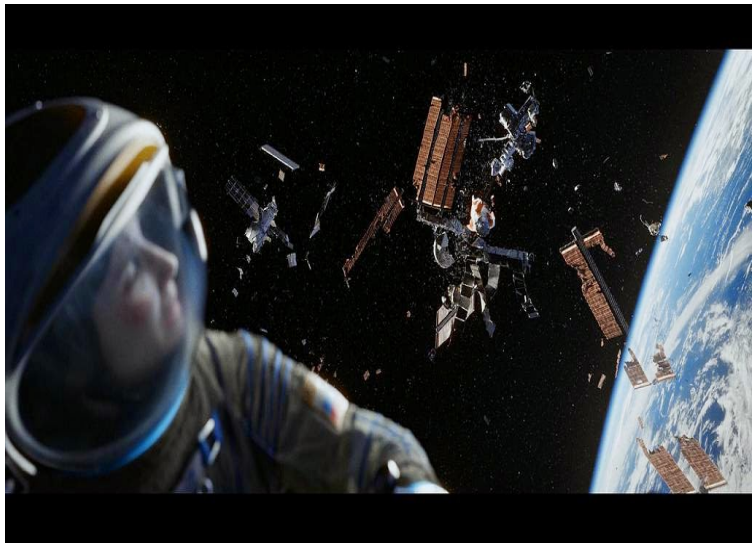

http://www.pcmag.com/encyclopedia/term/42554/embedded-system

Consequences of Embedded System Faults

Japanese X-ray astronomy satellite Hitomi lost in 2016



Fault



- Financial losses of $286 million USD
- "*It's a scientific tragedy*" - Richard Mushotzky, UMD

`http://www.nature.com/news/software-error-doomed-japanese-hitomi-spacecraft-1.19835`

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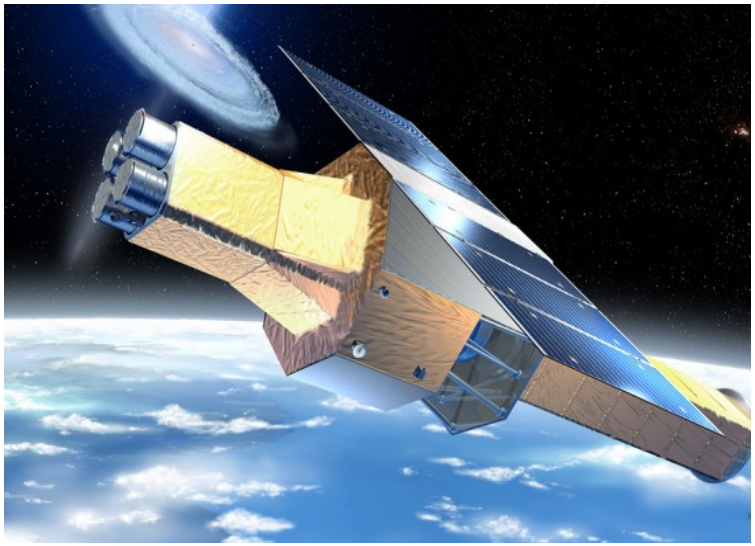

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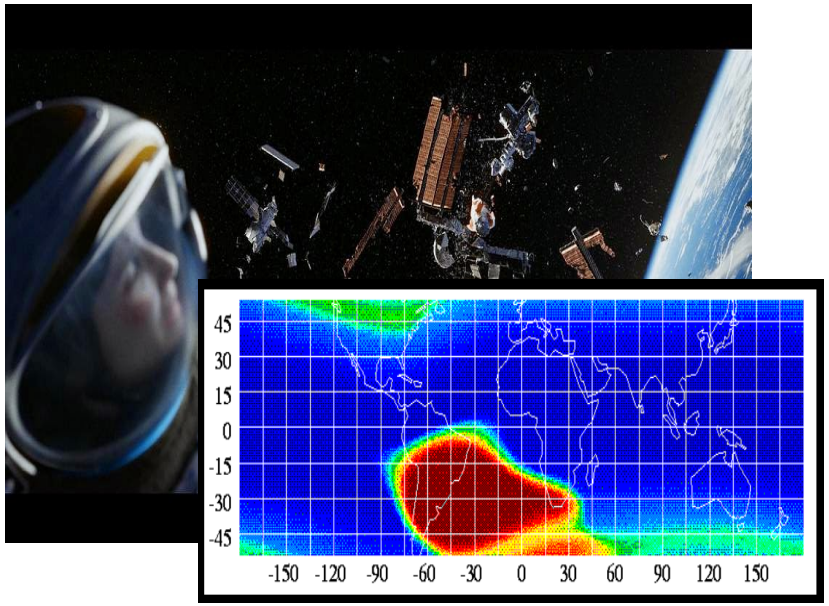

The South Atlantic Anomaly

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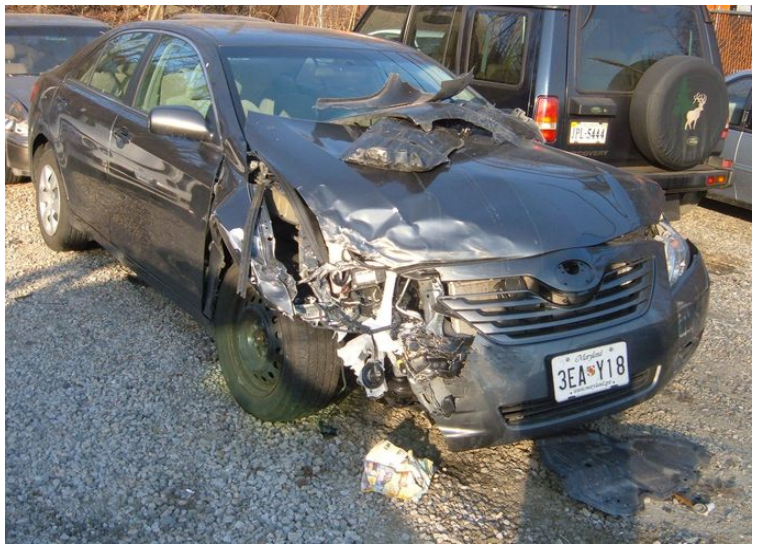
Consequences of embedded system faults

Toyota Sudden Unintended Acceleration (SUA) in 2004 – 2010

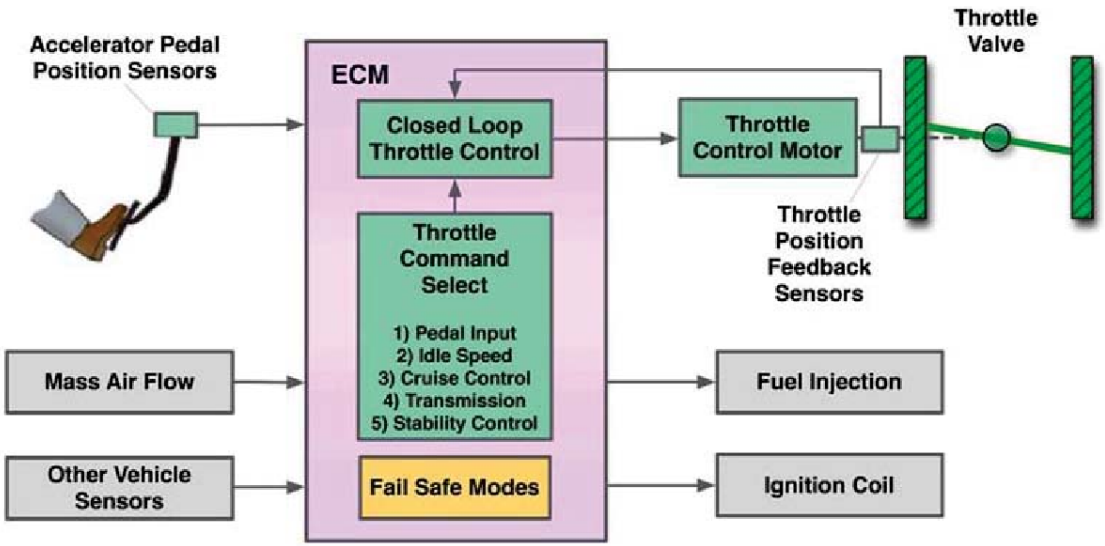
Fault

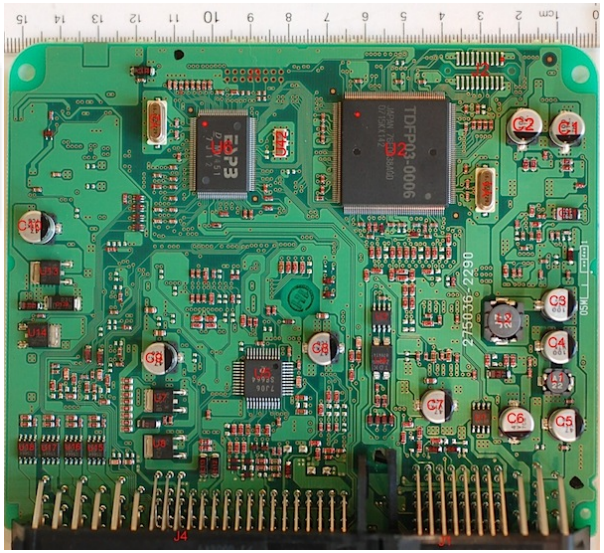


- 89 deaths as of May 2010 and nearly 400 U.S. lawsuits
- Recall 10+ million vehicles and pay $1.2 Billion USD fine

`http://www.cbsnews.com/news/toyota-unintended-acceleration-has-killed-89/`

Sudden Unintended Acceleration



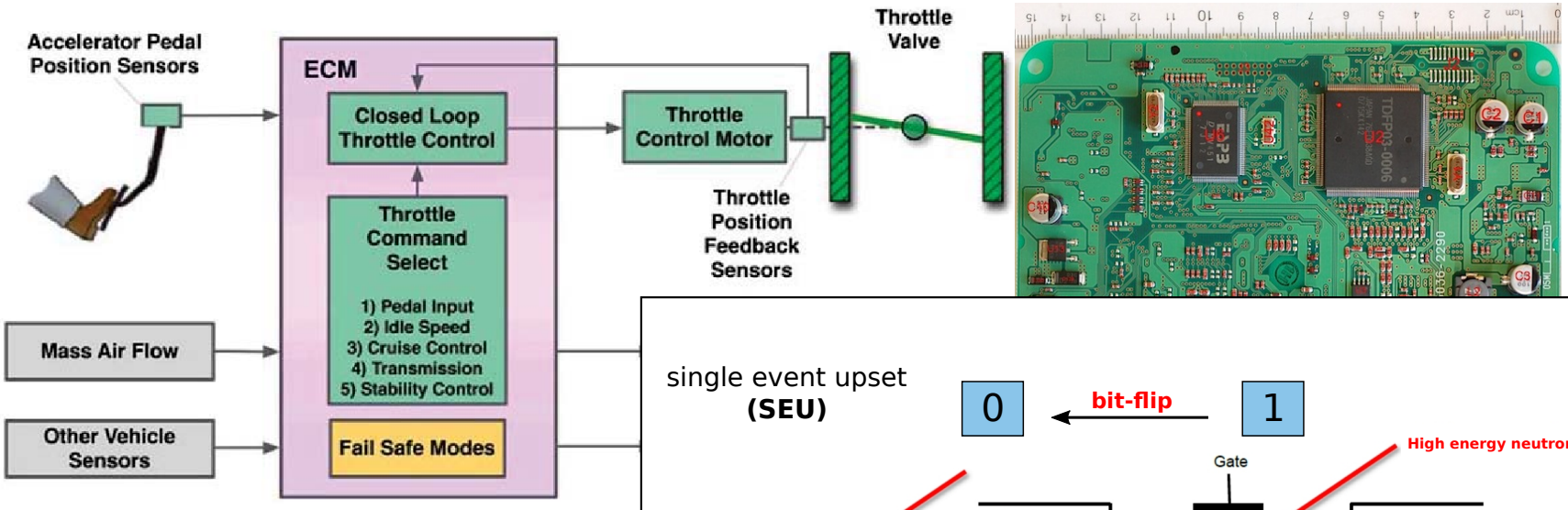


Uncontrolled acceleration in Toyota Camrys

- Electronic Throttle Control System (ETCS)
- OSEK OS, 24 tasks, 280K LOC of C
- bit flip in scheduler data-structures
  $\rightarrow$ reproducible 30-sec uncontrolled acceleration

"*a bit-flip there, will have the effect of killing one of the tasks*"
– Bookout v Toyota

Sudden Unintended Acceleration



Radiation strike causing transistor disruption [Gorini 2012]

Uncontrolled acceleration in

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- OSEK OS, 24 tasks, 28
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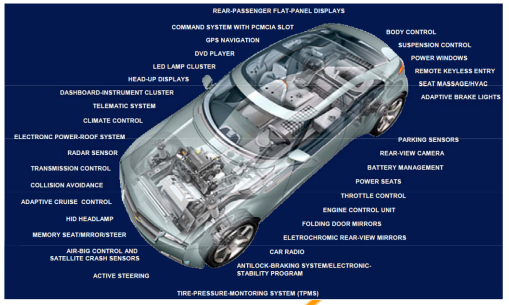
Embedded faults: Bad Now, Worse Tomorrow

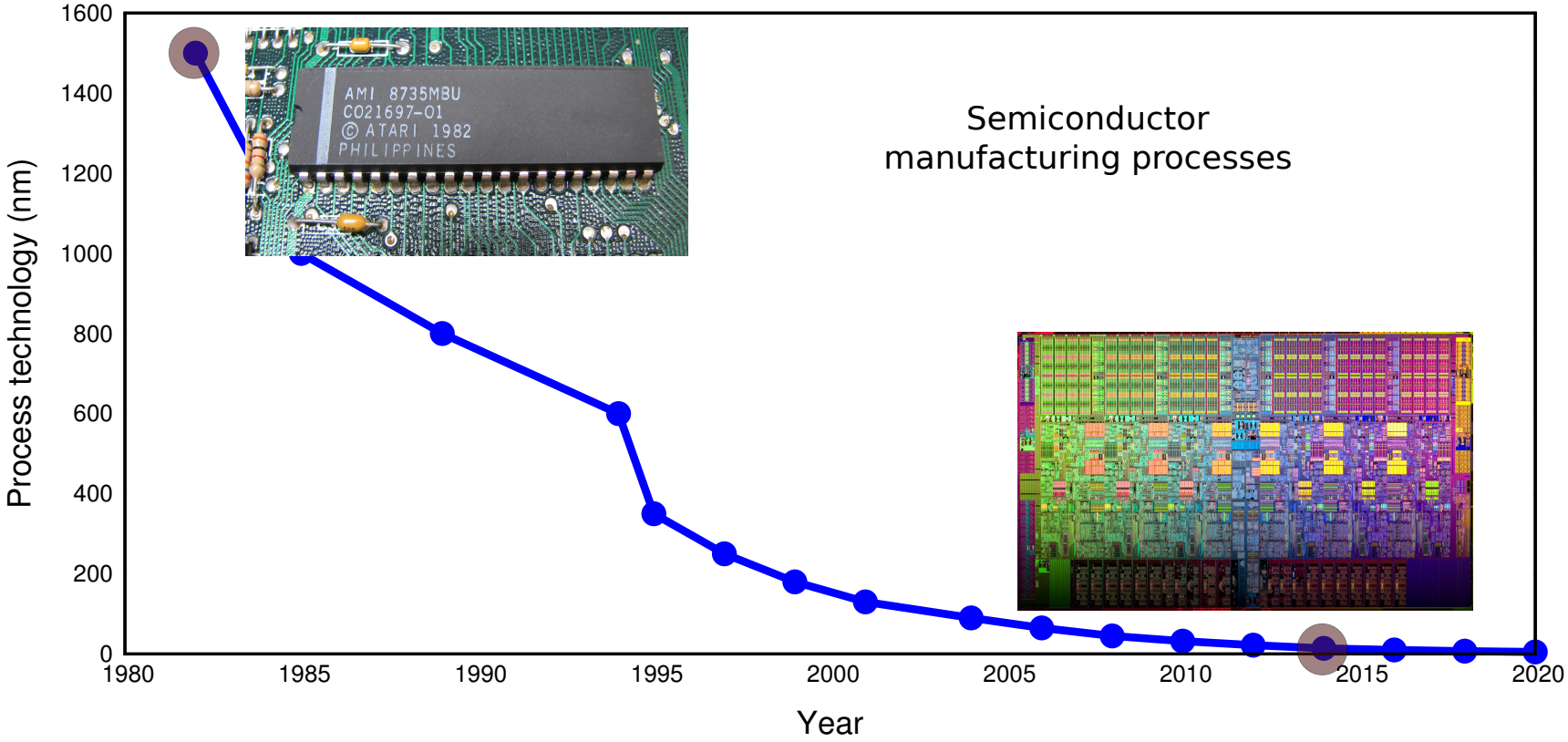
ABS: Antilock Brake System
ACC: Adaptive Cruise Control
BCM: Body Control Module
Cyl Deact: Cylinder Deactivation
ECS: Electronics, Controls, and Software
EGR: Exhaust Gas Recirculation.
GDI: Gas Direct Injection
OBD: Onboard Diagnostics
TCC: Torque Converter Clutch
PT: Powertrain
ESC: Electronic Stability Control



\+ more functionality
\− more complexity → dependability more challenging

https://www.src.org/calendar/e003506/03-sessionii-rajkumar.pdf

Embedded faults: Bad Now, Worse Tomorrow



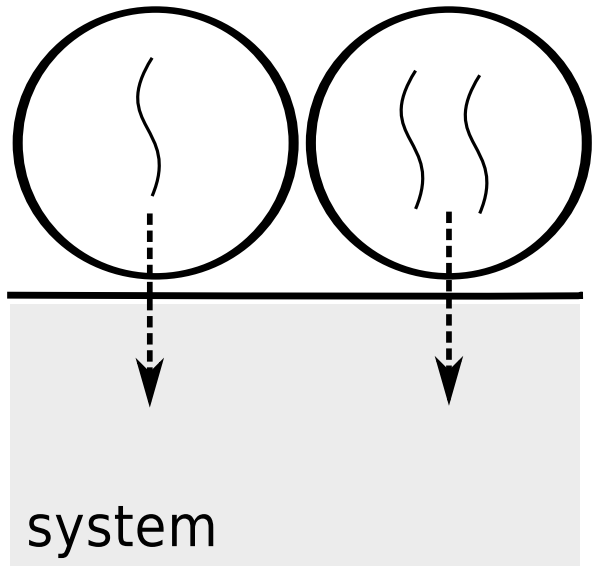
Decreasing process sizes $\rightarrow$ 5nm

- \+ faster
- \+ less power consumption
- \+ smaller
- – increased vulnerability to HW transient faults

