TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Informatik Institut für Systemarchitektur, Professur für Betriebssysteme

OPERATING-SYSTEM CONSTRUCTION

Material based on slides by Olaf Spinczyk, Universität Osnabrück

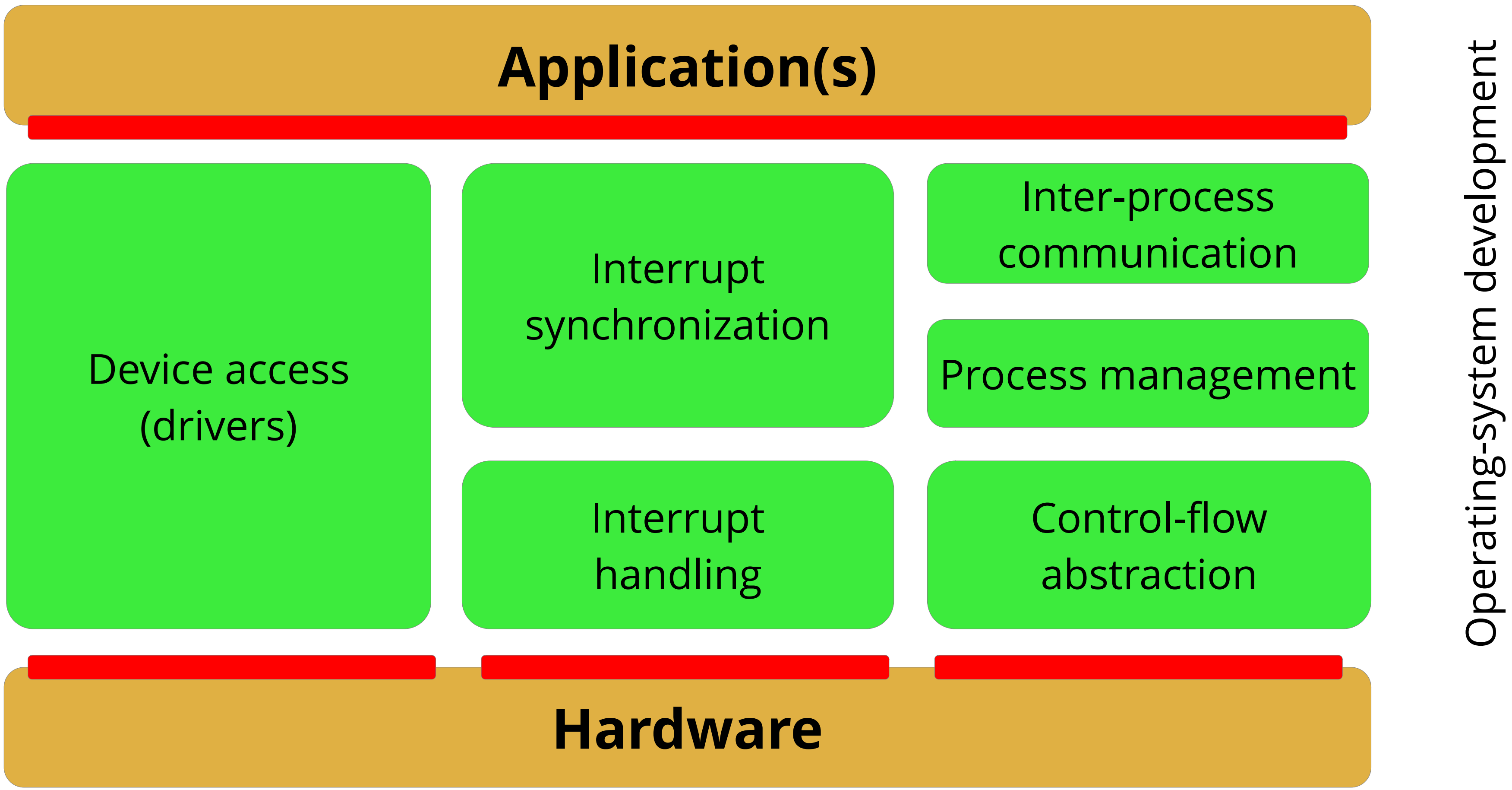
Inter-Process Communication (IPC)

https://tud.de/inf/os/studium/vorlesungen/betriebssystembau

HORST SCHIRMEIER

Overview: Lectures

Structure of the “OO-StuBS” operating system:



Overview: Lectures

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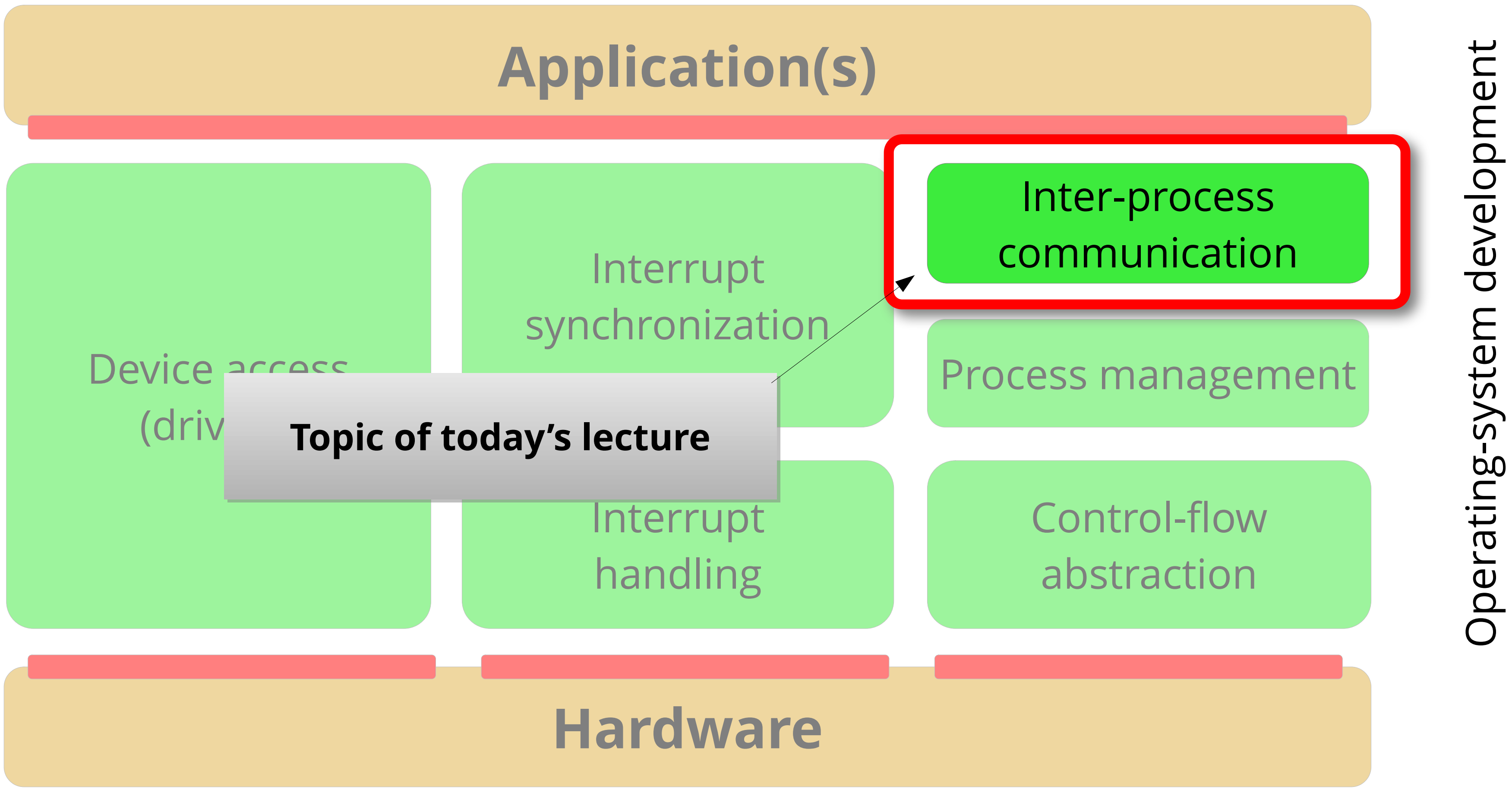

