Microkernel Construction

Interprocess Communication

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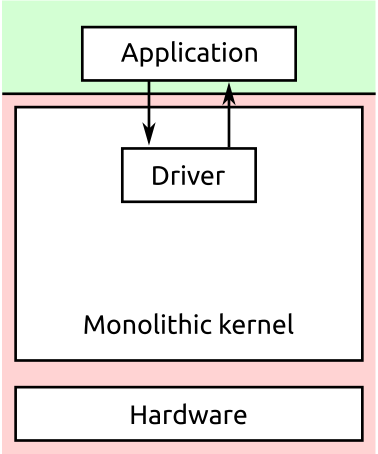
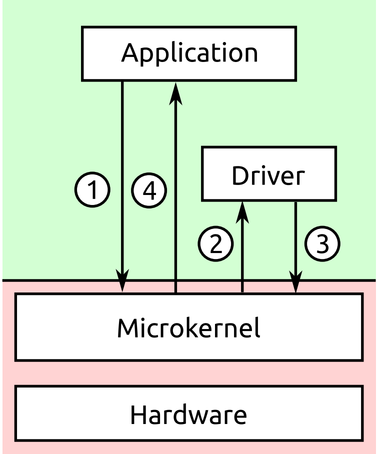
Outline

- Introduction
  - Microkernel vs. Monolithic kernel
  - Synchronous vs. Asynchronous
  - Different Implementations
- Synchronous IPC in NOVA
- Asynchronous IPC in NOVA
- Userspace API

Microkernel vs. Monolithic: Syscalls

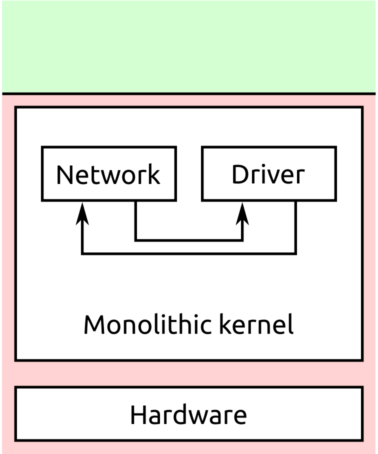
- Monolithic kernel: 2 kernel entries/exits
- Microkernel: 4 kernel entries/exits + 2 context switches

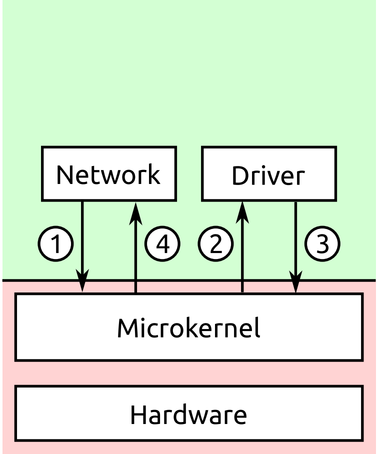




Microkernel vs. Monolithic: Calls Between Services

- Monolithic kernel: 2 function calls/returns
- Microkernel: 4 kernel entries/exits + 2 context switches