Application-Level Fault Tolerance

Application fault tolerance

- example recovery techniques
  - recovery blocks
  - checkpointing
  - re-fork
- temporal redundancy
  - detect fault by job completion
  - replay execution from saved state



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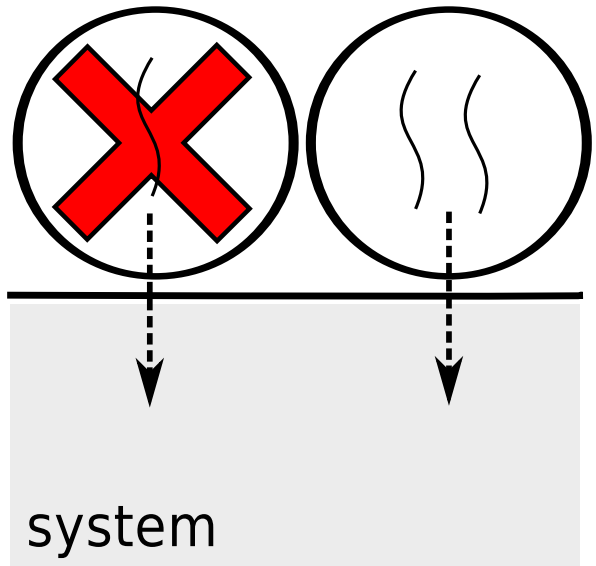

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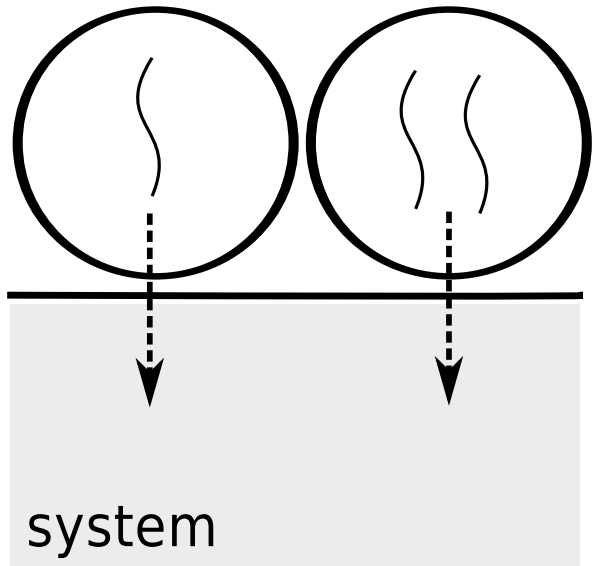
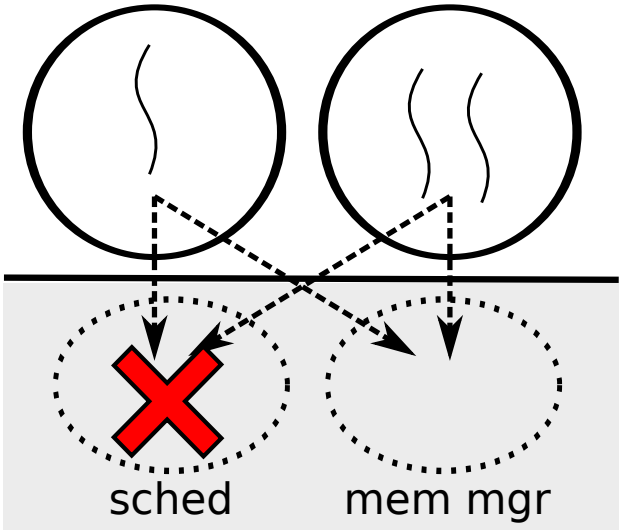


System-Level Fault Tolerance

System-level fault tolerance

- failures in
  - scheduler
  - memory mapping manager
  - file-systems
  - synchronization manager
  - ...



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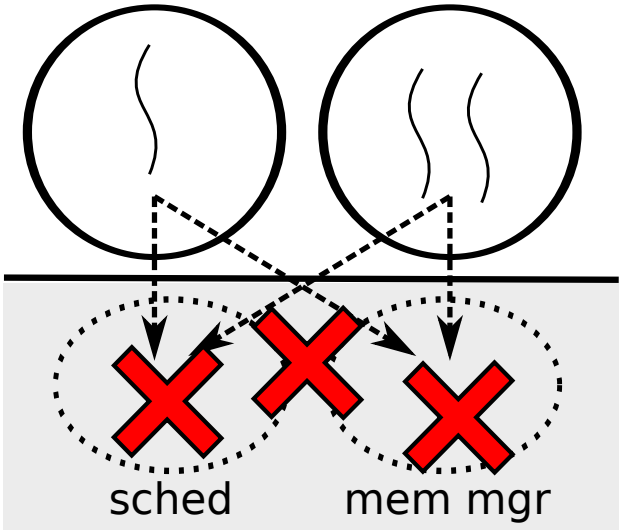

System components contain state for all tasks

- failure impacts memory of *all* tasks

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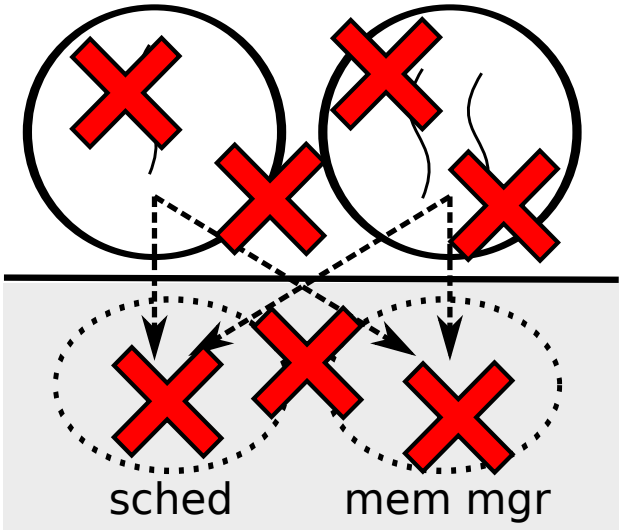

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Recovery requires resources

- processing time...to recovery scheduler
- memory...to recover memory mapper

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Outlines

C^3: The Computational Crash Cart

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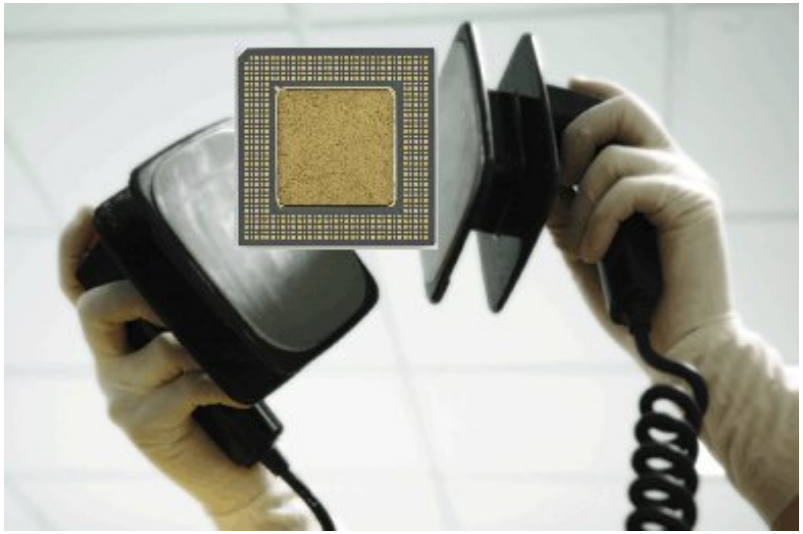
- resuscitate system
- from system-level faults
- predictably



Main ideas

- pervasive fault isolation $\rightarrow$ restrict propagation
- efficient μ-reboot of individual components
- interface-driven, application-oblivious recovery

C^3 – an interface-driven, predictable system-level fault recovery mechanism

J. Song, J. Wittrock, and G. Parmer, "Predictable, efficient system-level fault tolerance in C^3" in RTSS, 2013

Composite: A Component-Based OS

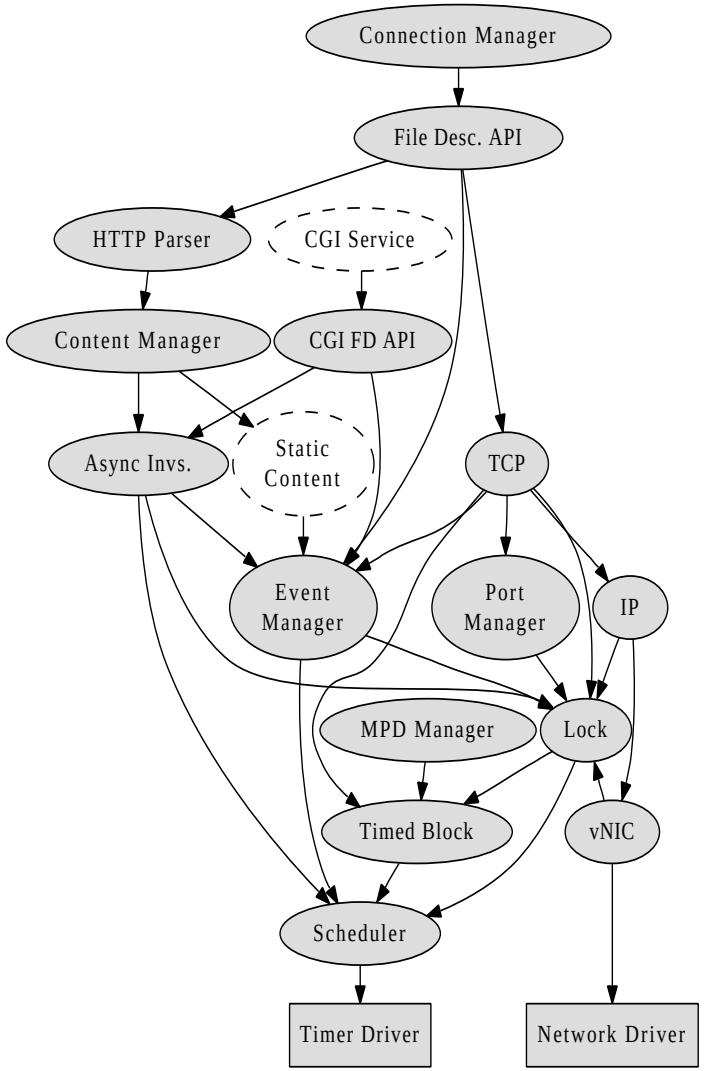
System functionality as *components*

- user-level, protection domains
- fine-grained fault isolation

Low-level services are components

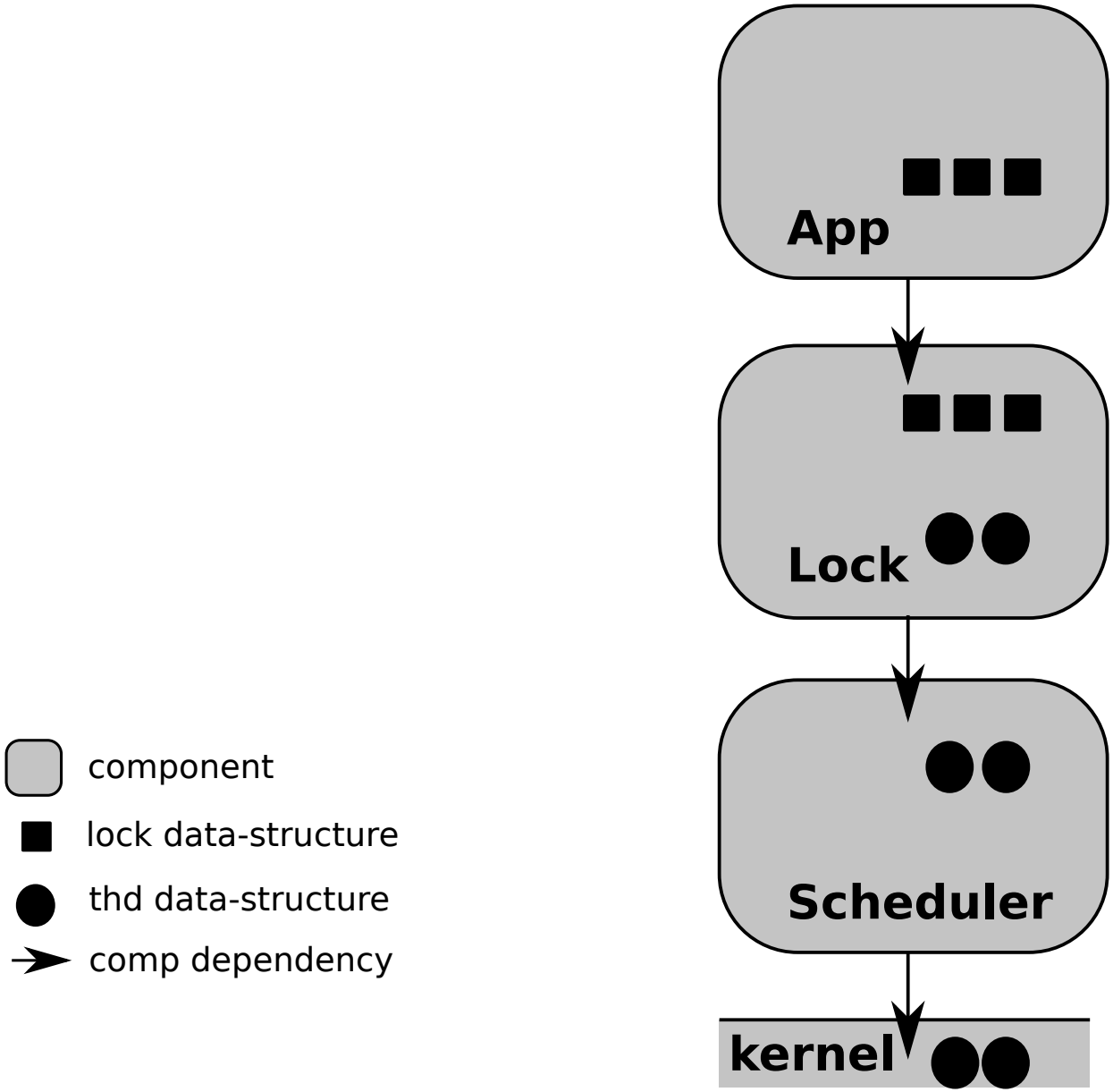
- kernel is small and policy-less
- scheduling, memory mapping, synchronization...are in user level

Components interact via *invocation* of interface functions

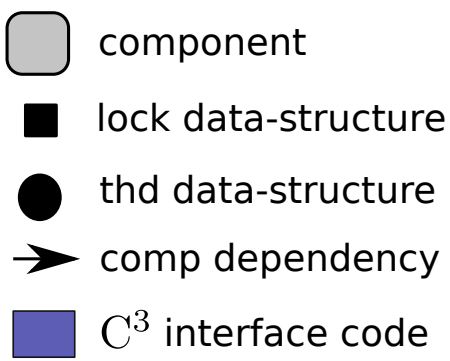


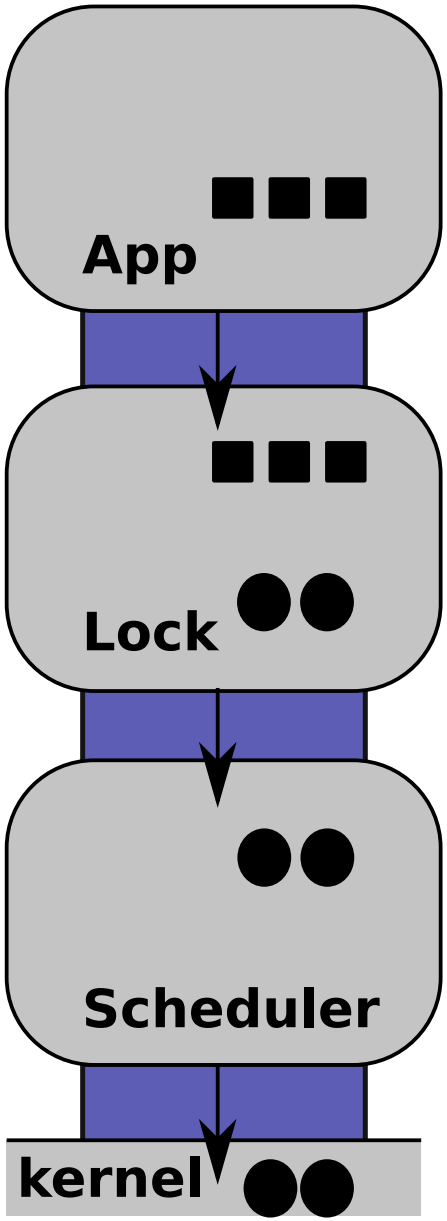
Example component graph

C^3 System-Level Fault Recovery



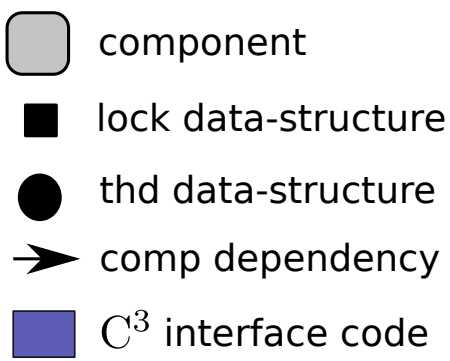
Recovery sequence in C^3

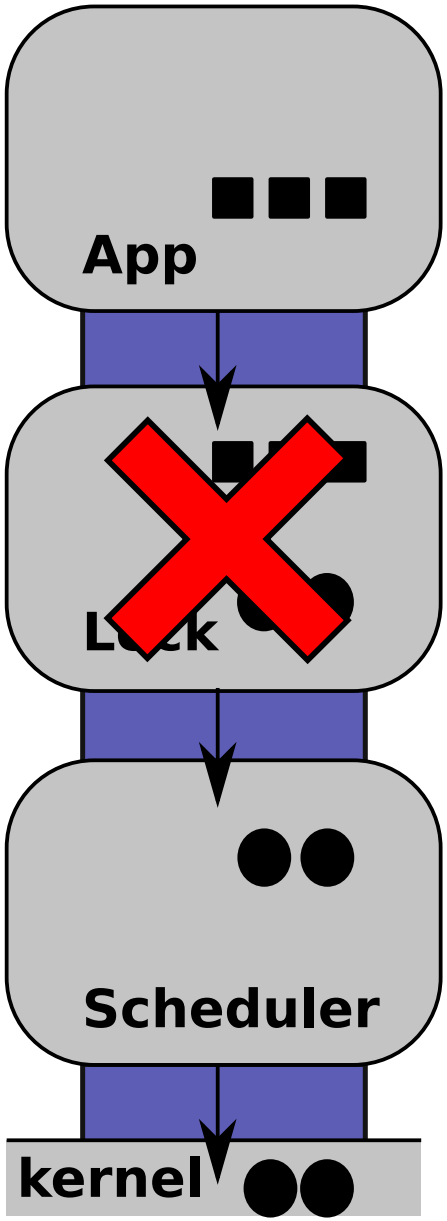




Recovery sequence in C³

1. fault detection





C^3 System-Level Fault Recovery

Recovery sequence in C^3

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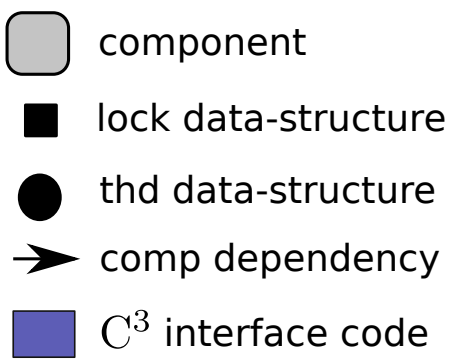
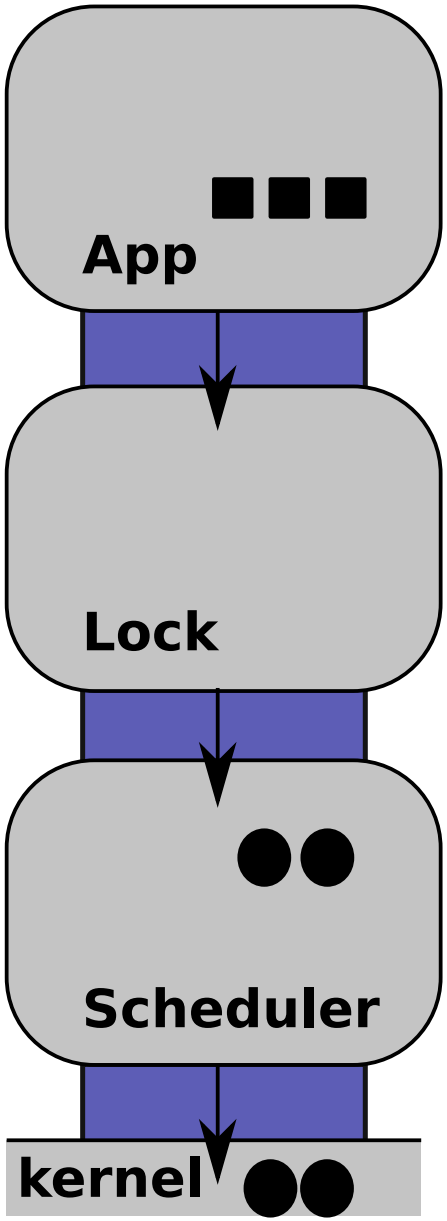
2. safe-state recovery
   - μ-reboot