Topic of today’s lecture

Agenda

- Communication and Synchronization
- IPC via Shared Memory
  - Semaphore, Monitor, Path Expressions
- IPC via Messages
  - Send/Receive
- Basic Abstractions in Operating Systems
- Duality of Concepts
- Summary

Agenda

- **Communication and Synchronization**
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Communication and Synchronization

- … are related through the principle of causality:

> If **A** needs a piece of information from **B** to continue its work, **A** must ***wait*** until **B** supplies that information.

→ Message-based communication (usually) implies synchronization (e.g. in **`send()`** and **`receive()`**)

→ Synchronization primitives are a suitable basis for implementing communication primitives (e.g. **semaphore**)

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IPC via Shared Memory

- **Use cases / constraints**
  - Unprotected system (all processes in same address space)
  - System with language-based memory protection
  - Communication between threads in the same address space
  - OS-supplied, MMU-based shared memory
    (e.g. UNIX System V Shared Memory, see man page **shm_overview(7)**)
  - Common kernel address space of isolated processes
- **Positive properties**
  - Atomic memory accesses do not require additional synchronization
  - Fast: zero-copy
  - Simple IPC applications easy to implement
  - Unsynchronized communication possible
  - M:N communication simple

Semaphore – Simple Interactions

- Mutual exclusion

```
// Shared memory
Semaphore mutex(1);
SomeType  shared;
```

```
void process_1() {
  mutex.wait();
  shared.access();
  mutex.signal();
}
```

```
void process_2() {
  mutex.wait();
  shared.access();
  mutex.signal();
}
```

- Unilateral synchronization

```
// Shared memory
Semaphore elem(0);
SomeQueue shared;
```

```
void producer() {
  shared.put();
  elem.signal();
}
```

```
void consumer() {
  elem.wait();
  shared.get();
}
```

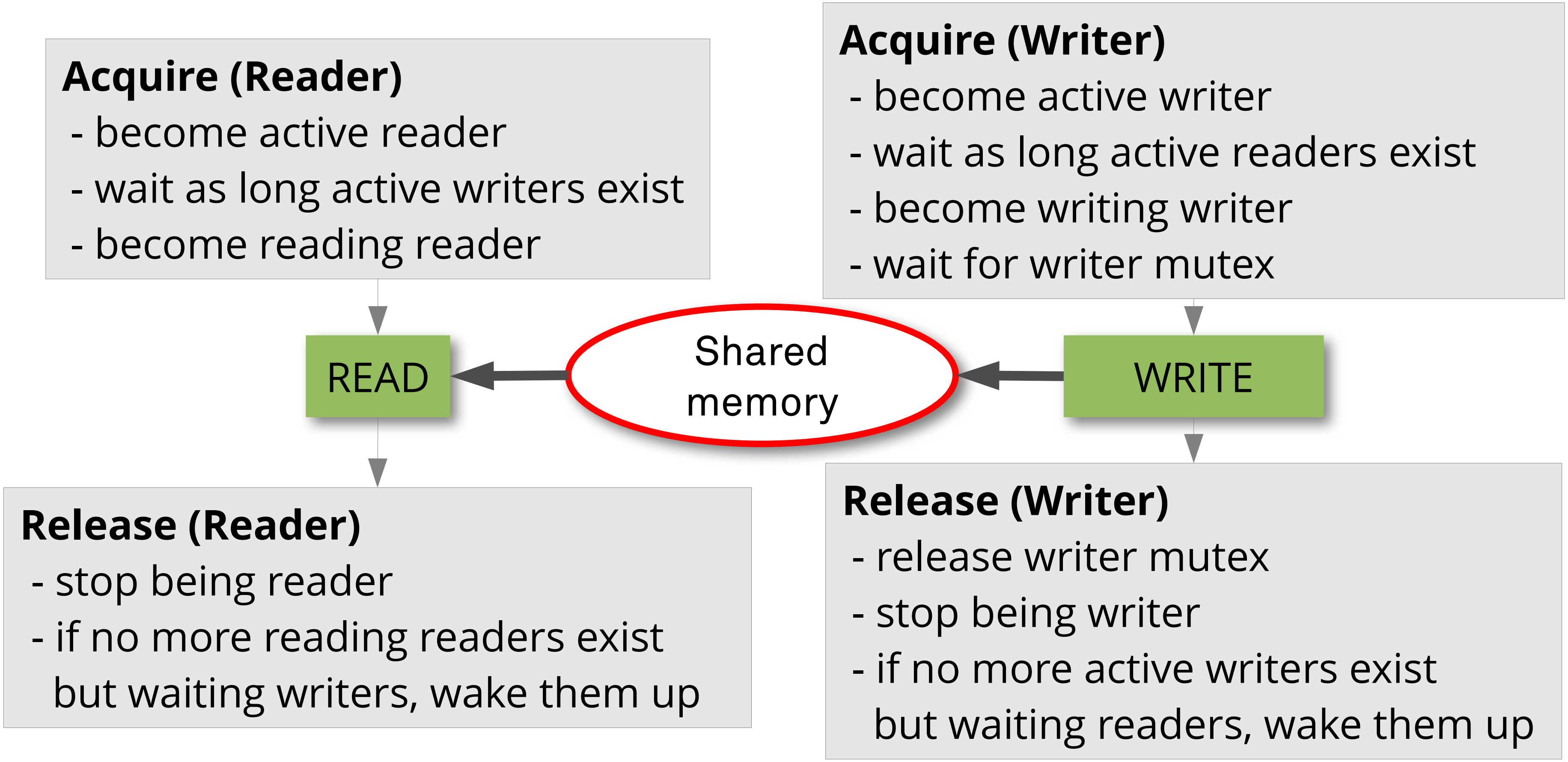
- Resource-oriented synchronization

```
// Shared memory
Semaphore     resource(N); // N>1
SomeResource  shared;
```

otherwise identical to
mutual exclusion

Semaphore – more Complex Interactions

- Readers–writers problem
  - Writers need exclusive access to memory
  - Multiple readers may work simultaneously