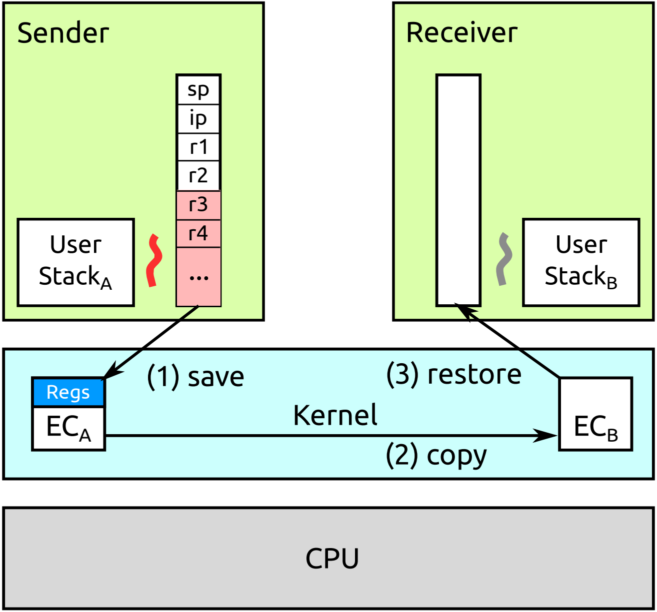
Synchronous vs. Asynchronous

- Synchronous
  - Sender is blocked until receiver is ready
  - Data and control transfer directly from sender to receiver
- Asynchronous
  - Data is transferred to temporary location
  - Sender continues execution
  - If receiver arrives, the data is transferred to him

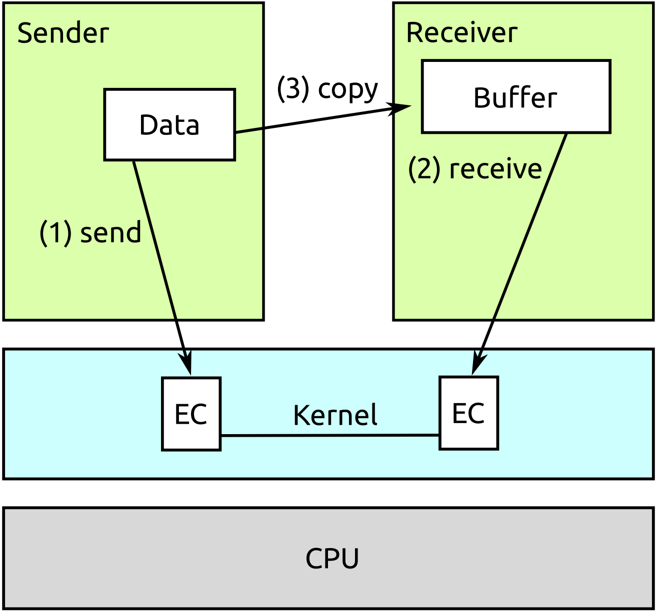
Comparison

- Synchronous is typically simpler and faster (no buffering)
- Synchronous is less prone to DoS attacks (buffer memory)
- Asynchronous is typically more flexible
- Asynchronous allows to do other work instead of waiting

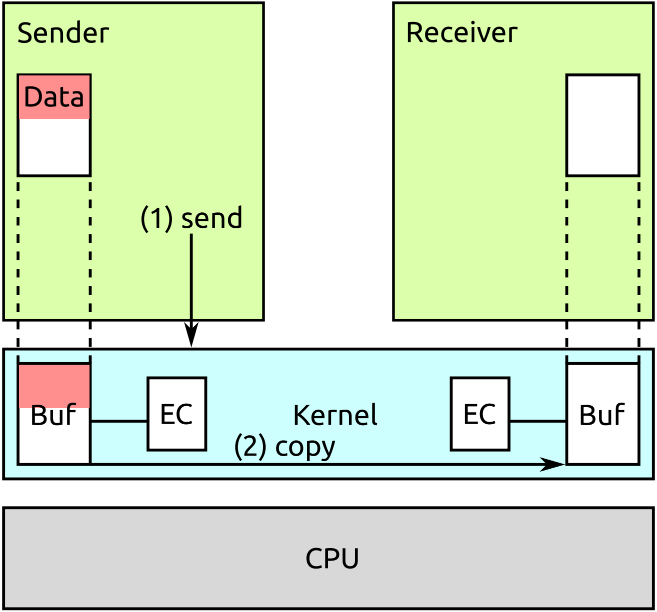
Register IPC



User Memory IPC



Kernel Memory IPC



Comparison

- Register IPC
  - + Very fast
  - – Amount of data limited to CPU registers
- User Memory IPC
  - + Amount of data not limited
  - + No copy to special location first
  - – Pagefaults can occur
  - – Slower (no direct copy)
- Kernel Memory IPC
  - + Fast
  - + No pagefaults
  - – Amount of data limited
  - – Copy to special location first