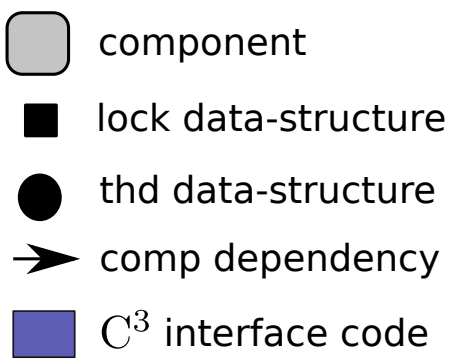


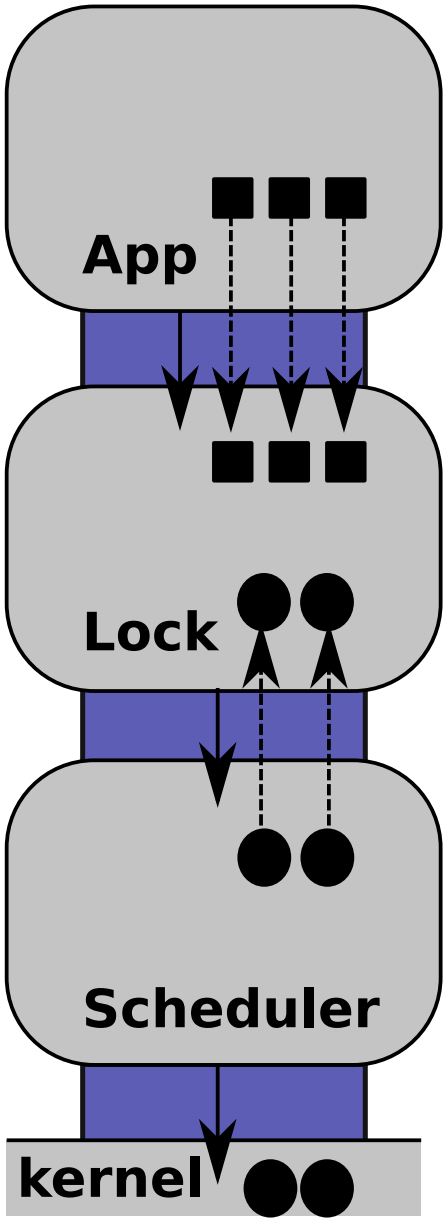


C^3 System-Level Fault Recovery

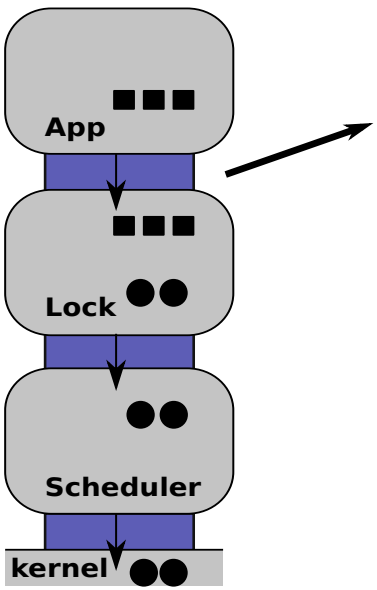
Recovery sequence in C^3

1. fault detection
2. safe-state recovery
   - μ-reboot
3. consistent-state recovery
   - object state recovery





C³ Implementation – Writing Code Manually




```
        rd->state        = state;
        rd->fcnt         = global_fault_cnt;

        return;
}

static void
rd_recover_state(struct rec_data_lk *rd)
{
        assert(rd && rd->c_lkid);

        struct rec_data_lk *tmp;
        int tmp_lkid = lock_component_alloc(cos_spd_id());
        assert(tmp_lkid);

        assert((tmp = rdlk_lookup(tmp_lkid)));
        rd->s_lkid = tmp->s_lkid;
        rdlk_dealloc(tmp_lkid);

        return;
}

CSTUB_FN(unsigned long, lock_component_alloc) (struct usr_inv_cap *uc,
                                               spdid_t spdid)
{
        long fault;
        unsigned long ret;

        struct rec_data_lk *rd = NULL;
        unsigned long ser_lkid, cli_lkid;

        if (first == 0) {
                cos_map_init_static(&uniq_lkids);
                first = 1;
        }

redo:
        CSTUB_INVOKE(ret, fault, uc, 1, spdid);

        if (unlikely (fault)){
                CSTUB_FAULT_UPDATE();
                goto redo;
        }

        assert(ret > 0);

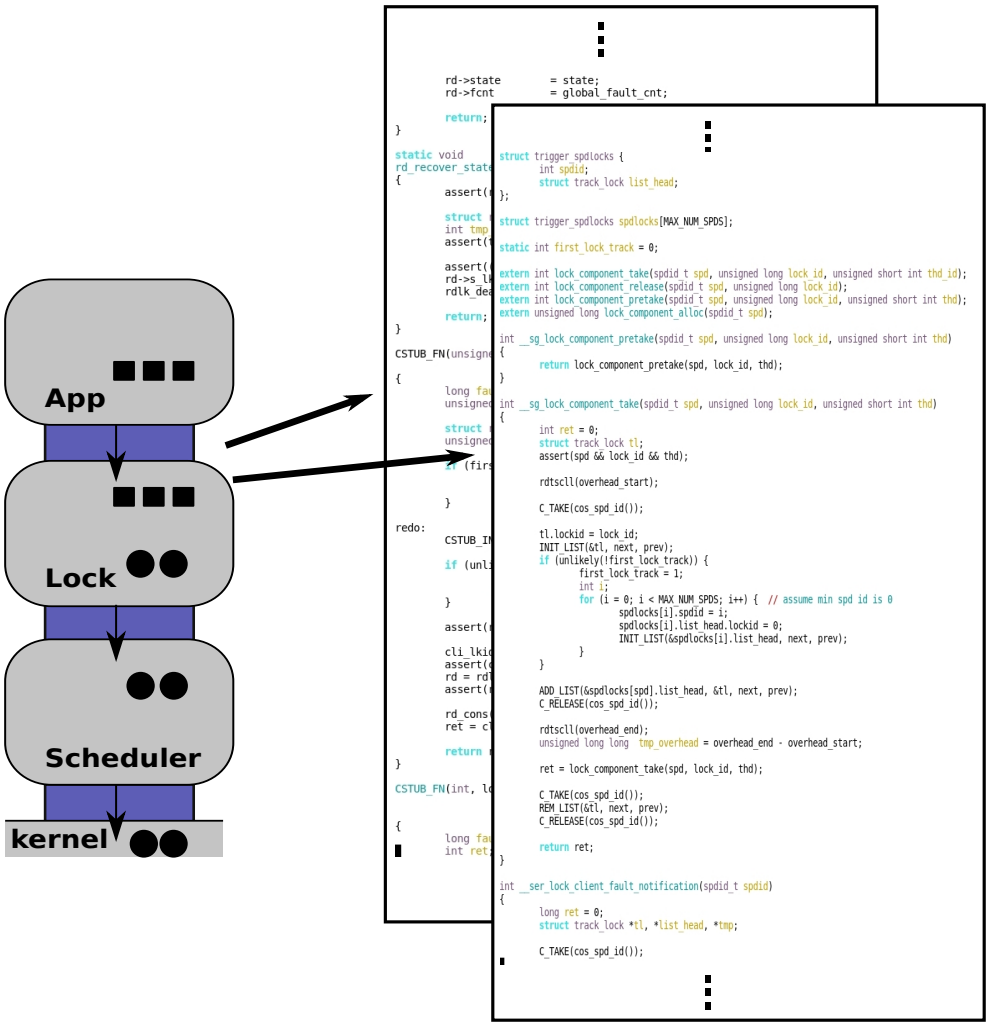
        cli_lkid = rdlk_alloc();
        assert(cli_lkid >= 1);
        rd = rdlk_lookup(cli_lkid);
        assert(rd);

        rd_cons(rd, cos_spd_id(), cli_lkid, ret, LOCK_ALLOC);
        ret = cli_lkid;

        return ret;
}

CSTUB_FN(int, lock_component_pretake) (struct usr_inv_cap *uc,
                                       spdid_t spdid, unsigned long lock_id,
                                       unsigned short int thd)
{
        long fault = 0;
        int ret;
```

C^3 Implementation – Writing Code Manually



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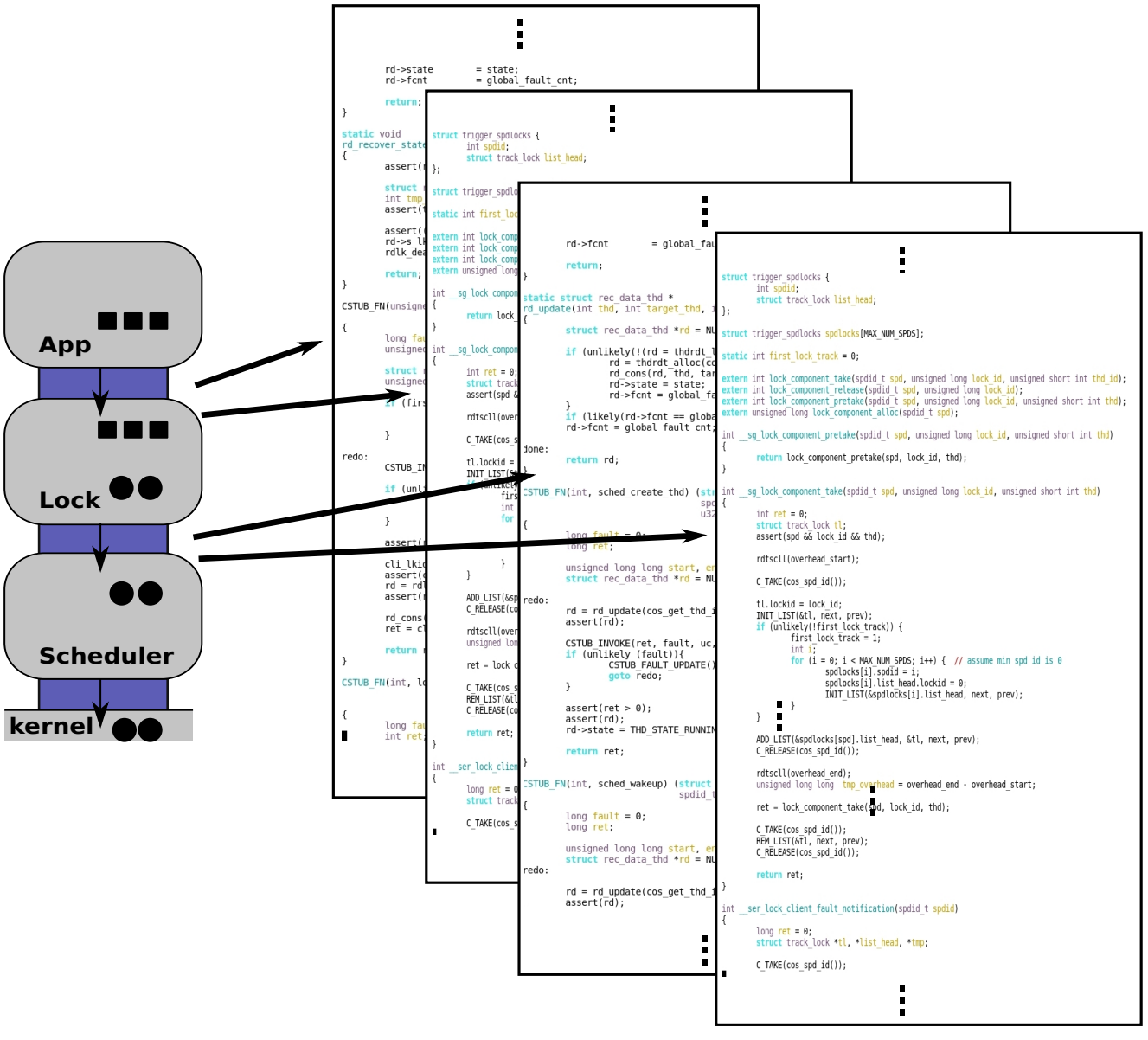

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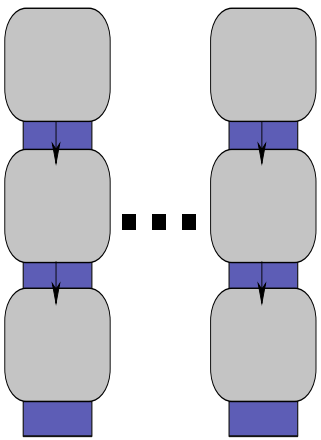

lock
scheduler
memory manager
file system
event manager
timer manager
...