Acquire (Reader)
- become active reader
- wait as long active writers exist
- become reading reader

Acquire (Writer)
- become active writer
- wait as long active readers exist
- become writing writer
- wait for writer mutex

READ

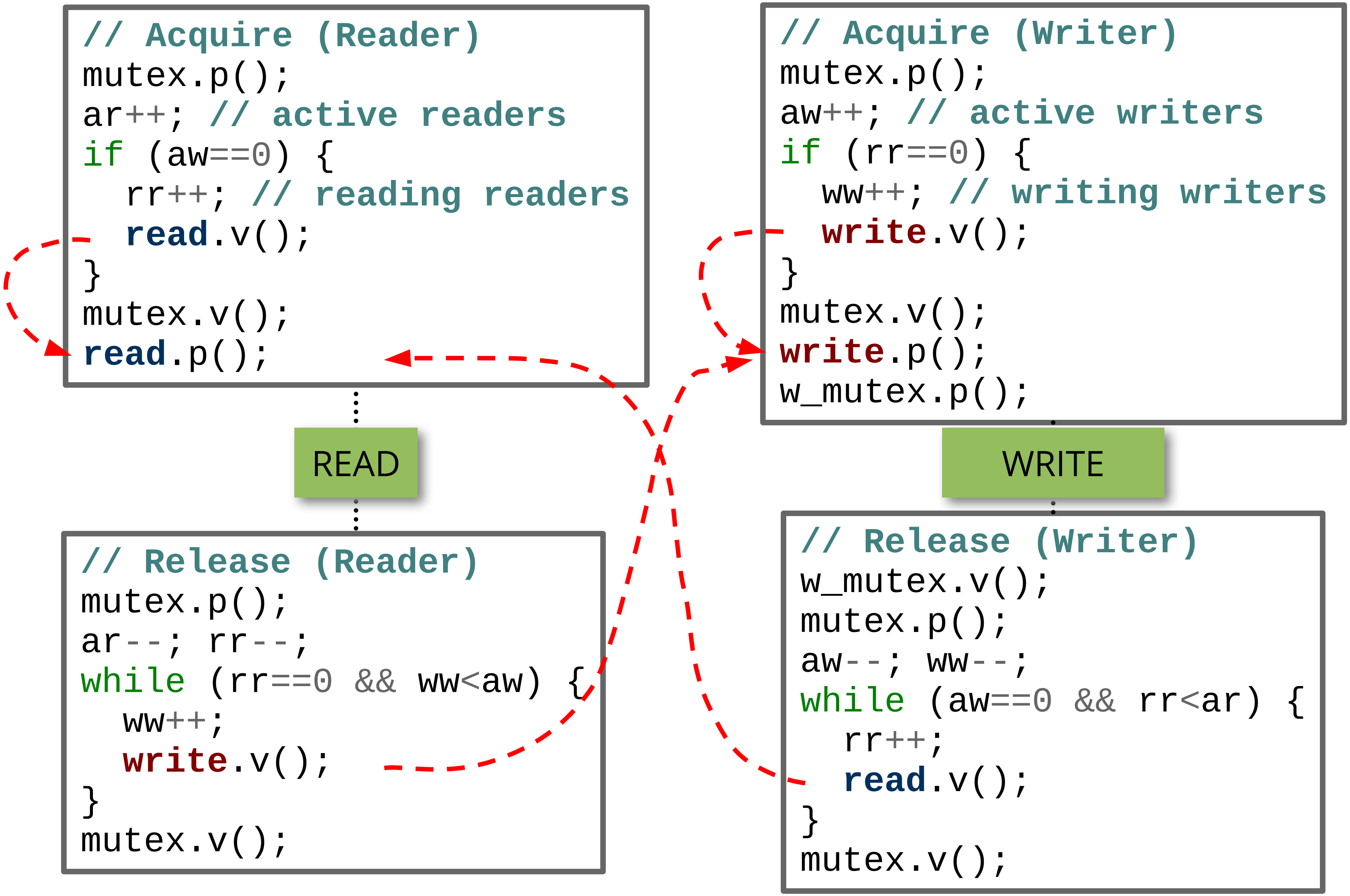
Shared memory

WRITE

Release (Reader)
- stop being reader
- if no more reading readers exist but waiting writers, wake them up

Release (Writer)
- release writer mutex
- stop being writer
- if no more active writers exist but waiting readers, wake them up

Semaphore – Readers–Writers Problem



```
// Acquire (Reader)
mutex.p();
ar++; // active readers
if (aw==0) {
  rr++; // reading readers
  read.v();
}
mutex.v();
read.p();
```

READ

```
// Release (Reader)
mutex.p();
ar--; rr--;
while (rr==0 && ww<aw) {
  ww++;
  write.v();
}
mutex.v();
```

```
// Acquire (Writer)
mutex.p();
aw++; // active writers
if (rr==0) {
  ww++; // writing writers
  write.v();
}
mutex.v();
write.p();
w_mutex.p();
```

WRITE

```
// Release (Writer)
w_mutex.v();
mutex.p();
aw--; ww--;
while (aw==0 && rr<ar) {
  rr++;
  read.v();
}
mutex.v();
```

Semaphore – Discussion

- Extensions
  - Non-blocking P()
  - Timeout
  - Counter array
- Sources of errors (bugs!)
  - Semaphore use is **not enforced**
  - Cooperating processes depend on each other
    - **All** must comply with the protocol
  - Implementation effort