Outline

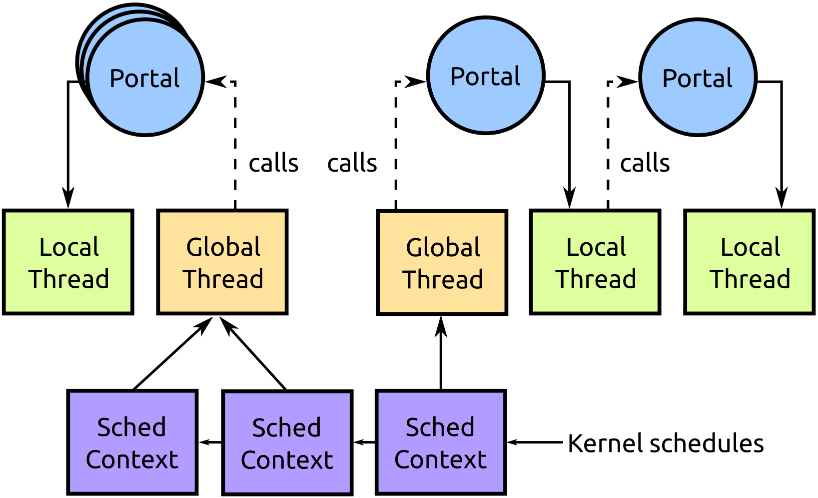
- Introduction
- Synchronous IPC in NOVA
  - Synchronous IPC in General
  - Exception IPC
- Asynchronous IPC in NOVA
- Userspace API

Introduction to IPC in NOVA

- NOVA uses synchronous kernel memory IPC to
  - Exchange data
  - Exchange capabilities
- Asynchronous IPC by semaphores for
  - Signaling
  - Deliver interrupts to user space
- Synchronous IPC is core-local
- Asynchronous IPC can be used cross-core

Synchronous IPC

- Uses kernel memory IPC
- Message buffer is called User Thread Control Block (UTCB)
- Each EC has exactly one UTCB
- A UTCB is one page, i.e., 4 KiB large
- All UTCBs are mapped in kernel space
- On EC creation, a UTCB is allocated and mapped to a specified address in user space
- UTCBs are pinned $\rightarrow$ no pagefaults


Portal
Portal
Portal
calls
calls
calls
Local Thread
Global Thread
Global Thread
Local Thread
Local Thread
Sched Context
Sched Context
Sched Context
Kernel schedules

Portal

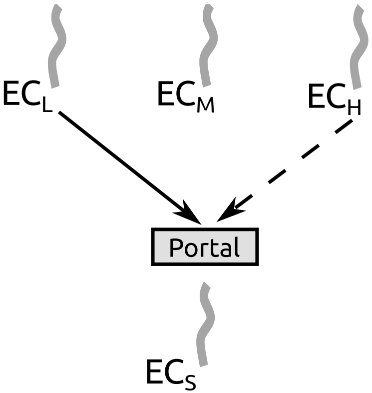
Properties

- Local Thread, that handles the portal
- Instruction Pointer (address of portal function)
- Id, delivered to the portal (parameter of portal function)

Code example from NRE

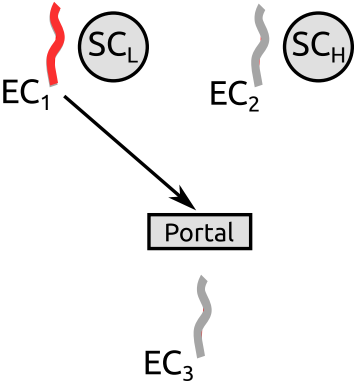
```
PORTAL static void portal_echo(void *id) {
}

int main() {
    Reference<LocalThread> lt = LocalThread::create();
    Pt echo(lt, portal_echo);
    echo.set_id(0x1234);
    echo.call();
}
```