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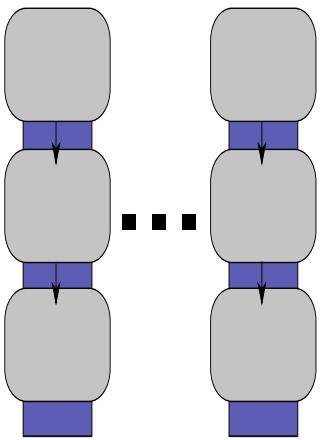
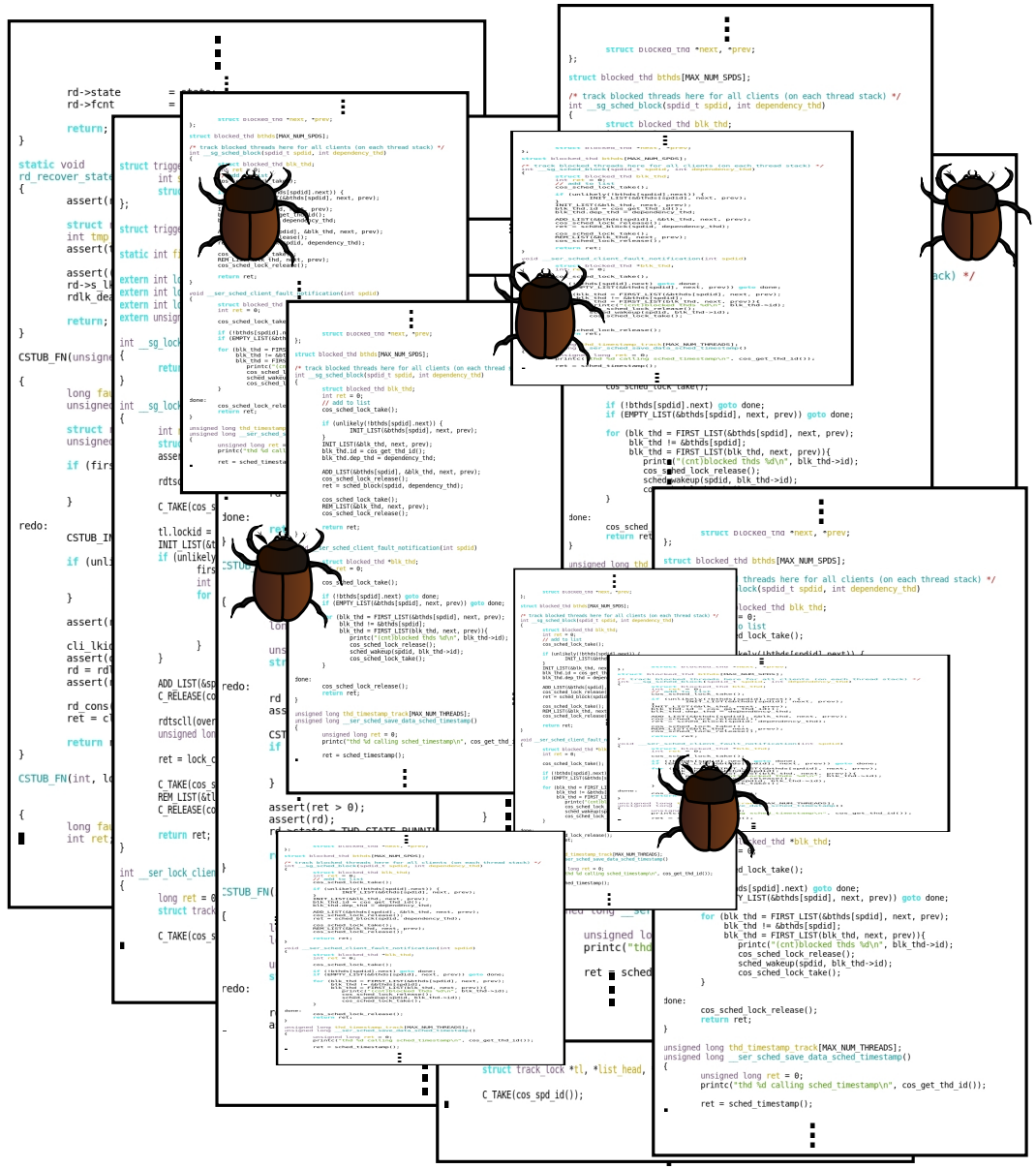
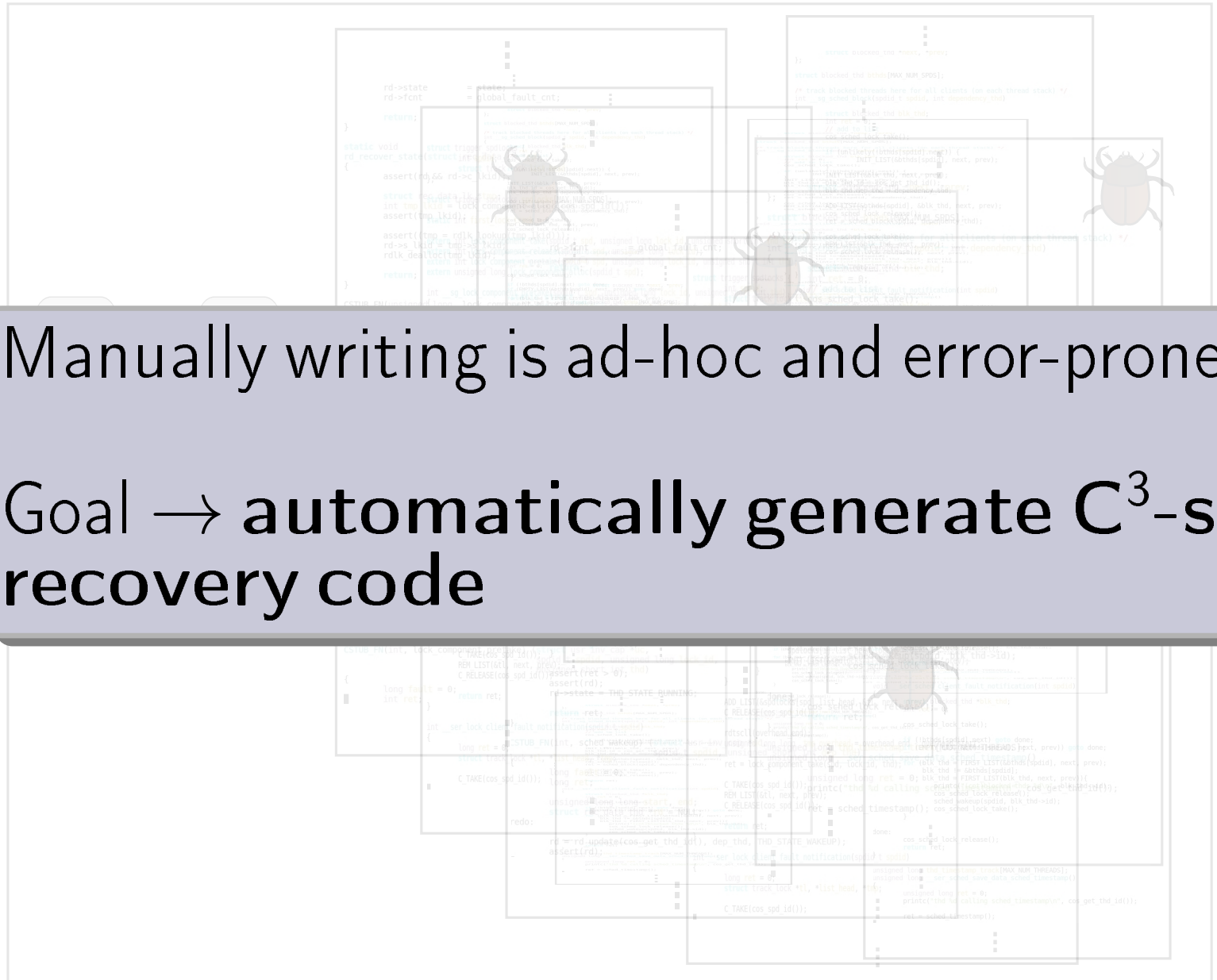




C^3 Implementation – Writing Code Manually



Manually writing is ad-hoc and error-prone

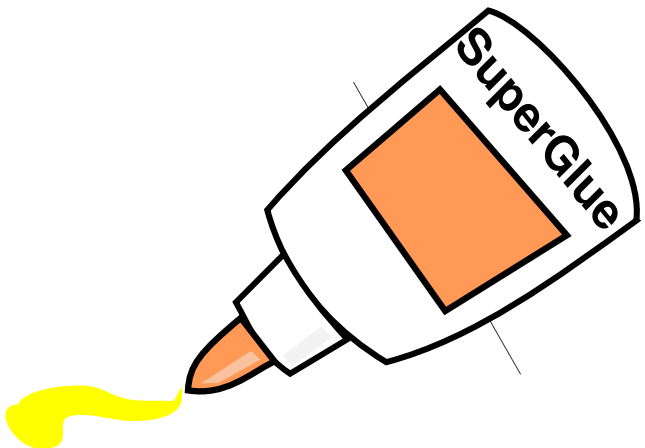
Goal $\rightarrow$ **automatically generate C^3-style recovery code**

Outlines

SuperGlue – IDL-based System-Level Fault Tolerance

SuperGlue

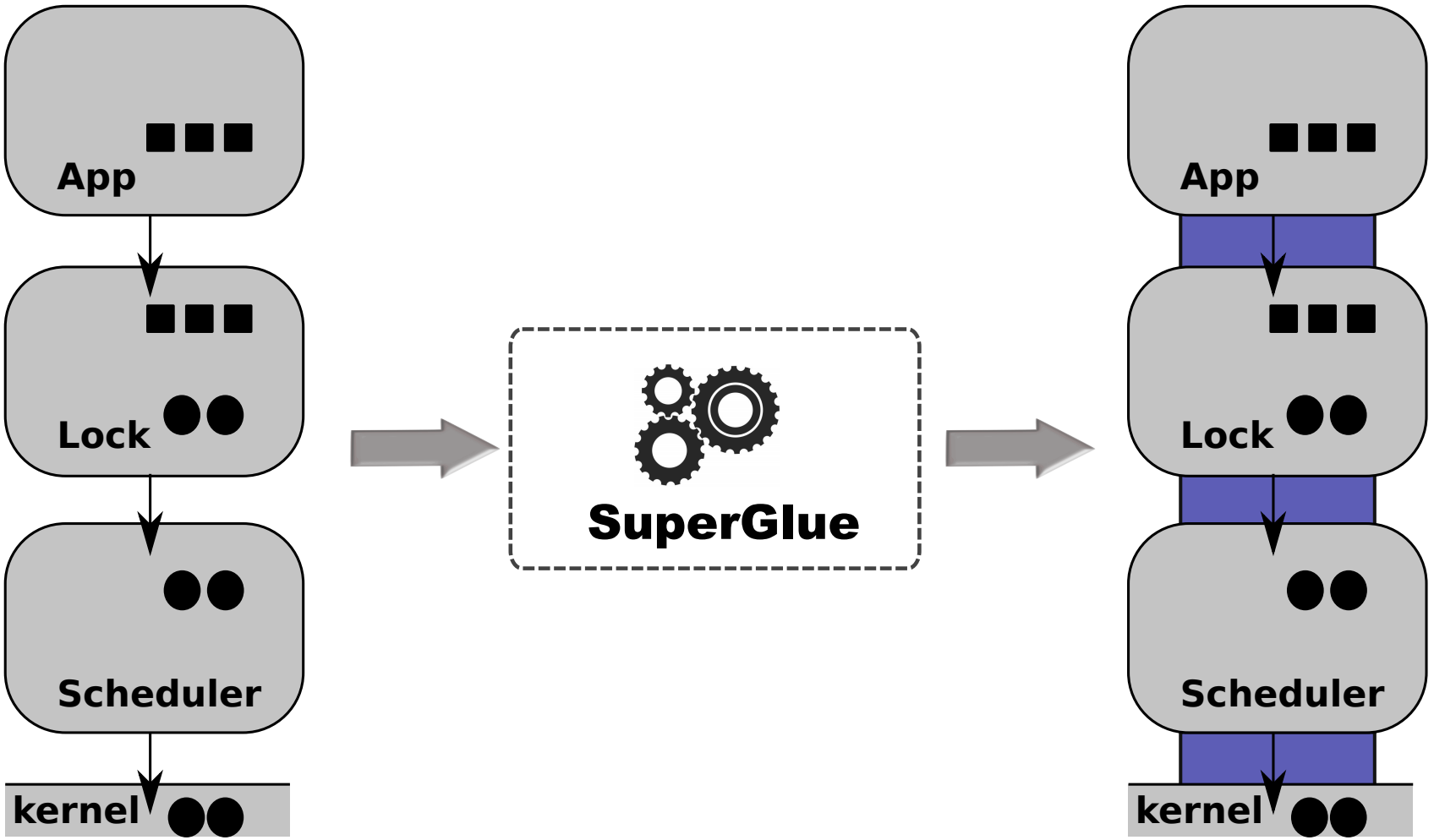
- automatically generate C^3 fault recovery code
- for all system-level services
- a system model and interface description language (IDL)
- an IDL compiler synthesizes recovery code from the model



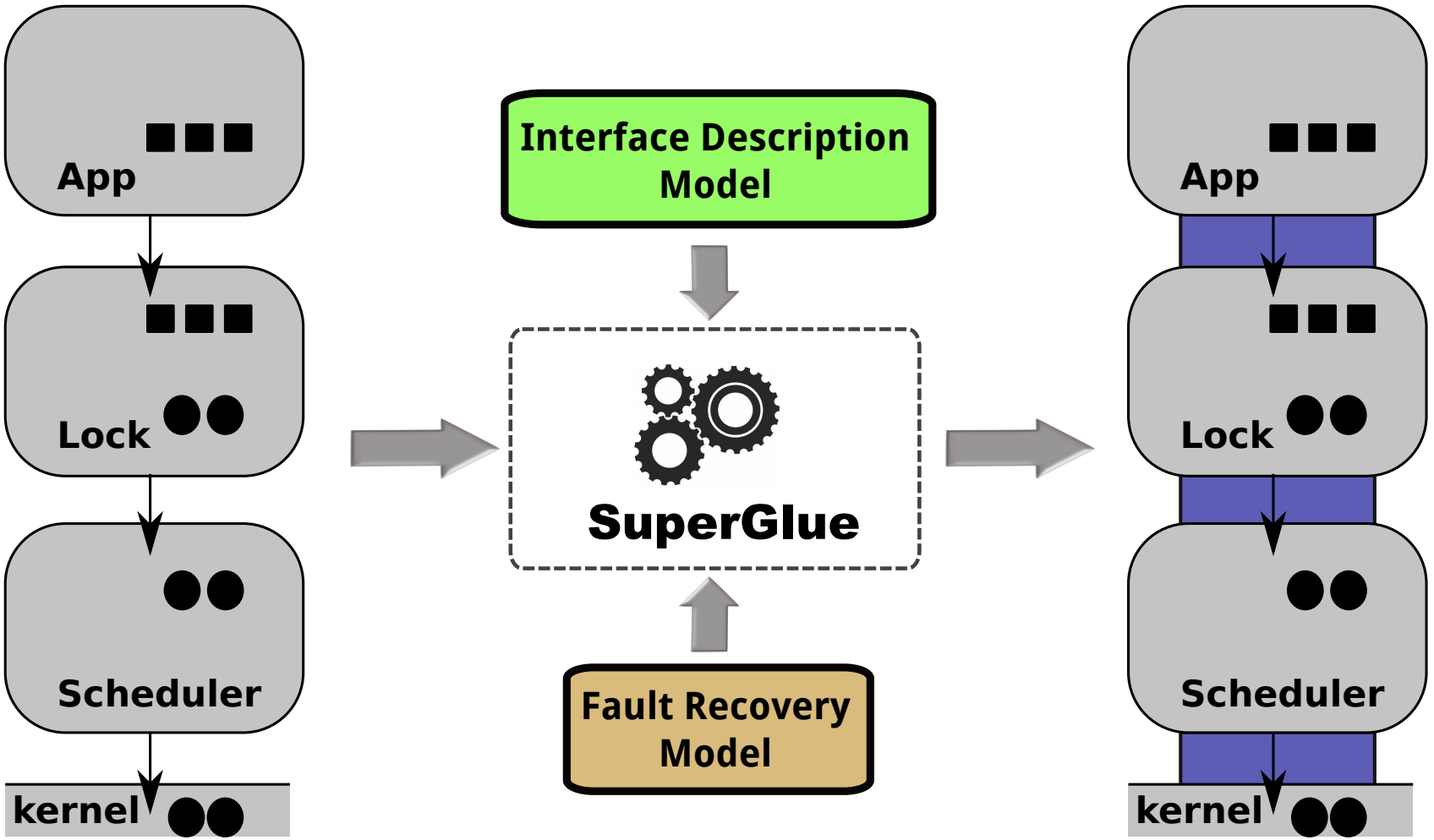
Fault Model (same as C^3):

- on-chip SEUs
- fault is detected immediately (*fail-stop*)

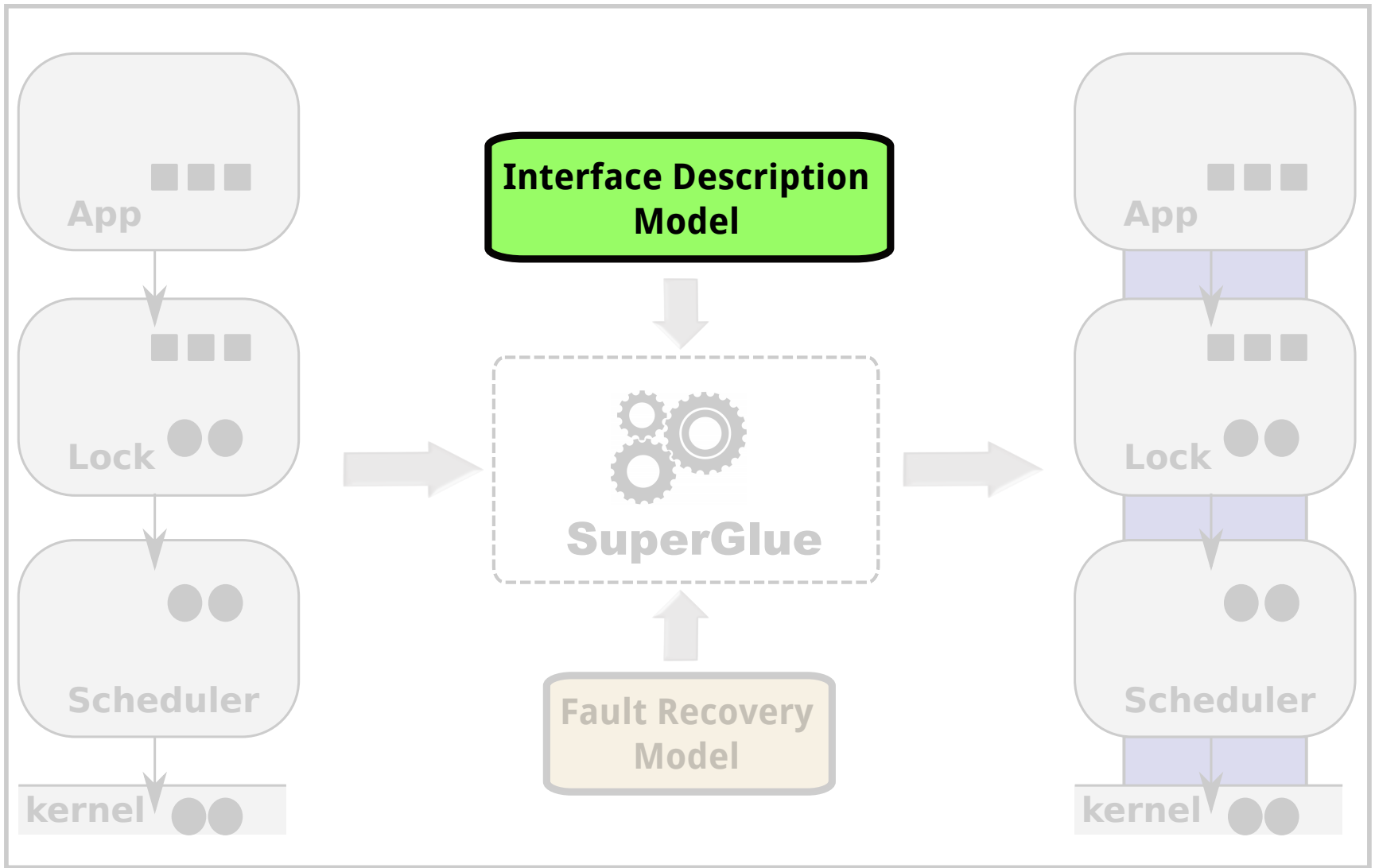
SuperGlue – IDL-based System-Level Fault Tolerance