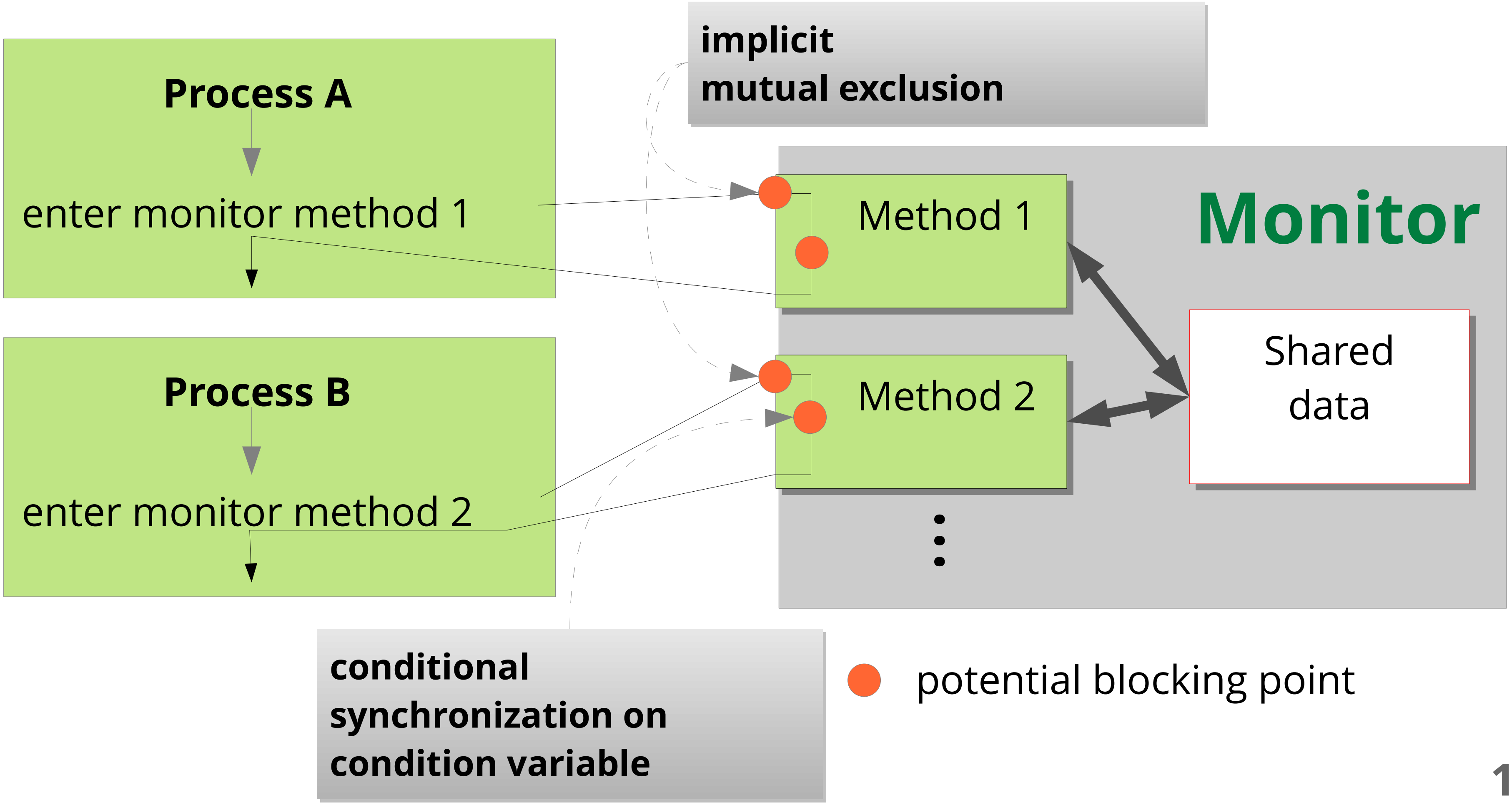
➔ Programming-language support

- Enforces correct synchronization

Monitors – Synchronized ADTs [1]

[1] C. A. R. Hoare, *Monitor – An Operating System Structuring Concept*, Communications of the ACM 17, 10, S. 549-557, 1974