Priority Inversion

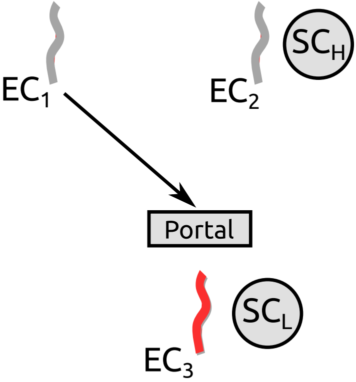


- High-priority EC_H blocked by low-priority EC_L
- Unbounded priority inversion if EC_M prevents EC_S from running

Timeslice Donation and Helping



- Timeslice donation:
  - EC_1 calls portal with SC_L
  - SC_L is donated to EC_3
- Helping:
  - If SC_L has no time left, SC_H helps EC_3
  - EC_3 runs with SC_H



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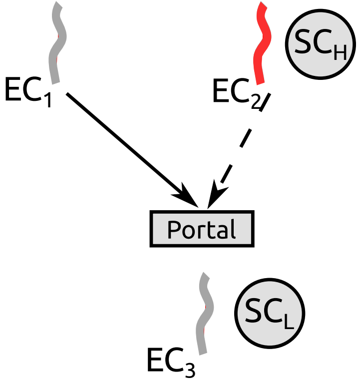

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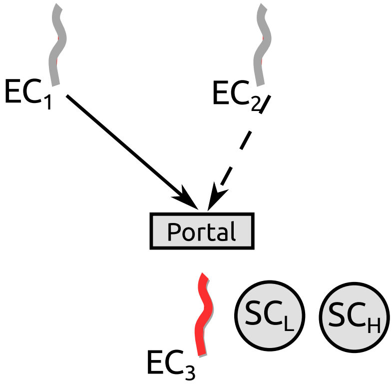

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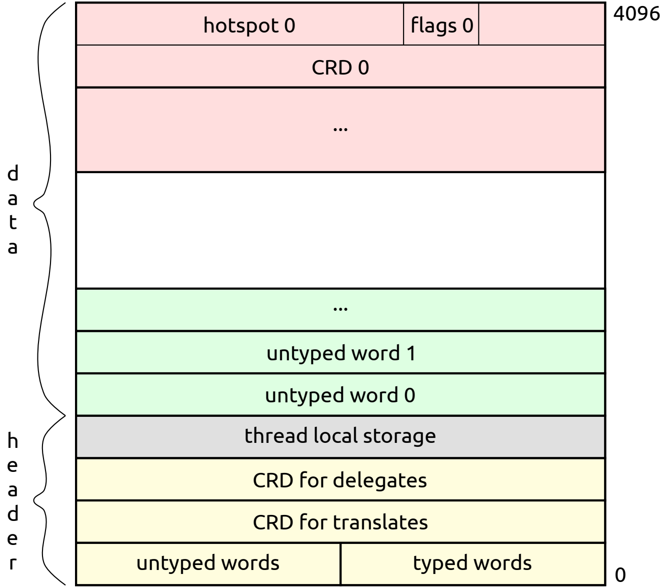
UTCB Layout



data
header
hotspot 0
flags 0
CRD 0
...
...
untyped word 1
untyped word 0
thread local storage
CRD for delegates
CRD for translates
untyped words
typed words
4096
0

Syscall: Call Portal (1)

```
Sys_call *s = static_cast<Sys_call *>(current->sys_regs());
Kobject *obj = Space_obj::lookup (s->pt()).obj();
Pt *pt = static_cast<Pt *>(obj);
Ec *ec = pt->ec;

if (EXPECT_FALSE (current->cpu != ec->xcpu))
    sys_finish<Sys_regs::BAD_CPU>();

if (EXPECT_TRUE (!ec->cont)) {
    current->cont = ret_user_sysexit;
    current->set_partner (ec);      // sets Ec::rcap
    ec->cont = recv_user;
    ec->regs.set_pt (pt->id);
    ec->regs.set_ip (pt->ip);
    ec->make_current();
}

ec->help (sys_call);
```