SuperGlue – IDL-based System-Level Fault Tolerance

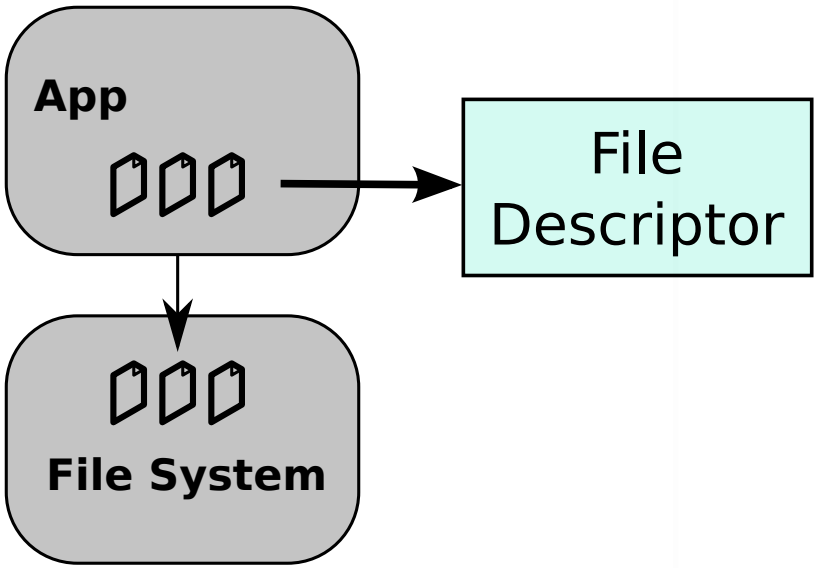


SuperGlue – IDL-based System-Level Fault Tolerance

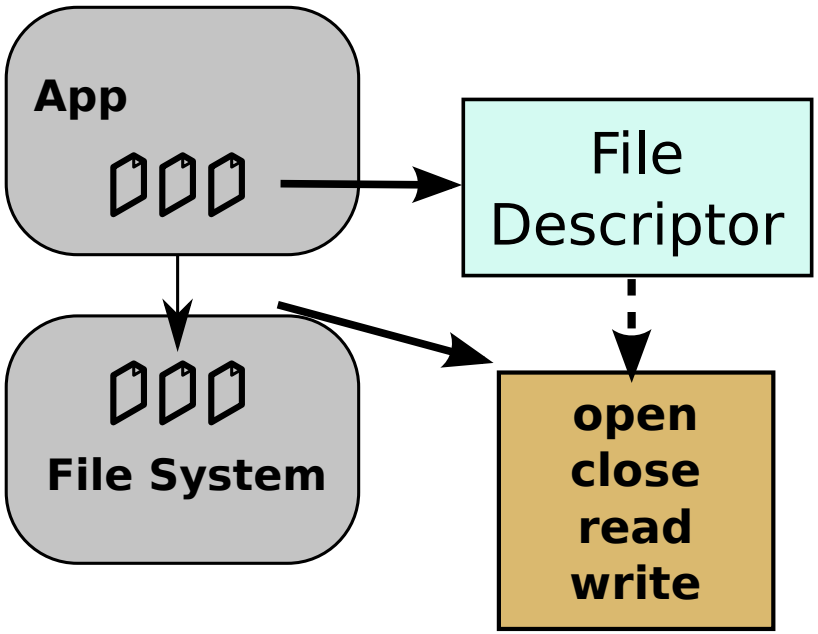


Interface Description Model – Descriptor and Resource

- File descriptor (descriptor)

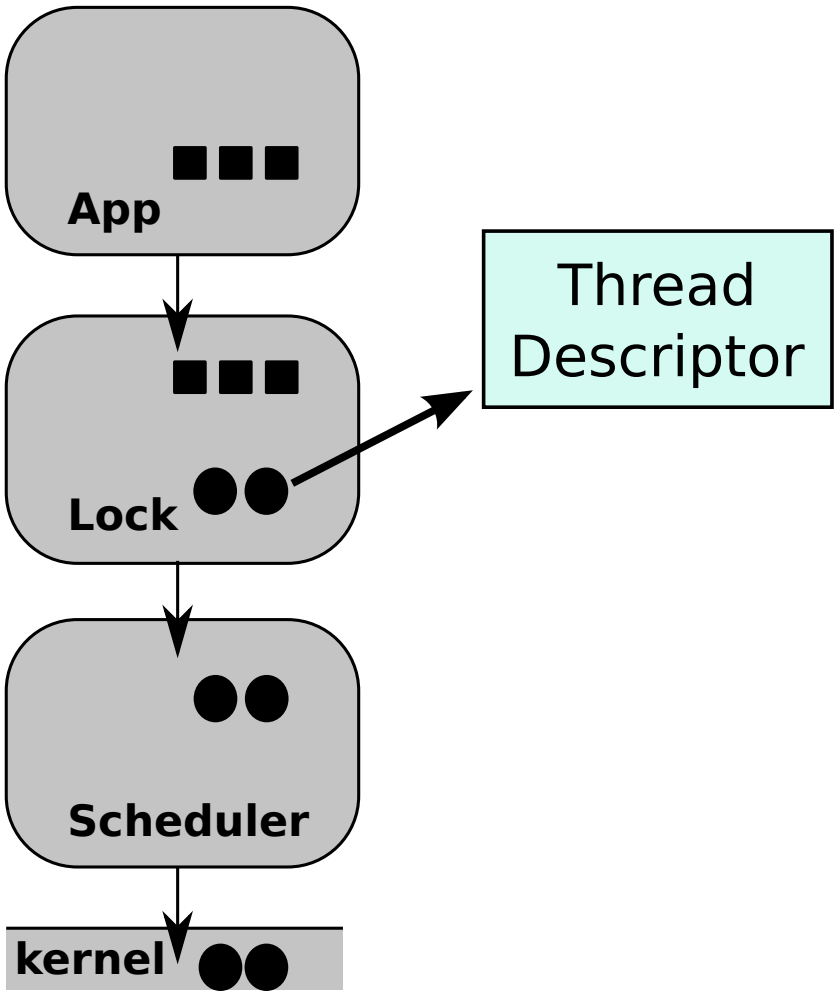


Interface Description Model – Descriptor and Resource



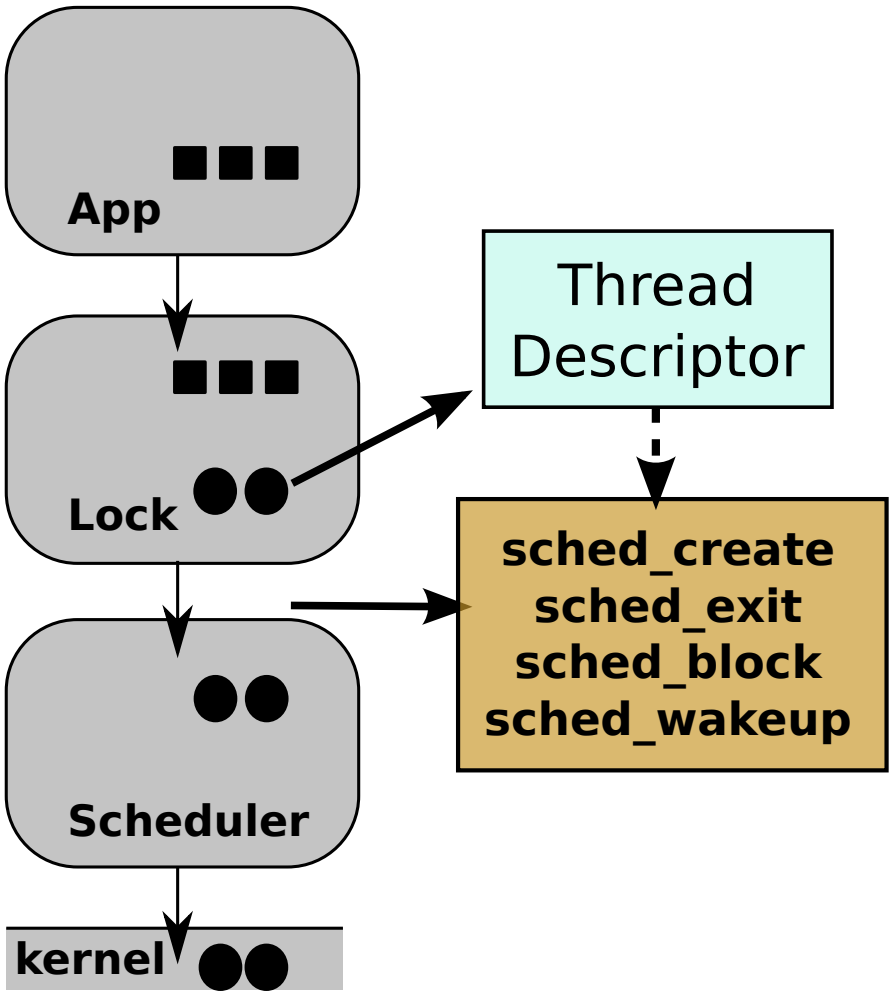
- File descriptor (descriptor)
- Interface functions operate on the file descriptor
  - open/close file, read/write file...

Interface Description Model – Descriptor and Resource



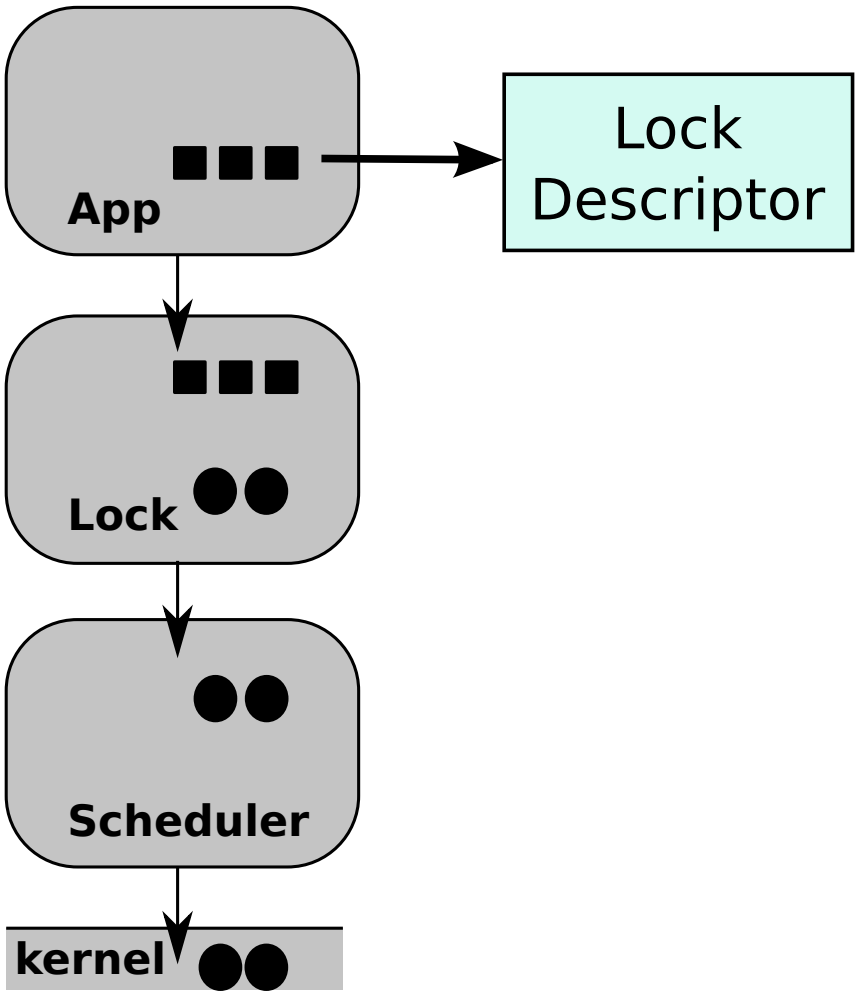
- Thread id (descriptor)

Interface Description Model – Descriptor and Resource



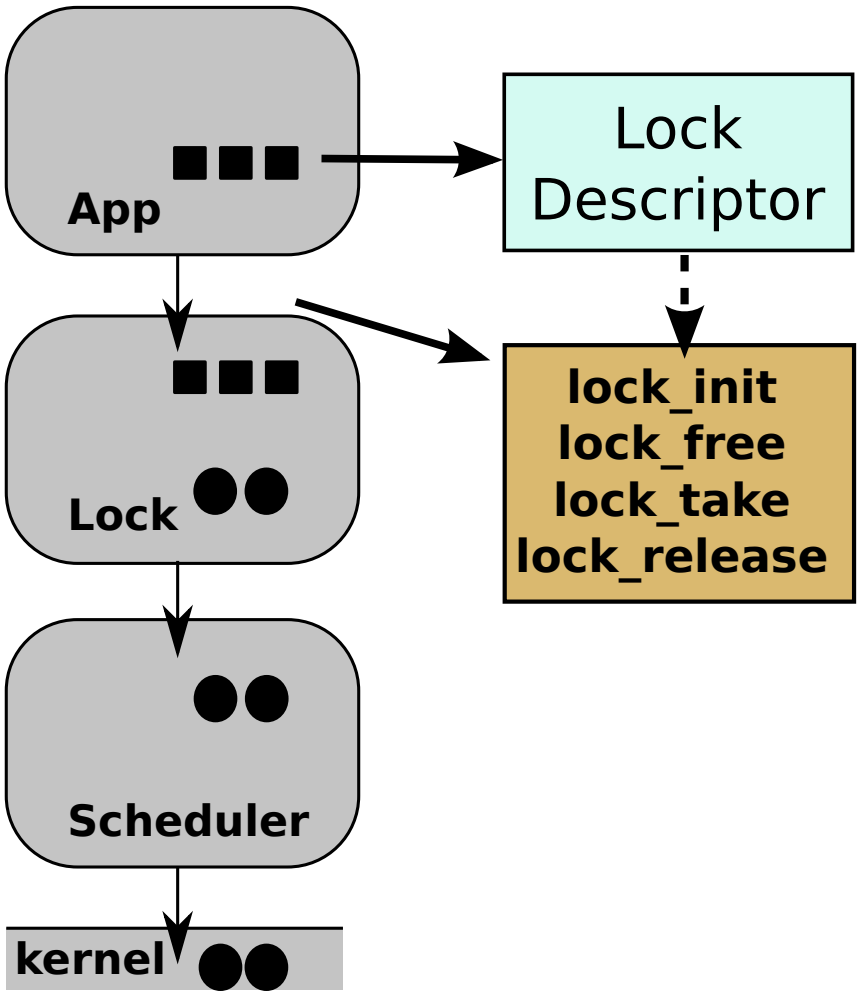
- Thread id (descriptor)
- Interface functions operate on thread descriptor
  - block/wake up thread...

Interface Description Model – Descriptor and Resource



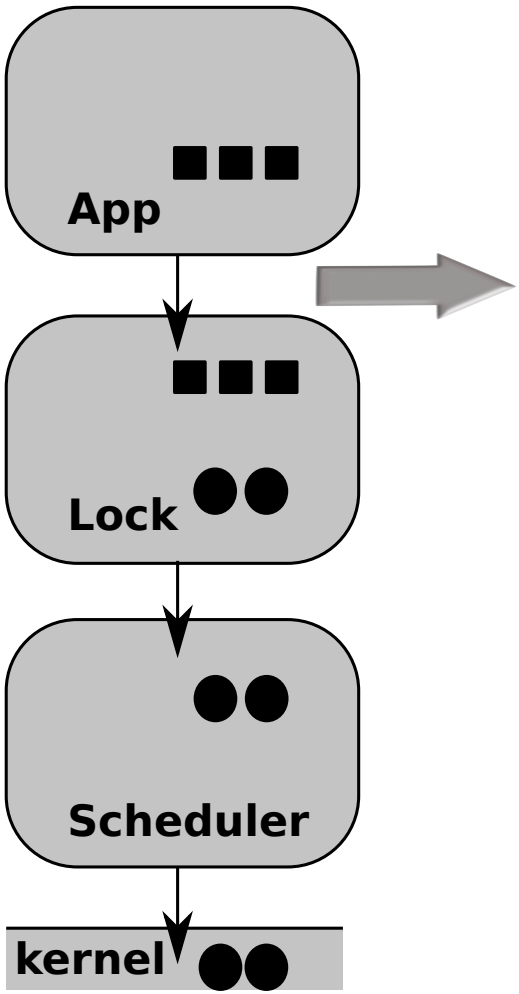
- Lock id (descriptor)

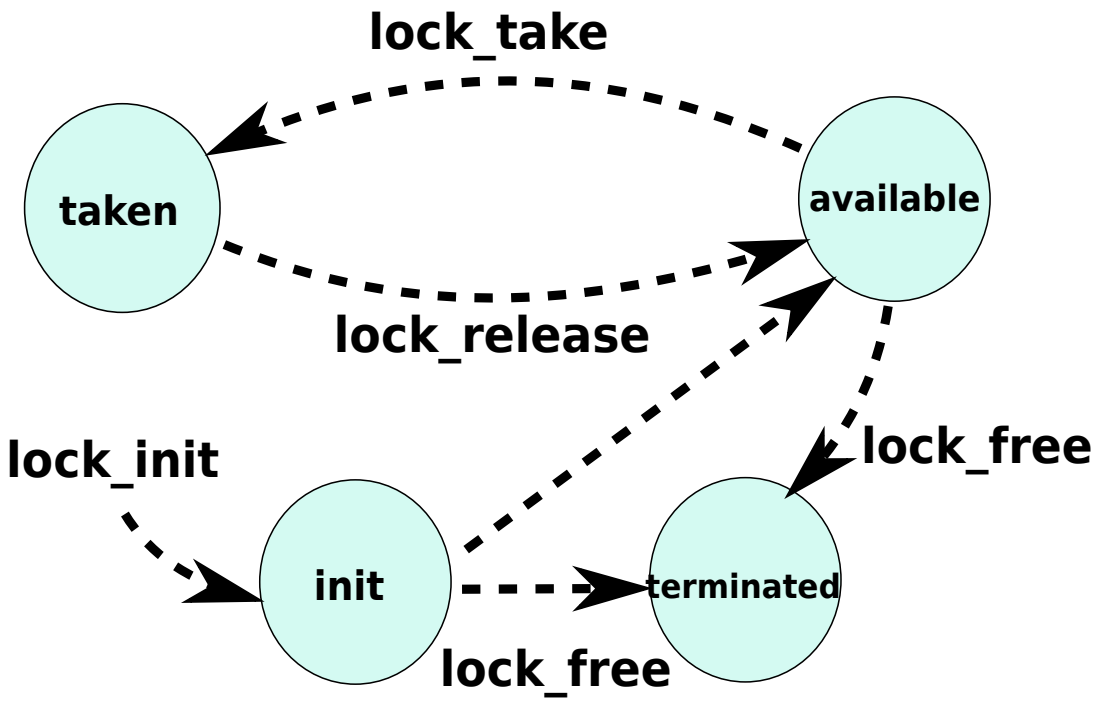
Interface Description Model – Descriptor and Resource



- Lock id (descriptor)
- Interface functions operate on lock descriptor
  - take/release lock...