- Idea: Couple abstract data type with synchronization properties



Process A

enter monitor method 1

Process B

enter monitor method 2

implicit mutual exclusion

conditional synchronization on condition variable

Monitor

Method 1

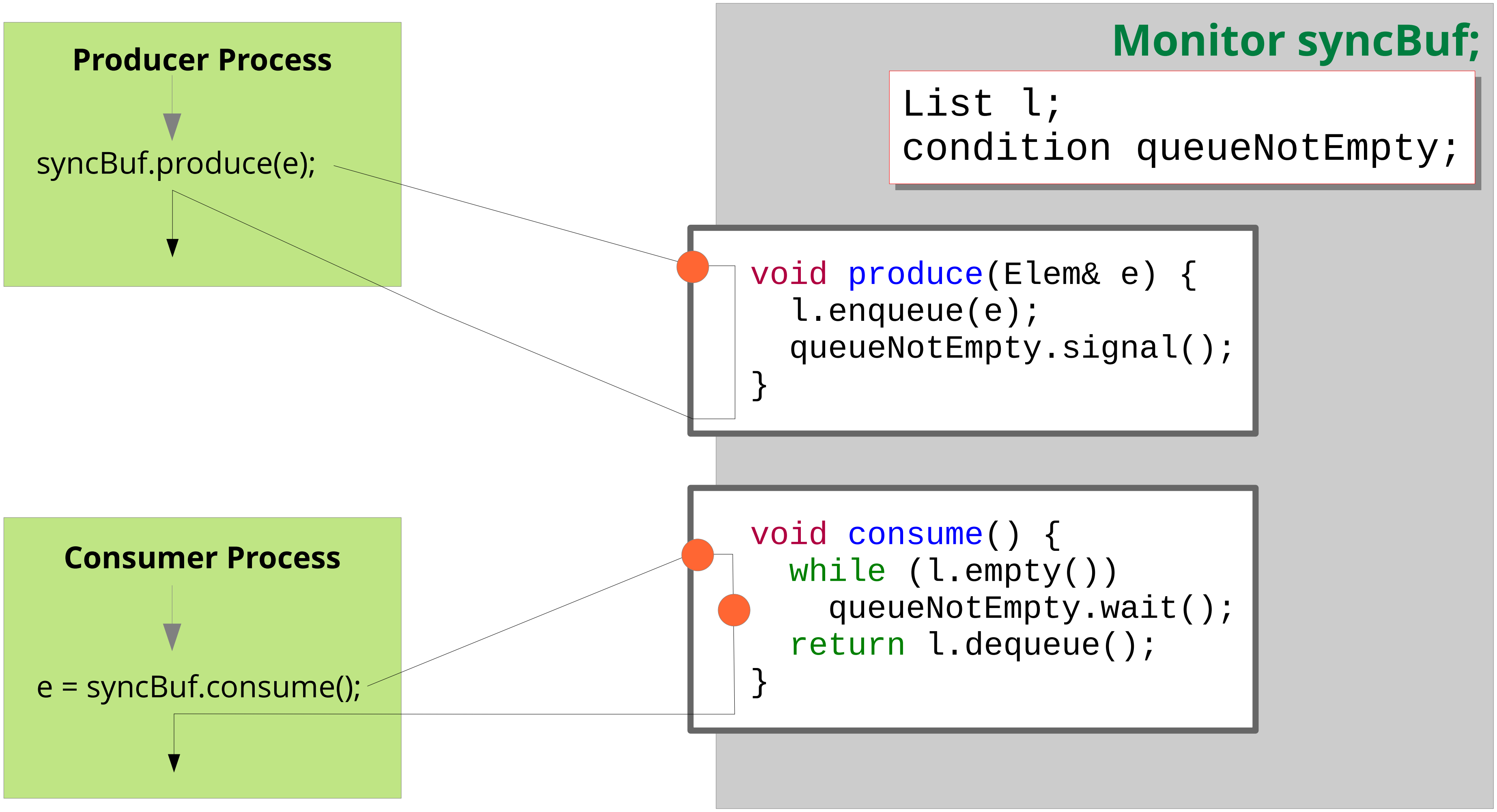
Method 2

Shared data

⋮

● potential blocking point

Monitors – Producer–Consumer



Producer Process

syncBuf.produce(e);

Consumer Process

e = syncBuf.consume();

Monitor syncBuf;

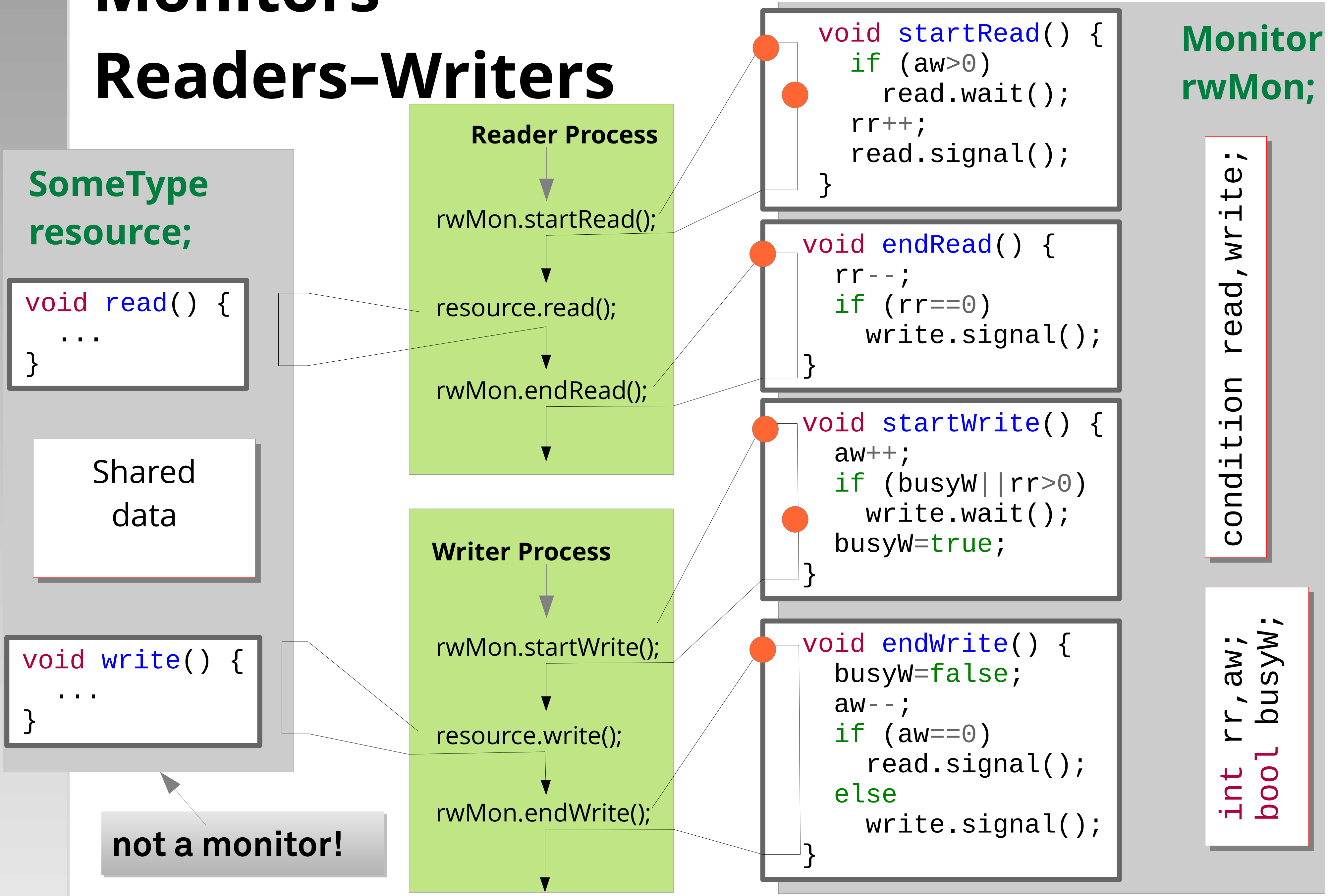
```
List l;
condition queueNotEmpty;
```

```
void produce(Elem& e) {
  l.enqueue(e);
  queueNotEmpty.signal();
}
```

```
void consume() {
  while (l.empty())
    queueNotEmpty.wait();
  return l.dequeue();
}
```

● potential blocking point

Monitors – Readers–Writers



SomeType resource;

```
void read() {
  ...
}
```

Shared data

```
void write() {
  ...
}
```

not a monitor!