Syscall: Call Portal (2)

```
void Ec::recv_user() {
    Ec *ec = current->rcap;
    ec->utcb->save (current->utcb);
    if (EXPECT_FALSE (ec->utcb->tcnt()))
        delegate<true>();
    ret_user_sysexit();
}

void Ec::help (void (*c)()) {
    current->cont = c;
    if (EXPECT_TRUE (++Sc::ctr_loop < 100)) {
        Ec *ec = this;
        while(ec->partner)
            ec = ec->partner;
        ec->make_current();
    }
    die ("Livelock");
}
```

Exception IPC

- The kernel should have no policy
- Userland should decide what to do in case of an exception
- In particular, memory management is done in userland
- Each EC has an exception portal selector offset
- At this offset, portals are expected for all exceptions

Exception IPC: Details

```
void Ec::handle_exc (Exc_regs *r) {
    switch (r->vec) {
        case Cpu::EXC_NM:
            handle_exc_nm();
            return;

        case Cpu::EXC_PF:
            if (handle_exc_pf (r))
                return;
            break;
        ...
    }
    send_msg<ret_user_iret>();
}
```

Exception IPC: Details

```
template <void (*C)()>
void Ec::send_msg() {
    Exc_regs *r = &current->regs;
    Kobject *obj = Space_obj::lookup (
        current->evt + r->dst_portal).obj();
    Pt *pt = static_cast<Pt *>(obj);
    Ec *ec = pt->ec;
    if (EXPECT_TRUE (!ec->cont)) {
        ec->cont = recv_kern;
        ...
    }
    ec->help (send_msg<C>);
}

void Ec::recv_kern() {
    Ec *ec = current->rcap;
    current->utcb->load_exc (&ec->regs);
    ret_user_sysexit();
}
```

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- Synchronous IPC in NOVA
- Asynchronous IPC in NOVA
  - Synchronization
  - Interrupts
- Userspace API

Semaphores

- A semaphore is a kernel object
- Properties:
  - Counter
  - Queue of ECs
- Operations (via syscall):
  - Down
  - Down to zero
  - Up

Semaphores: Usecases

- Synchronization with shared memory (e.g., multithreading)
  - Typically combined with atomic operations
  - Atomic operations in case of no contention
  - System call in case of contention
- Signaling (e.g., producer-consumer scenarios)
- Delivery of interrupts to userspace

Interrupt Semaphores

- Object cap space of root PD has semaphore per interrupt
- Can be delegated to device drivers, ...
- Is up'ed by the kernel on IRQ

Usage example: Keyboard driver in NRE

```
static void kbhandler(void*) {
    Gsi gsi(KEYBOARD_IRQ);
    while(1) {
        gsi.down();

        Keyboard::Packet data;
        if(hostkb->read(data))
            broadcast(kbsrv, data);
    }
}
```

Semaphore Operations

```
void Sm::dn (bool zero) {
    Ec *e = Ec::current;
    {   Lock_guard <Spinlock> guard (lock);
        if (counter) {
            counter = zero ? 0 : counter - 1;
            return;
        }
        enqueue (e);
    }
    e->block_sc();
}

void Sm::up() {
    Ec *e;
    {   Lock_guard <Spinlock> guard (lock);
        if (!(e = dequeue())) { counter++; return; }
    }
    e->release();
}
```

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- Synchronous IPC in NOVA
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- Userspace API
  - UTCB Frames
  - IPC with C++ shift operators

Many Approaches

- Plain C API
- C++ shift operators to get/put values from/into UTCB
- C++ templates generate server and client stubs
- IDL compiler
- ...

NOVA Runtime Environment (NRE)

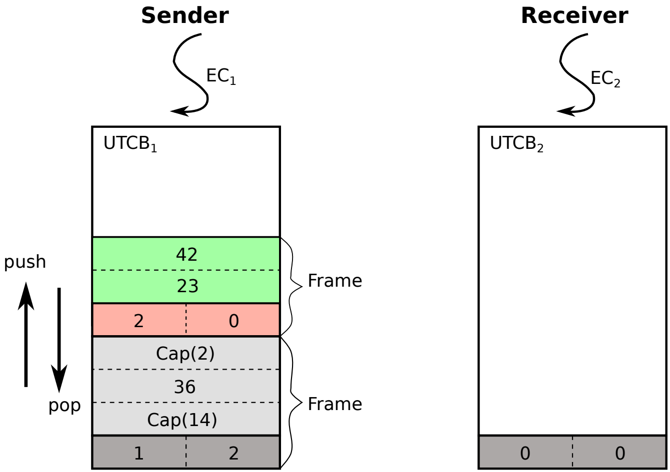
Uses C++ shift operators:

+ No external tool required
+ No separate language to learn
+ Rather simple to implement
+ Much simpler to use than C implementations
- Need to implement stub functions manually, if desired
- Need to keep client and server consistent (types, order, ...)

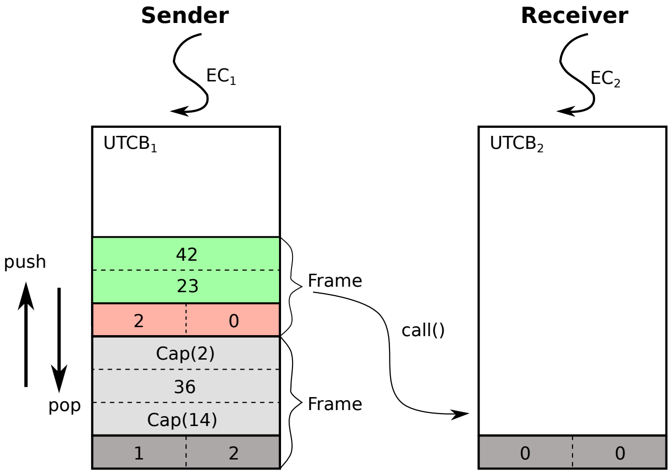
Supports multiple frames within one UTCB:

- Allows nested usages of the UTCB
- Important for calling library functions

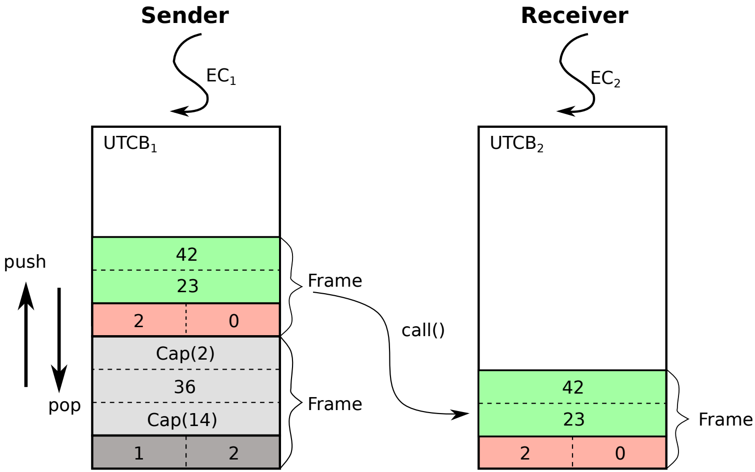
NRE UTCB Frames



NRE UTCB Frames



NRE UTCB Frames



Usage Example

Client

```
UtcbFrame uf;
uf << 1 << String("foo");
portal.call(uf);
int res;
uf >> res;
```

Server

```
PORTAL static void myportal(void*) {
    UtcbFrameRef uf;
    int i; String s;
    uf >> i >> s;
    // handle the request
    uf << 0;
}
```

Implementation

```
template<typename T>
UtcbFrameRef & operator<<(const T& value) {
    const size_t words =
        (sizeof(T) + sizeof(word_t) - 1) / sizeof(word_t);
    *reinterpret_cast<T*>(
        _utcb->msg + untyped() * sizeof(word_t)) = value;
    _utcb->untyped += words;
    return *this;
}

template<typename T>
UtcbFrameRef & operator>>(T &value) {
    const size_t words =
        (sizeof(T) + sizeof(word_t) - 1) / sizeof(word_t);
    value = *reinterpret_cast<T*>(
        _utcb->msg + _upos * sizeof(word_t));
    _upos += words;
    return *this;
}
```