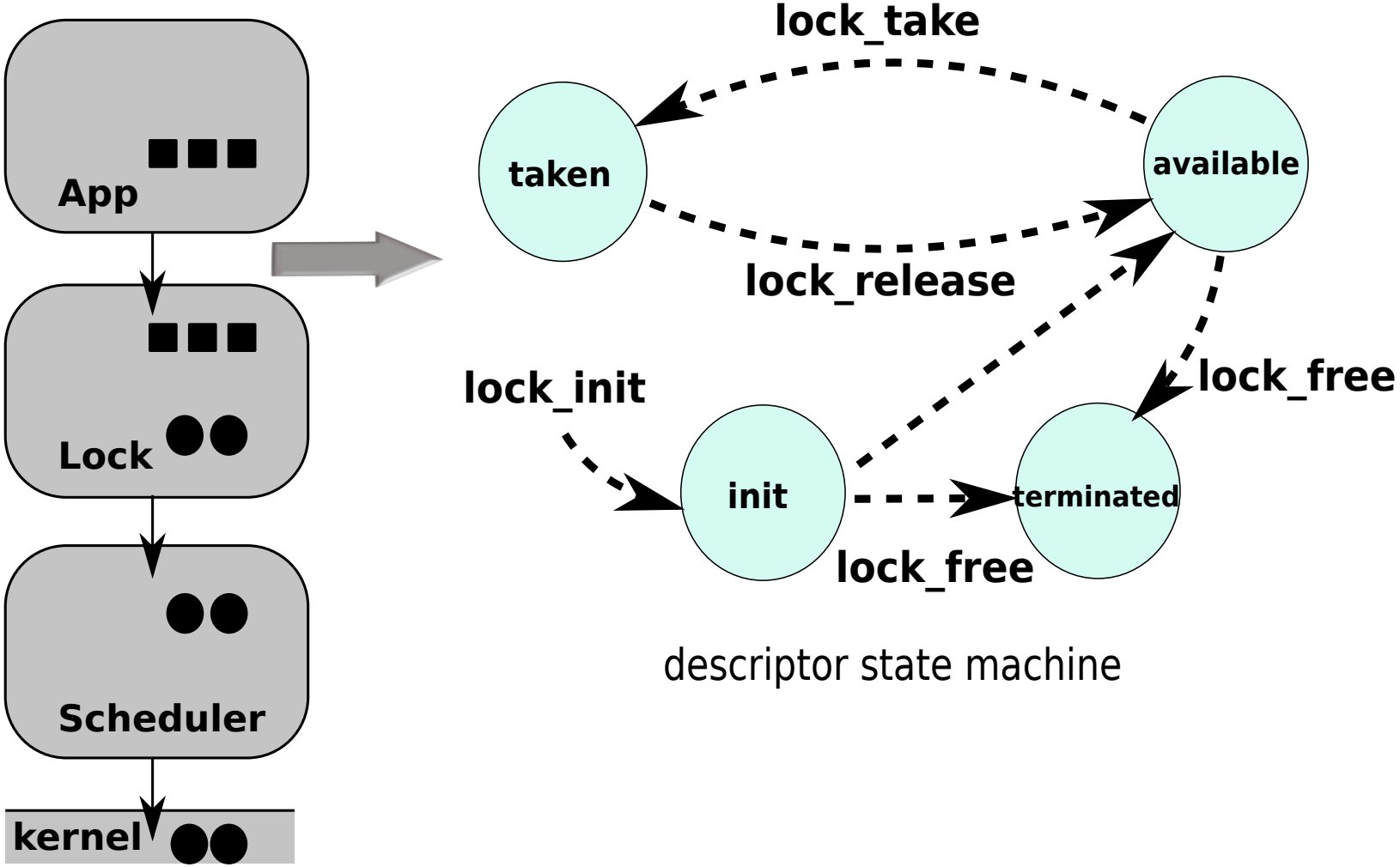
Interface Description Model – Descriptor and Resource





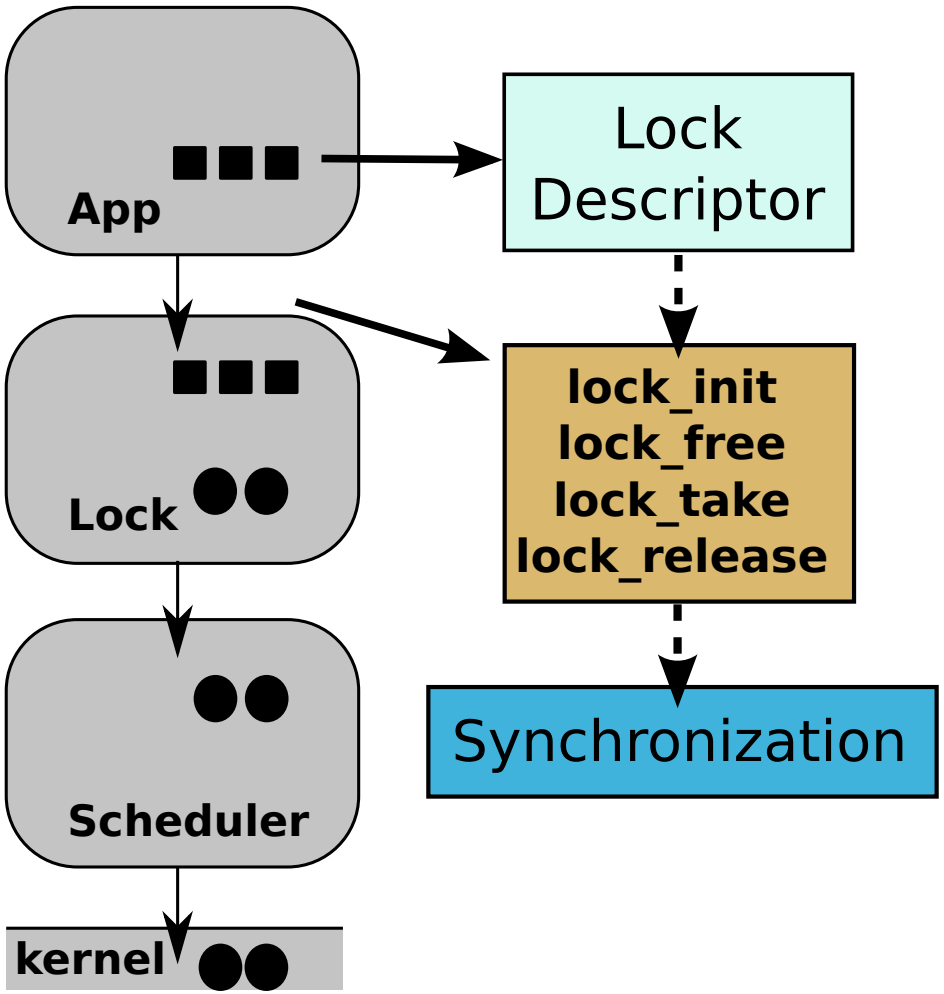
descriptor state machine

Interface Description Model – Descriptor and Resource



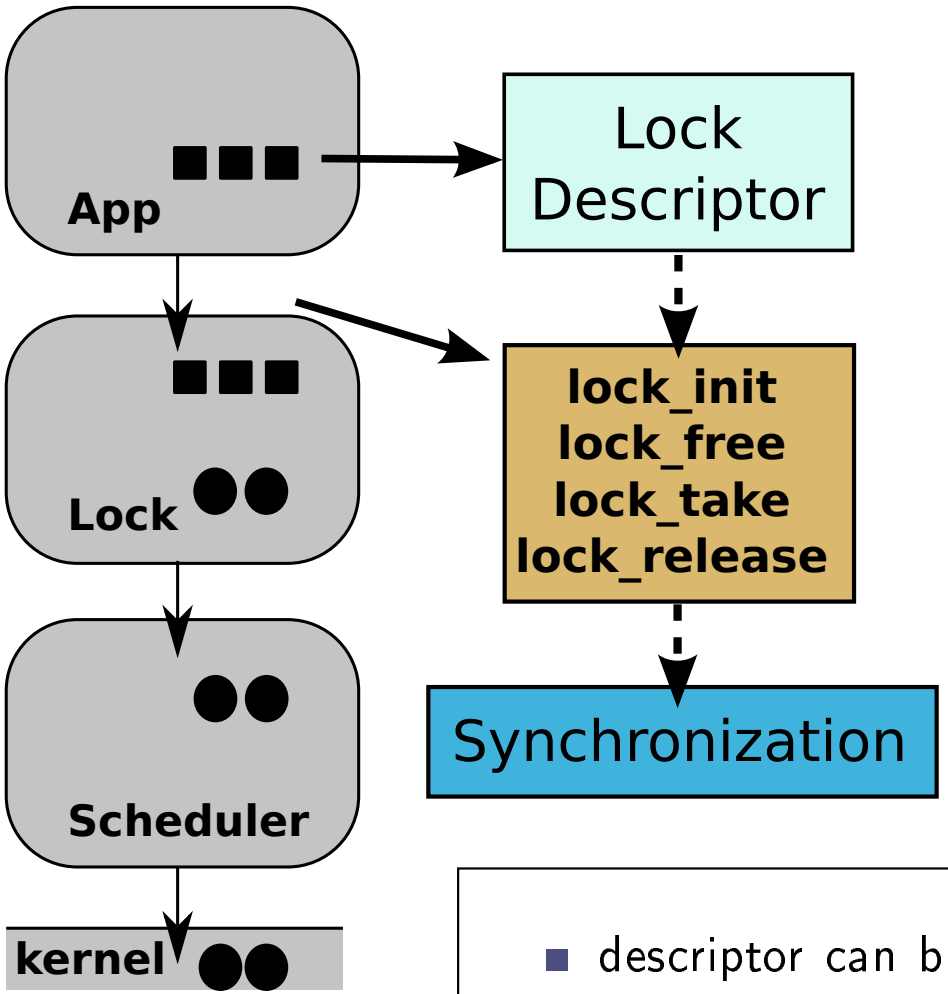
lock, scheduler, memory manager, file system, event...

Interface Description Model – Descriptor and Resource



- Lock id (descriptor)
- Interface functions operate on lock descriptor
  - take/release lock...
- Access the synchronization (resource)

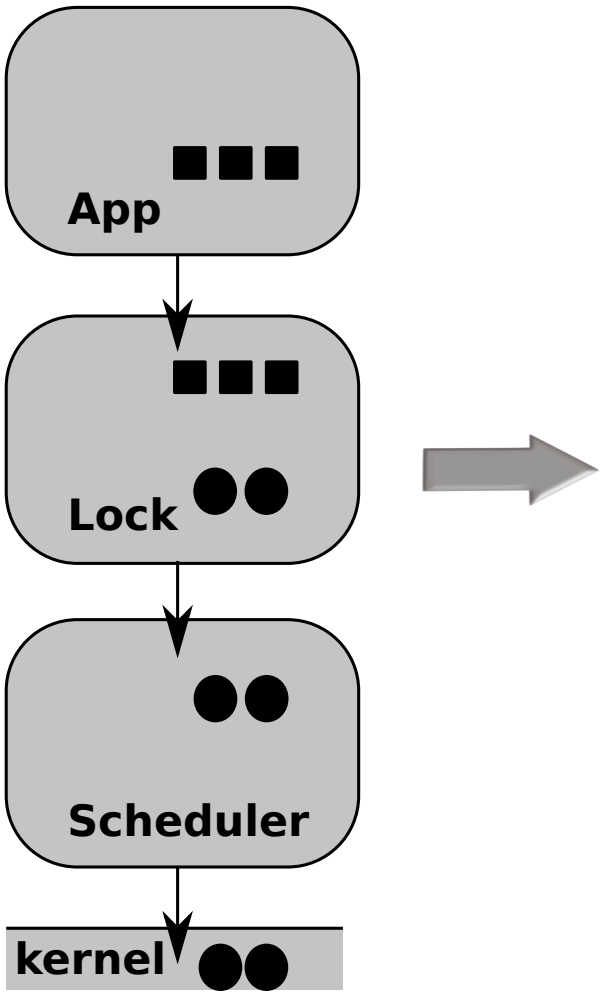
Interface Description Model – Descriptor and Resource



- Lock id (descriptor)
- Interface functions operate on lock descriptor
  - take/release lock...
- Access the synchronization (resource)

- descriptor can be accessed by multiple components
- thread can block when access a resource
- ...

System Model in IDL-based Specification




```
service_global_info = {
        service                 = lock,

        desc_close_self_only    = true,
        desc_dep_create_none    = true,
        desc_remove_tracking    = true,
        desc_global             = false,
        desc_block              = true,
        desc_has_data           = false,
        resc_has_data           = false,
};

sm_creation(lock_component_alloc);
sm_transition(lock_component_alloc, lock_component_free);
sm_transition(lock_component_alloc, lock_component_pretake);
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sm_transition(lock_component_release, lock_component_pretake);
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desc_data_retval(ul_t, lock_id)
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int lock_component_take(spdid_t spdid, ul_t desc(lock_id),
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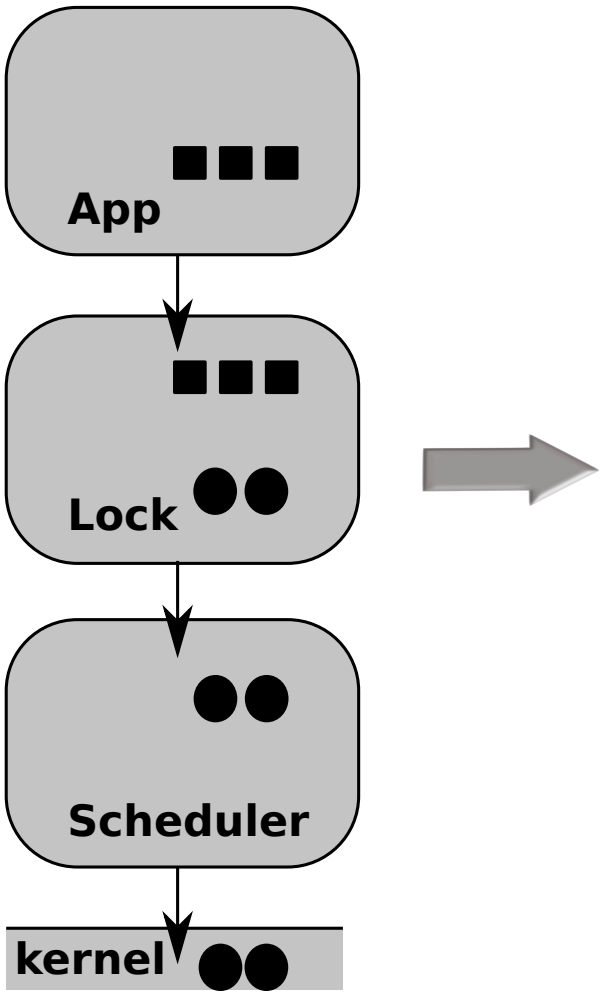
```

“descriptor and resource” + “interface functions”
$\rightarrow$ described using IDL