Reader Process

```
rwMon.startRead();
resource.read();
rwMon.endRead();
```

Writer Process

```
rwMon.startWrite();
resource.write();
rwMon.endWrite();
```

Monitor rwMon;

```
void startRead() {
  if (aw>0)
    read.wait();
  rr++;
  read.signal();
}
```

```
void endRead() {
  rr--;
  if (rr==0)
    write.signal();
}
```

```
void startWrite() {
  aw++;
  if (busyW||rr>0)
    write.wait();
  busyW=true;
}
```

```
void endWrite() {
  busyW=false;
  aw--;
  if (aw==0)
    read.signal();
  else
    write.signal();
}
```

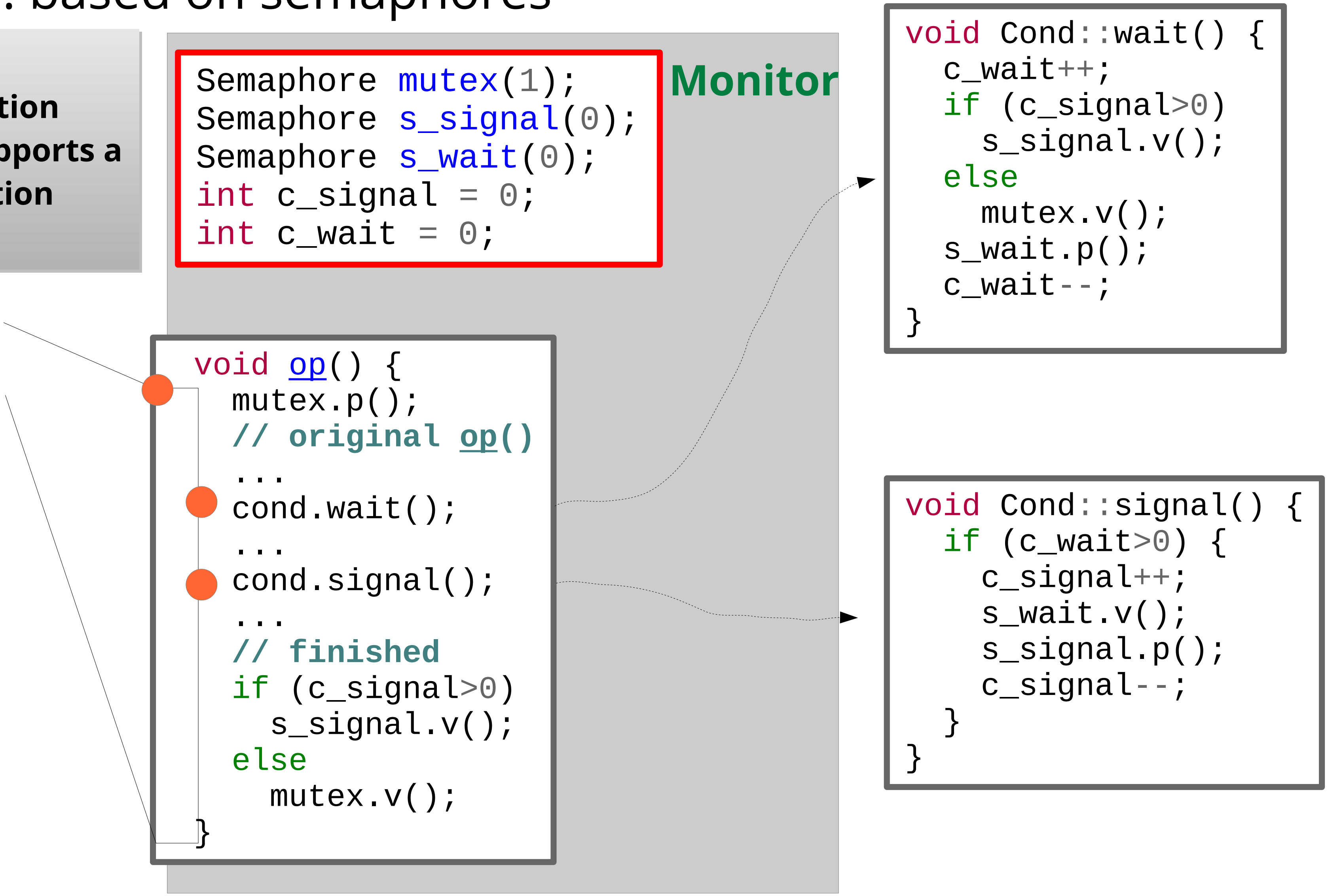
```
condition read,write;
```

```
int rr,aw;
bool busyW;
```

Monitors – Implementation

- … based on semaphores

Simple implementation that only supports a single condition variable



```
Semaphore mutex(1);
Semaphore s_signal(0);
Semaphore s_wait(0);
int c_signal = 0;
int c_wait = 0;
```

```
void op() {
  mutex.p();
  // original op()
  ...
  cond.wait();
  ...
  cond.signal();
  ...
  // finished
  if (c_signal>0)
    s_signal.v();
  else
    mutex.v();
}
```

```
void Cond::wait() {
  c_wait++;
  if (c_signal>0)
    s_signal.v();
  else
    mutex.v();
  s_wait.p();
  c_wait--;
}
```

```
void Cond::signal() {
  if (c_wait>0) {
    c_signal++;
    s_wait.v();
    s_signal.p();
    c_signal--;
  }
}
```

Monitors – Discussion

- Limits concurrency to **full** mutual exclusion
  - That's why Java allows **`synchronized`** for individual methods.
- Coupling of logical structure and synchronization not necessarily "natural"
  - see readers–writers example
  - Same problem: Just like with the semaphore, programmers must comply with a protocol

→ Synchronization should be **separated** from data organization and methods.

Path Expressions [2]

- Idea: Flexible expressions describe permitted sequences of execution and the object-access degree of concurrency
- **path** *name1, name2, name3* **end**
  - Arbitrary order and arbitrarily concurrent execution of *name1–3*
- **path** *name1; name2* **end**
  - Before each execution of *name2* at least once *name1*
- **path** *name1* + *name2* **end**
  - Alternative execution: either *name1* or *name2*
- **path** *N:(path expression)* **end**
  - max. N control flows are permitted to be in path expression

[2] R. H. Campbell and A. N. Habermann, *The Specification of Process Synchronization by Path Expressions*, Lecture Note in Computer Science 16, Springer, 1974

Path Expressions – Example

- Idea: Flexible expressions describe permitted sequences of execution and the degree of concurrency, e.g.:
- **path** 10:(1:(*insert*); 1:(*remove*)) **end**
- Synchronization of a 10-element buffer
  - Mutual exclusion during execution of *insert* and *remove*
  - At least one *insert* before each *remove*
  - Never more than 10 finalized *inserts* that have not been *remove*d yet

Path Expressions – Implementation (1)

- Transformation to a state machine
  - State transition at entry/exit into/from operation
- Example:

For each 'X:(..)' and ';' we introduce a counter.

$$\underbrace{N{:}(\ \underbrace{1{:}(\ \textit{insert}\ )}_{c2}\ \overbrace{;}^{seq1}\ \underbrace{1{:}(\ \textit{remove}\ )}_{c3}\ )}_{c1}$$

```
int c1=0;
int c2=0;
int c3=0;
int seq1=0;
```

```
bool mayInsert () {
  return c1<N && c2<1;
}

void startInsert () {
  c1++; c2++;
}

void endInsert () {
  c2--; seq1++;
}
```

```
bool mayRemove () {
  return c1<N && seq1>0 && c3<1;
}

void startRemove () {
  c3++; seq1--;
}

void endRemove () {
  c3--; c1--;
}
```

Path Expressions – Implementation (2)

- Transforming the operations

For each operation we introduce a semaphore and a counter.

$$N{:}(\ \underbrace{1{:}(\ \mathit{insert}\ )}_{\textbf{sem1/csem1}}\ ;\ \underbrace{1{:}(\ \mathit{remove}\ )}_{\textbf{sem2/csem2}}\ )$$

```
Semaphore mutex(1);
int csem1=0;
Semaphore sem1(0);
int csem2=0;
Semaphore sem2(0);
```

```
void Insert() {
  mutex.p();
  if (!mayInsert()) {
    csem1++;
    mutex.v();
    sem1.wait();
  }
  startInsert();
  mutex.v();
  // [orig. insert code]
  mutex.p();
  endInsert();
  if (!wakeup())
    mutex.v();
}
```

```
bool wakeup() {
  if (csem1>0 &&
    mayInsert()) {
    csem1--;
    sem1.v();
    return true;
  }
  if (csem2>0 &&
    mayRemove()) {
    csem2--;
    sem2.v();
    return true;
  }
  return false;
}
```

Path Expressions – Discussion

- Advantages
  - More **complex interaction patterns** possible than with monitors
    - read + 1: write
  - Compliance with interaction protocols is **enforced**
    - Less bugs!
- Disadvantages
  - Synchronization behavior cannot depend on state variables or parameters
    - Extension: Path expressions with predicates
  - **Synchronization of the state machine itself** can become the bottleneck
  - **No support** for path expressions in common programming languages

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- **IPC via Messages**
  - Send/Receive
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IPC via Messages

- **Use cases/Constraints**
  - IPC across machine boundaries
  - Interaction of isolated processes
- **Positive properties**
  - Uniform paradigma for IPC with local and remote processes
  - Buffering and synchronization if necessary
  - Indirection allows for transparent protocol extensions
    - Encryption, error correction, …
  - High-level language mechanisms such as OO messages or procedure calls can be mapped to IPC via messages (RPC, RMI)

Message-based Communication

- Already well-known from *“Betriebssysteme und Sicherheit”*: Variations of send() and receive()
  - synchronous / asynchronous (blocking / non-blocking)
  - buffered / not buffered
  - direct / indirect addressing
  - fixed / variable message sizes
  - symmetric / asymmetric communication
  - with / without timeout
  - broadcast / multicast

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Basic Abstractions

- Which basic IPC abstractions do operating systems offer?
  - **UNIX:** Sockets, System V Semaphore, messages, shared memory
  - **Windows NT/2000/...:** Shared memory, events, Semaphore, Mutant, sockets, asynchronous I/O, ...
  - **Mach:** Messages to *ports* and shared memory (with copy-on-write)
- System-internal abstractions
  - **Practically always:** Semaphore
    - Mutual exclusion & unilateral synchronization → very common use cases
  - **Microkernels** and **distributed operating systems**: Messages
    - Basis for message implementations: Synchronization primitives
  - **Monolithic systems:** Semaphore and shared memory

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Duality – Messages in Shared Memory

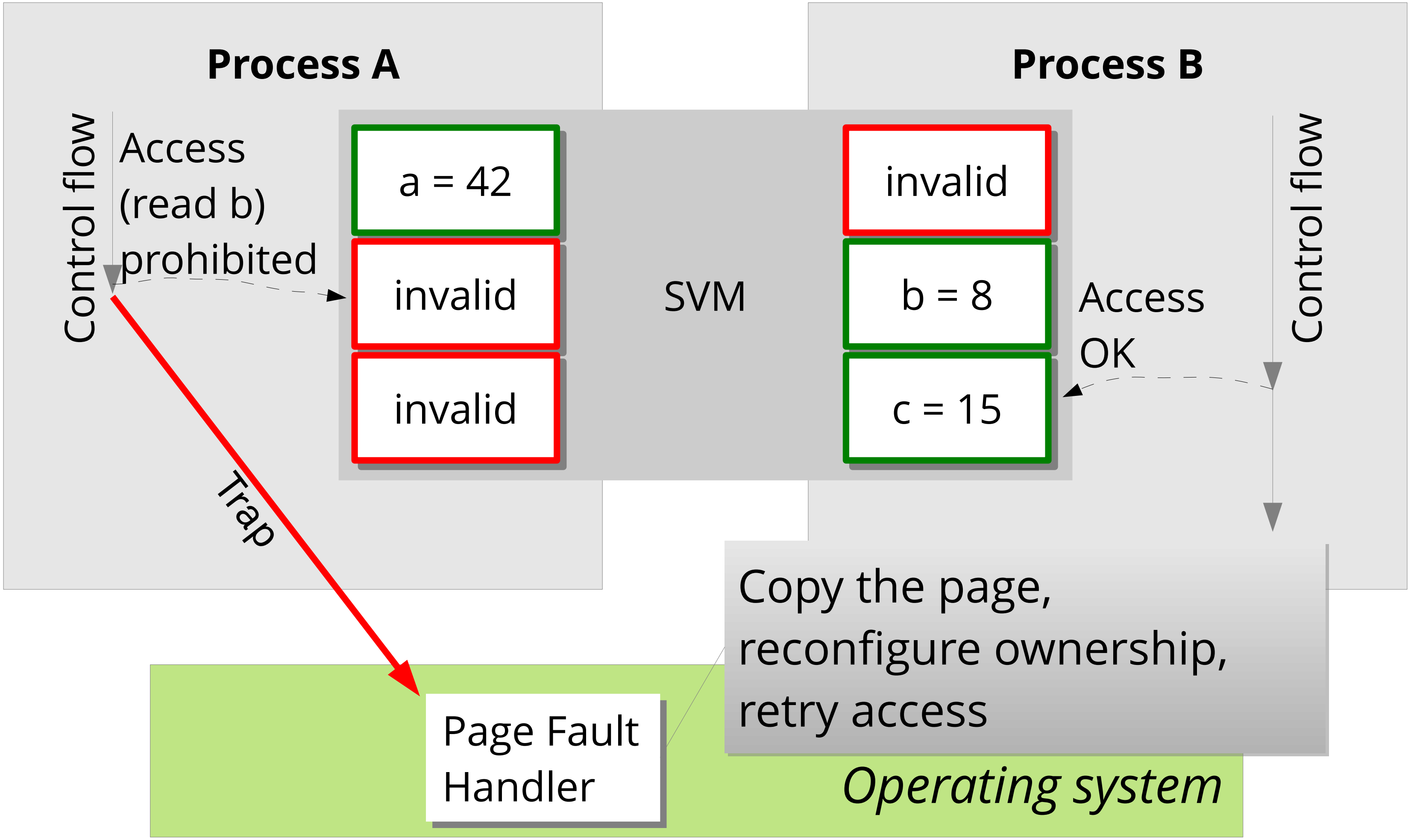
- Semaphores + shared memory → **Mailbox** abstraction