System Model in IDL-based Specification

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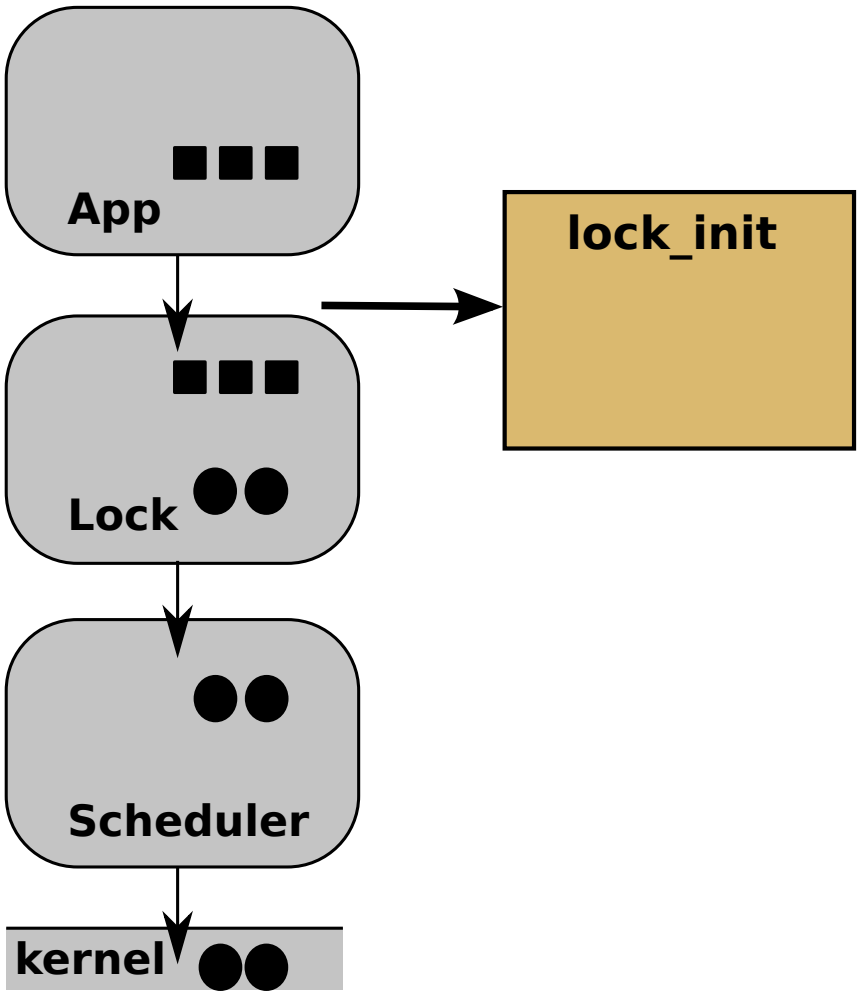
```

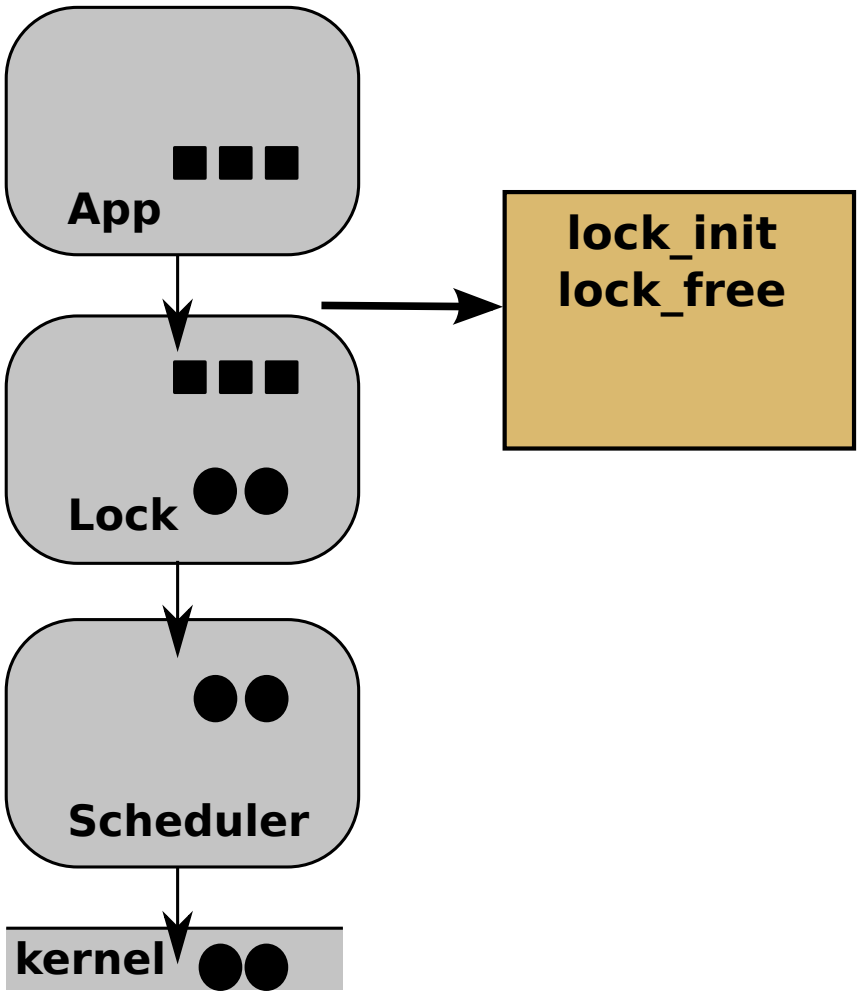
"descriptor and resource" + "interface functions"
$\rightarrow$ described using IDL in average 37 LOC

Component Interface Function Types



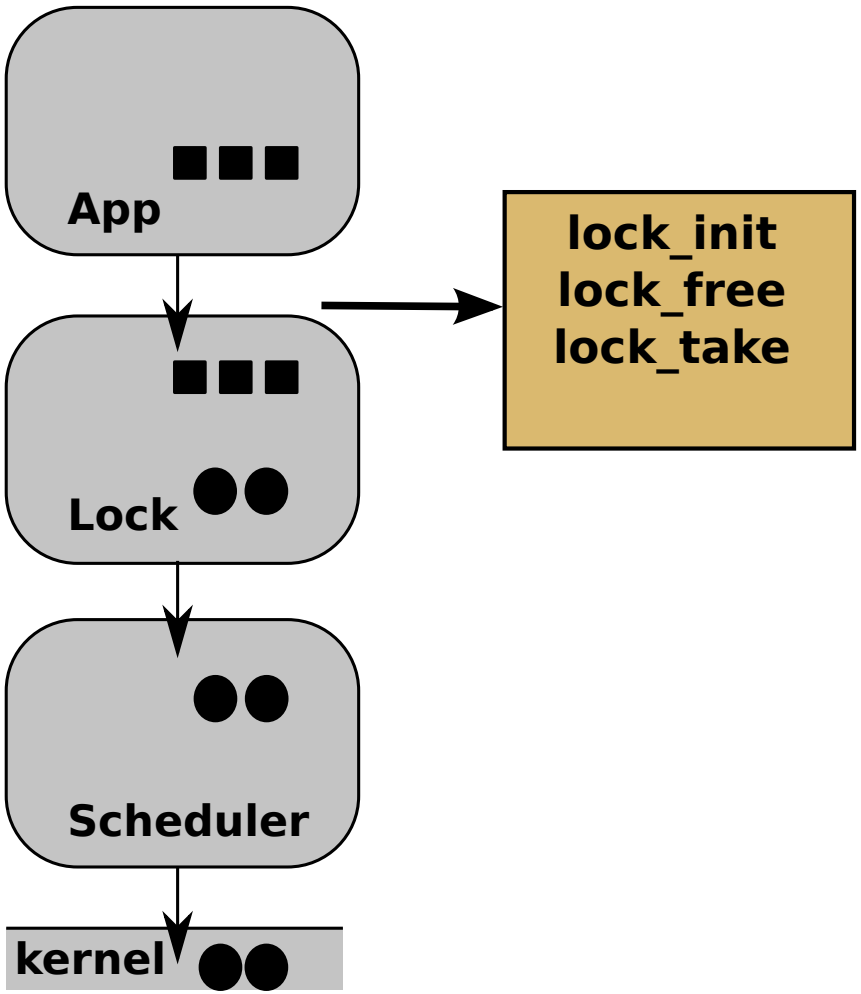
- create new descriptor

Component Interface Function Types



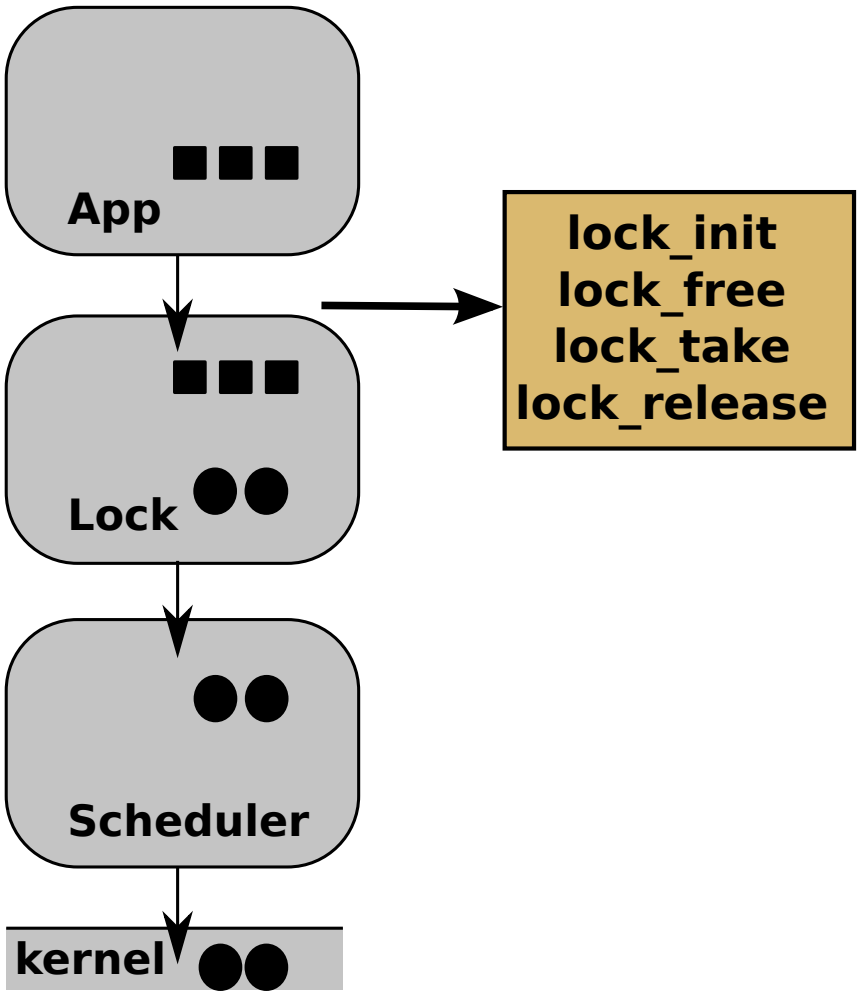
- create new descriptor
- terminate descriptor

Component Interface Function Types



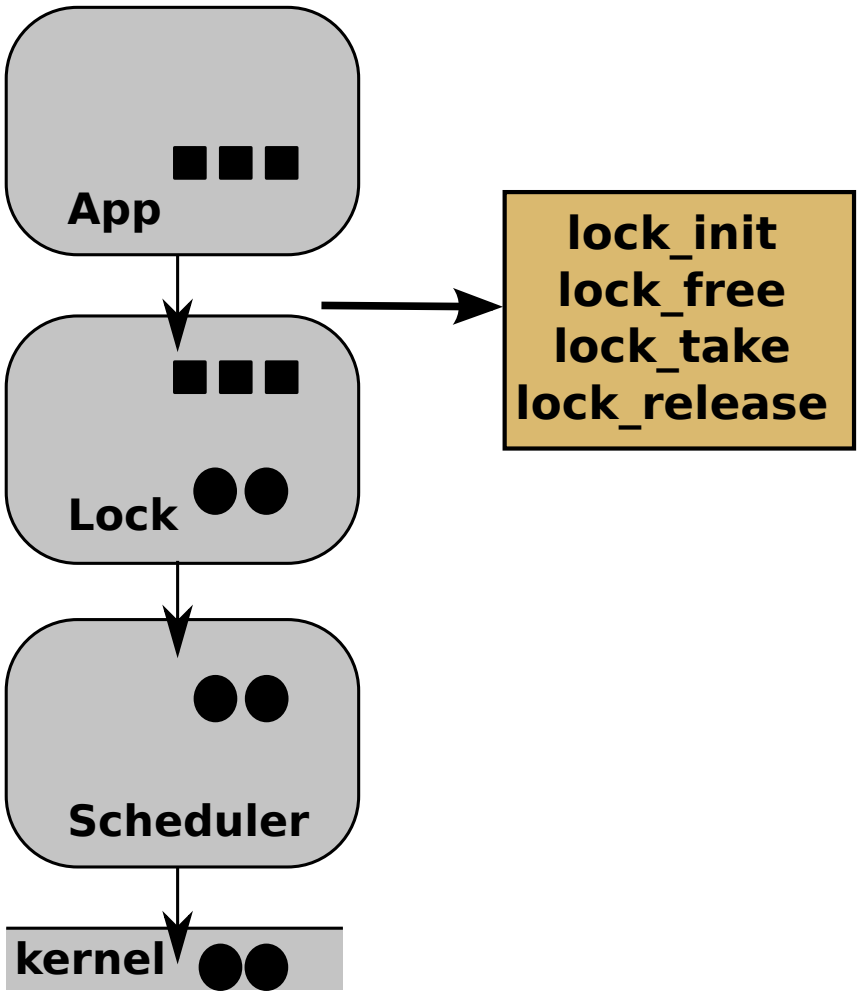
- create new descriptor
- terminate descriptor
- block invoking thread

Component Interface Function Types



- create new descriptor
- terminate descriptor
- block invoking thread
- wake up blocking thread

Component Interface Function Types



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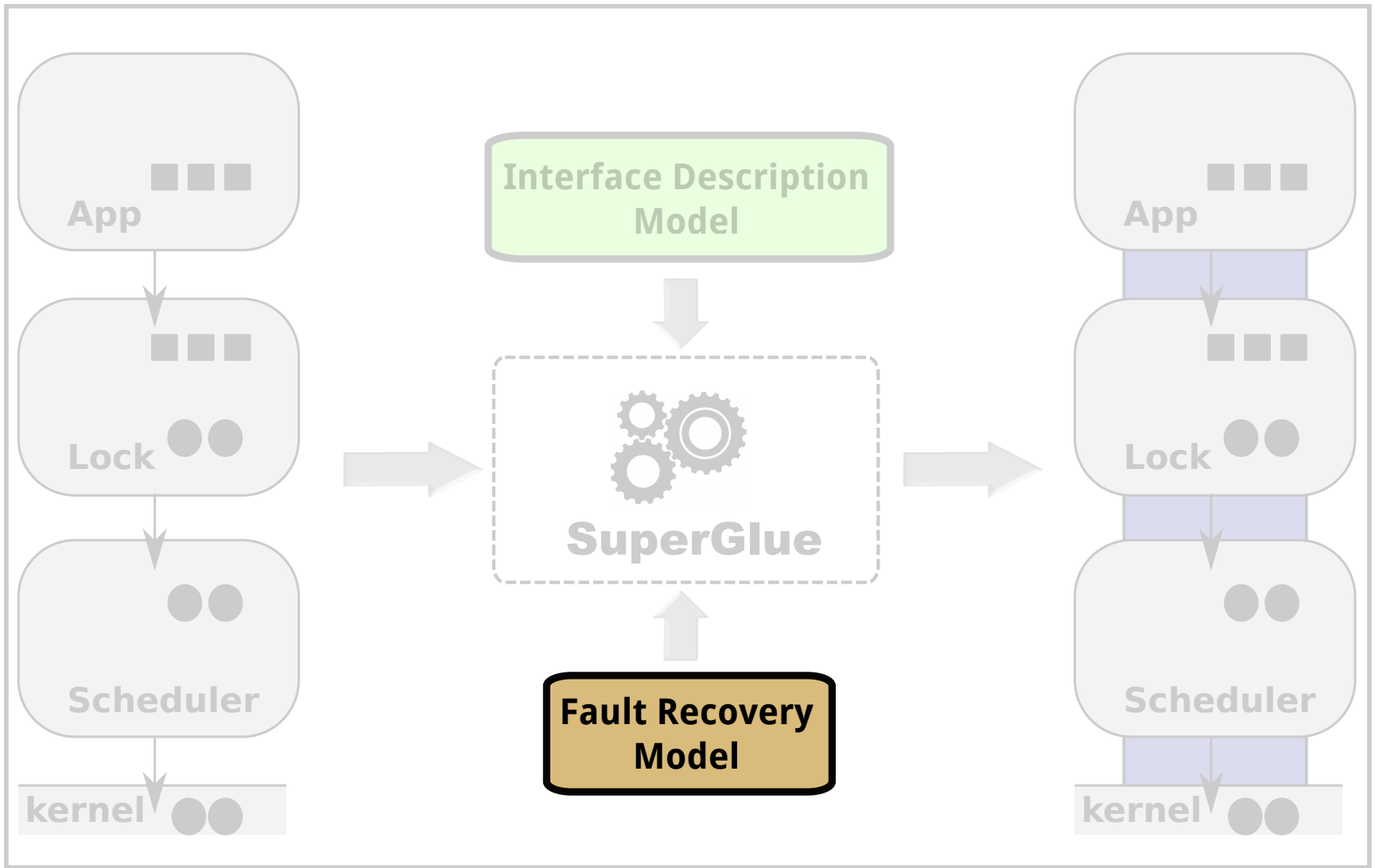
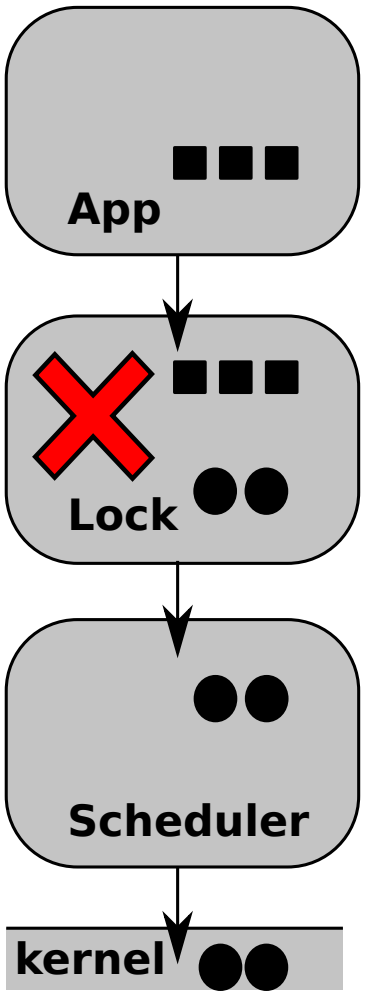
lock, scheduler, memory manager, file system, event...

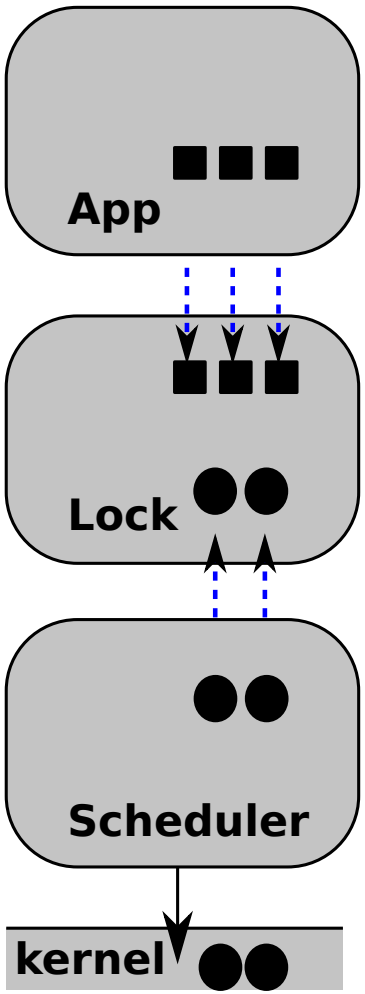
SuperGlue – IDL-based System-Level Fault Tolerance



Fault Recovery Model



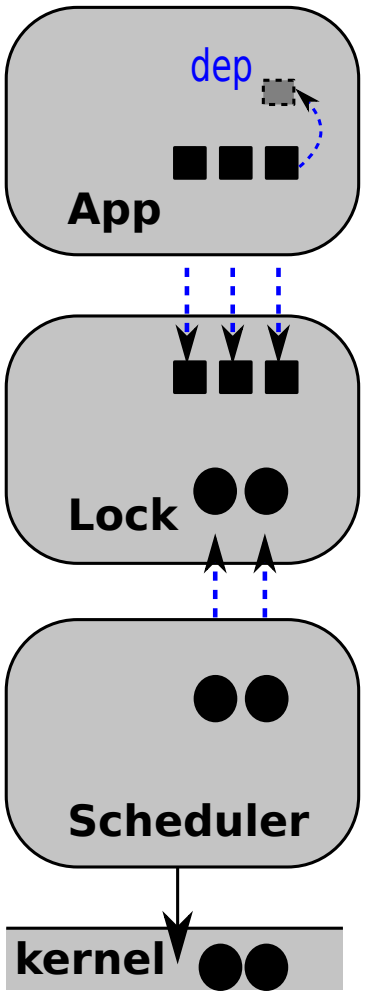
Fault Recovery Model



Basic Recovery

- always through component operation

Fault Recovery Model



Basic Recovery

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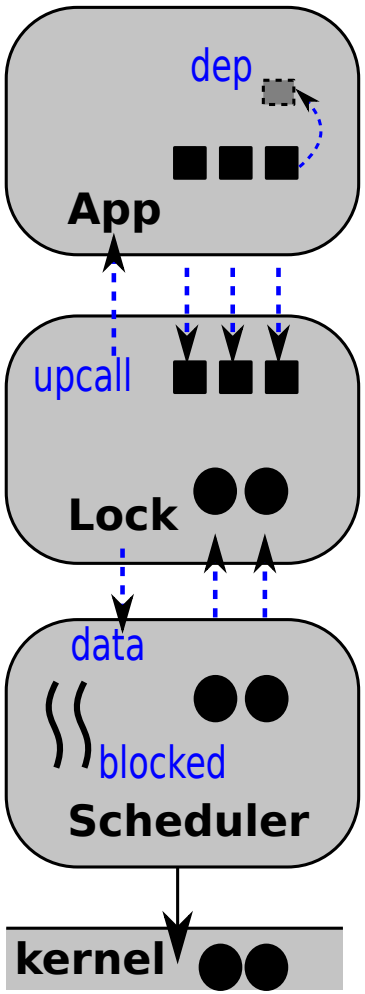
Recovery with Dependency

- recover the dependency descriptor first
- e.g., *new_fd = accept(fd)*. Descriptor *fd* must be recovered before *new_fd*

Fault Recovery Model



Basic Recovery

- always through component operation

Recovery with Dependency

- recover the dependency descriptor first
- e.g., *new_fd = accept(fd)*. Descriptor *fd* must be recovered before *new_fd*

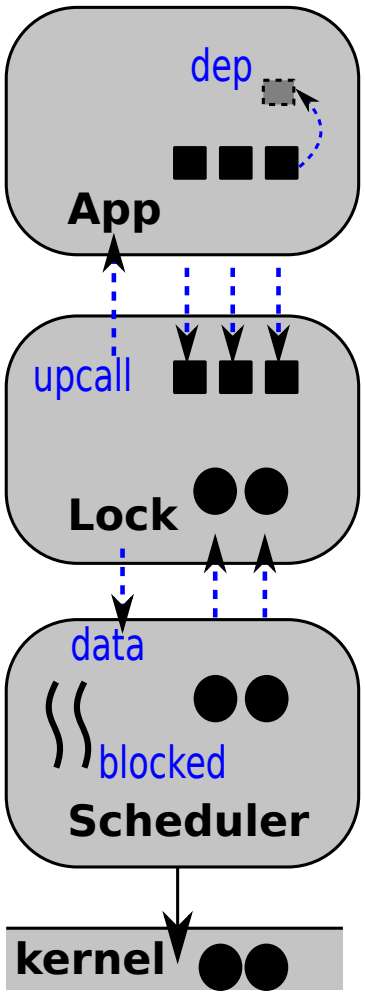
Timing of Recovery

- on-demand: recover only when access
- eager: wake up all blocking threads

Recovery with Data Storage

Recovery with Upcall

Fault Recovery Model



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Recovery with Data Storage

Recovery with Upcall

lock, scheduler, memory manager, file system, event...

System Model → Recovery Mechanisms

System Model in IDL

```
service_global_info = {
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        desc_dep_create_none    = true,
        desc_remove_tracking    = true,
        desc_global             = false,
        desc_block              = true,
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};

sm_creation(lock_component_alloc);
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sm_transition(lock_component_take, lock_component_release);
sm_transition(lock_component_release, lock_component_pretake);
sm_transition(lock_component_release, lock_component_free);
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desc_data_retval(ul_t, lock_id)
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```

Recovery Mechanisms

Basic Recovery

Timing of Recovery

Recovery with Dependency

Recovery with Storage

Recovery with Upcall

System Model → Recovery Mechanisms

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service_global_info = {
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        desc
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        desc
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        resc
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sm_creation(
sm_transitio
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```

Recovery Mechanisms

Basic Recovery

Which recovery mechanisms to use?

How to generate the recovery code?

Recovery with Dependency

Recovery with Storage

Recovery with Upcall

System Model → Recovery Mechanisms

System Model in IDL

```
service_global_info = {
        service                 = lock,

        desc_close_self_only    = true,
        desc
        desc
        desc
        desc
        resc
};

sm_creation(
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sm_transitio
sm_transitio
sm_transitio
sm_transitio
sm_terminal(
sm_block(loc
sm_wakeup(lo

desc_data_retv
lock_component_alloc(spdid_t desc_data(spdid));
int lock_component_take(spdid_t spdid, ul_t desc(lock_id),
                        u32_t desc_data(thd_id));
int lock_component_pretake(spdid_t spdid, ul_t desc(lock_id),
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int lock_component_release(spdid_t spdid, ul_t desc(lock_id));
int lock_component_free(spdid_t spdid, ul_t desc_terminate(lock_id));
```

Recovery Mechanisms

Basic Recovery

endency

age

Recovery with Upcall

Which recovery mechanisms to use?

How to generate the recovery code?

Idea: an IDL compiler parses IDL specifications and generates the code

Example – Client Invocation Stub

- Predicate ⇒ *"always included"*
- Code Template ⇒

```
/* predicate: true */
CSTUB_FN(IDL_fntype, IDL_fname) (IDL_parsdecl) {
  long fault = 0;
  int  ret   = 0;
redo:
  cli_if_desc_update_IDL_fname(IDL_params);

  ret = cli_if_invoke_IDL_fname(IDL_params);
  if (fault){
    CSTUB_FAULT_UPDATE();
    if (cli_if_desc_update_post_fault_IDL_fname()) goto
        redo;
  }
  ret = cli_if_track_IDL_fname(ret, IDL_params);
  return ret;
}
```

Example – Client Invocation Stub

- Predicate ⇒ *"always included"*
- Code Template ⇒

```
/* predicate: true */
CSTUB_FN(IDL_fntype, IDL_fname) (IDL_parsdecl) {
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    CSTUB_FAULT_UPDATE();
    if (cli_if_desc_update_post_fault_IDL_fname()) goto
        redo;
  }
  ret = cli_if_track_IDL_fname(ret, IDL_params);
  return ret;
}
```

Example – Client Stub Descriptor State Tracking

- Predicate $\Rightarrow$ *"the interface function creates descriptor AND the descriptor is not accessed between components"*
- Code Template $\Rightarrow$

```
/* predicate: f ∈ I_{d_r}^{create} ∧ ¬G_{d_r} */
static inline int cli_if_track_IDL_fname(int ret,
                                         IDL_parsdecl) {
  if (ret == -EINVAL) return ret;

  struct desc_track *desc = call_desc_alloc();
  if (!desc) return -ENOMEM;
  call_desc_track(desc, ret, IDL_params);

  return desc->IDL_id;
}
```

Example – Generated Recovery Code Snippet

```
        desc->server_lock_id = new_desc->server_lock_id;
        desc->state = state_lock_component_alloc;
        desc->fault_cnt = global_fault_cnt;

        call_desc_dealloc(new_desc);
        block_cli_if_recover_data(desc);
}

static inline struct desc_track *call_desc_update(ul_t id, int next_state)
{
        struct desc_track *desc = NULL;
        unsigned int from_state = 0;
        unsigned int to_state = 0;

        if (id == 0)
                return NULL;

        desc = call_desc_lookup(id);
        if (unlikely(!desc))
                goto done;

        desc->next_state = next_state;

        if (likely(desc->fault_cnt == global_fault_cnt))
                goto done;
        desc->fault_cnt = global_fault_cnt;

 done:
        return desc;
}

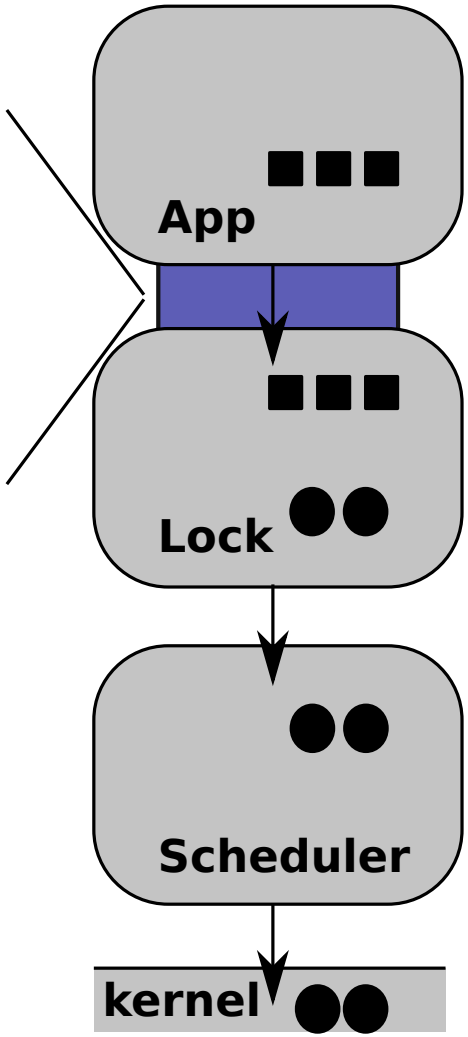
CSTUB_FN(int, lock_component_take)(struct usr_inv_cap * uc, spdid_t spdid,
                                   ul_t lock_id, u32_t thd_id) {
        long fault = 0;
        int ret = 0;

        call_map_init();

 redo:
        block_cli_if_desc_update_lock_component_take(spdid, lock_id, thd_id);

        ret =
            block_cli_if_invoke_lock_component_take(spdid, lock_id, thd_id, ret,
                                                    &fault, uc);
        if (unlikely(fault)) {

                CSTUB_FAULT_UPDATE();
                if (block_cli_if_desc_update_post_fault_lock_component_take()) {
                        goto redo;
                }
```



Example – Generated Recovery Code Snippet

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        desc->server_lock_id = new_desc->server_lock_id;
        desc->state = state_lock_component_alloc;
        desc->fault_cnt = global_fault_cnt;

        call_desc_dealloc(new_desc);
        block_cli_if_recover_data(desc);
}

static inline struct desc_track *call_desc_update(ul_t id, int next_state)
{
        struct desc_track *desc = NULL;
        unsigned int from_state = 0;
        unsigned int to_state = 0;

        if (id == 0)
                return NULL;

        desc = call_desc_lookup(id);
        if (unlikely(!desc))
                goto done;

        desc->next_state = next_state;

        if (likely(desc->fault_cnt == global_fault_cnt))
                goto done;
        desc->fault_cnt = global_fault_cnt;

 done:
        return desc;
}

CSTUB_FN(int, lock_component_take)(struct usr_inv_cap * uc, spdid_t spdid,
                                   ul_t lock_id, u32_t thd_id) {
        long fault = 0;
        int ret = 0;

        call_map_init();

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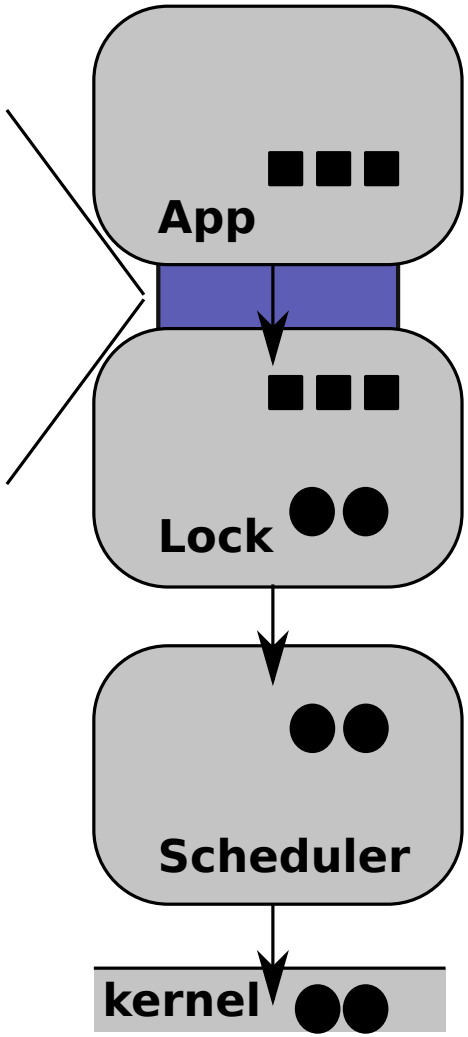
        block_cli_if_desc_update_lock_component_take(spdid, lock_id, thd_id);

        ret =
            block_cli_if_invoke_lock_component_take(spdid, lock_id, thd_id, ret,
                                                    &fault, uc);
        if (unlikely(fault)) {

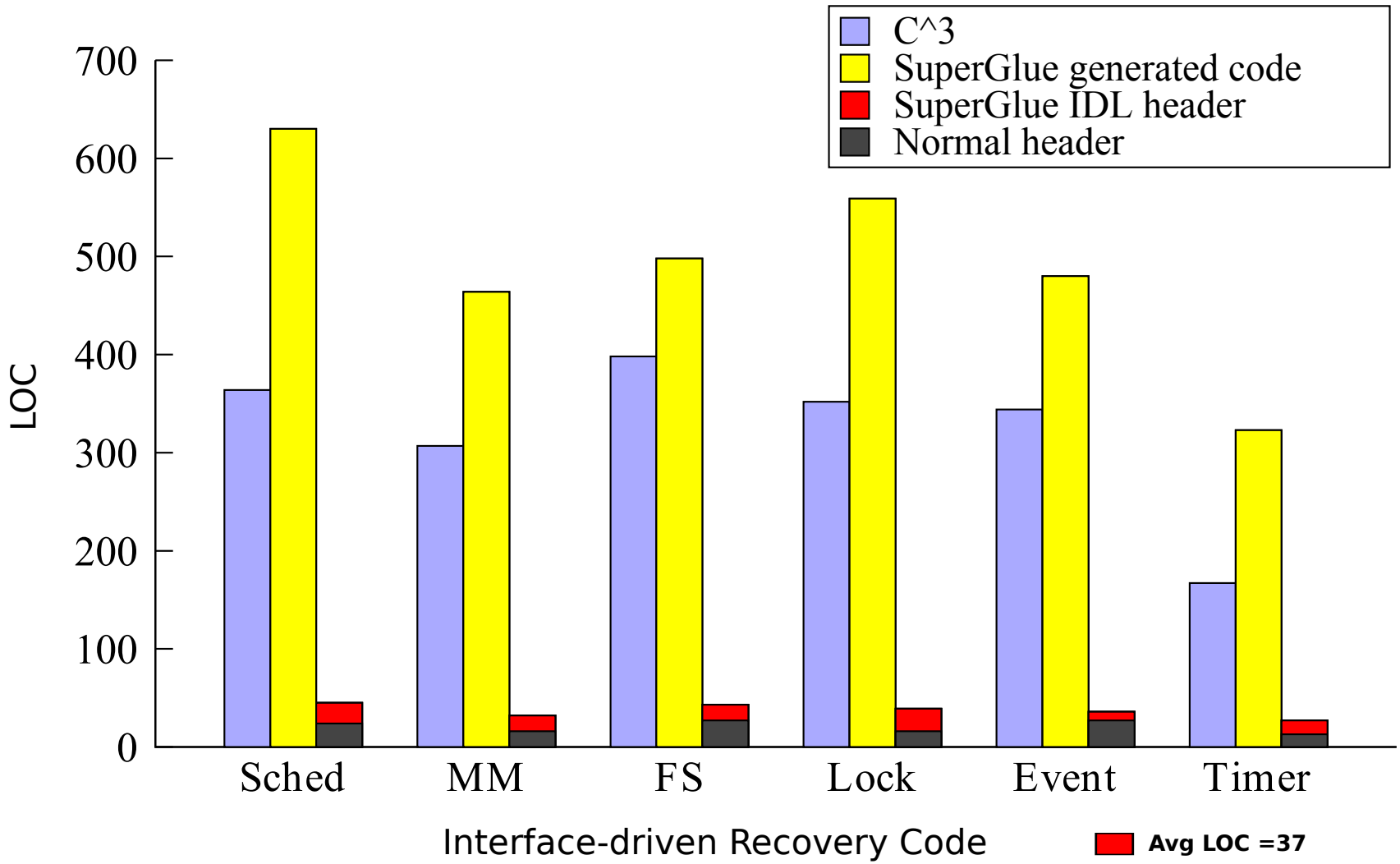
                CSTUB_FAULT_UPDATE();
                if (block_cli_if_desc_update_post_fault_lock_component_take()) {
                        goto redo;
                }
```



lock, scheduler, memory manager, file system, event...

Outlines

Code Generation Result



Fault Injection Campaign Results

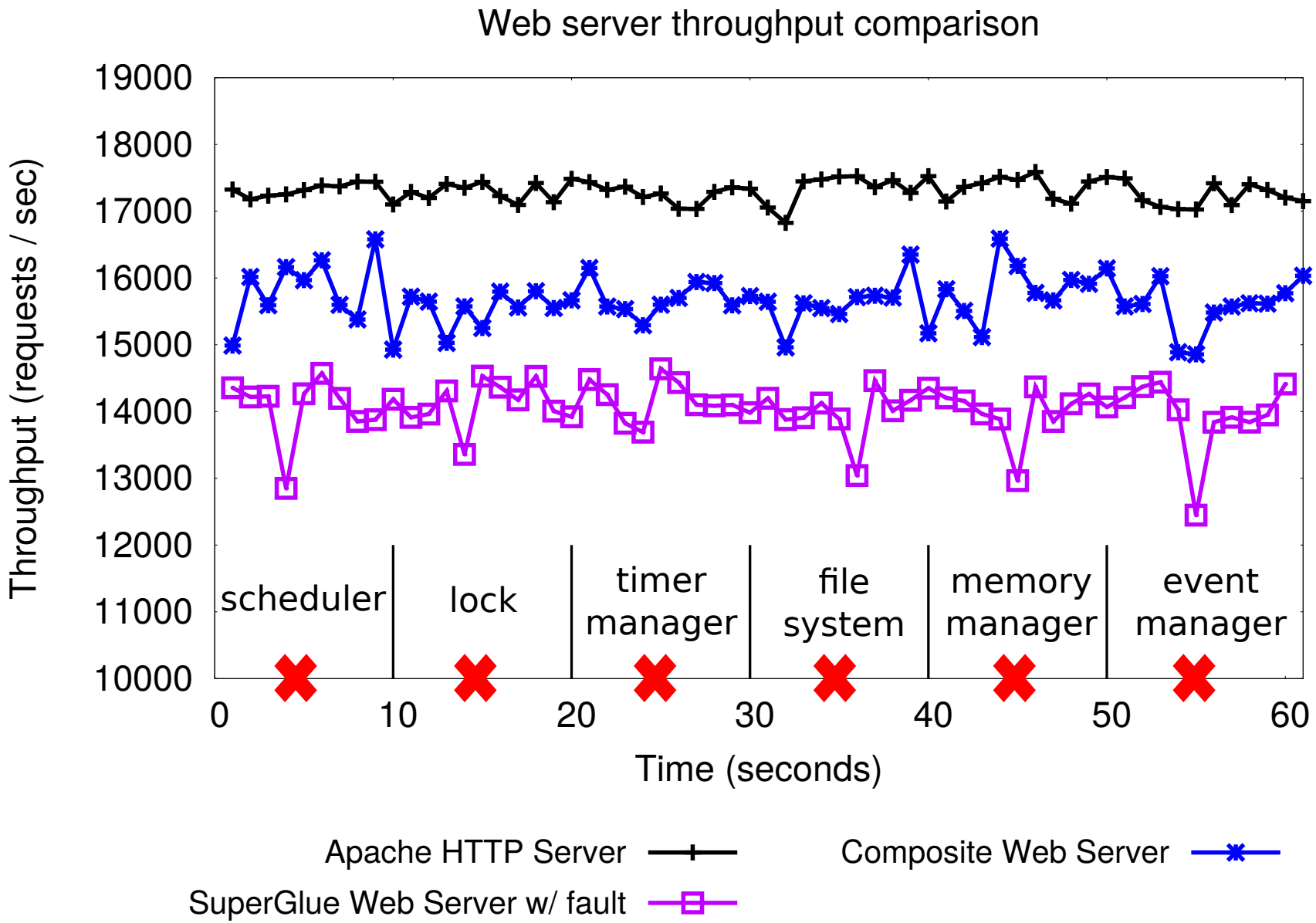
- SuperGlue implemented in *Composite* component-based OS
- Transient faults modeled as random register bit-flips
  - Software-implemented Fault Injection (SWIFI)

System Component	Injected	Fault Activation Ratio	Recovery Success Rate
Sched	500	98.36%	88.58%
MM	500	94.26%	91.48%
FS	500	94.7%	96.14%
Lock	500	93.82%	92.35%
Event	500	93.83%	96%
Timer	500	97.23%	94.62%

∗ fault activation ratio = activated faults/injected faults

∗ recovery success ratio = recovered faults/activated faults

Web Server Evaluation with Injected Faults



Outlines

Conclusion

SuperGlue – code generation for system-level fault tolerance

- synthesizes recovery code from the high-level system model
- effectively eases the programmer burden
- efficient and predictable system-level fault recovery

Thanks

? || /* */

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