- Messages are not copied
  - Sender provides memory
- Receive may block
- Mailbox abstraction allows for M:N IPC

```
class Mailbox : public List {
  Semaphore mutex(1);
  Semaphore has_elem(0);
public:
  void send(Message *msg) {
    mutex.p();
    enqueue(msg); // from List
    mutex.v();
    has_elem.v();
  }
  Message *receive() {
    has_elem.p();
    mutex.p();
    Message *result = dequeue(); // List
    mutex.v();
    return result;
  }
};
```

Duality – Shared Memory with Messages

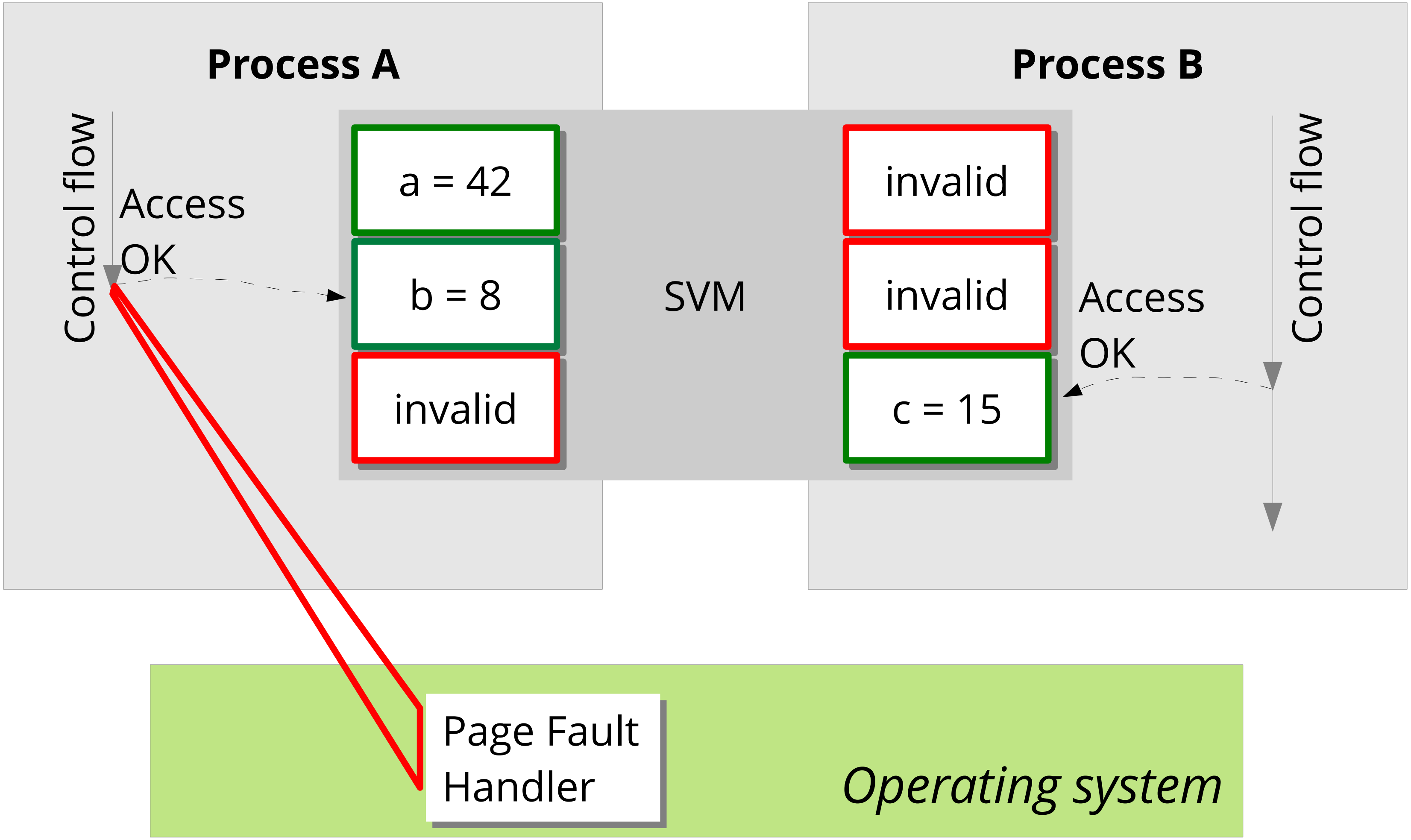
[3] K. Li, ***Shared Virtual Memory*** *on Loosely Coupled Multiprocessors*, PhD Thesis, Yale University, 1986



Copy the page, reconfigure ownership, retry access

Duality – Shared Memory with Messages

[3] K. Li, ***Shared Virtual Memory*** *on Loosely Coupled Multiprocessors*, PhD Thesis, Yale University, 1986



Duality – Discussion SVM

- Distributed virtual shared memory allows …
  - to apply the multiprocessor programming model on distributed systems
  - IPC via (virtual) shared memory in spite of isolated address spaces
- Problems:
  - Communication and trap-handling latency
  - “False sharing” – Page size does not match object size
- Approaches:
  - Weak consistency models, e.g.:
    - Not every access causes a trap, accept outdated values
    - Distribute changes asynchronously via broadcast / multicast

Duality – Active Objects

- Objects with control flow
- Suited for access synchronization in systems with message-based IPC

```
void client1() {
  Message msg(DO_THIS);
  send(srv, msg);
}
```

```
void client2() {
  Message msg(DO_THAT);
  send(srv, msg);
}
```

```
class Server : public ActiveObject {
  Msg msg; // Message buffer
public:
  ...
  // Object with control flow!
  void action() {
    while (true) {
      receive(ANY, msg); // receive msg.
      switch (msg.type()) {
        case DO_THIS:  doThis(); break;
        case DO_THAT:  doThat(); break;
        default:       handleError();
      }
      reply(msg);
    }
  }
};
```

Mutual exclusion guaranteed by processing loop in the server. Synchronous *send* blocks a client as long as the server is still busy.

- just like a monitor

Duality – Active Objects

- Reader–writer synchronization with message exchange

```
void reader() {
  Msg start_read(START_READ);
  send(srv, start_read);
  Msg read_msg(DO_READ);
  send(srv, read_msg);
  Msg end_read(END_READ);
  send(srv, end_read);
  // use data in 'read_msg'
}
```

```
void writer() {
  Msg start_write(START_WRITE);
  send(srv, start_write);
  // fill message here
  Msg write_msg(DO_WRITE);
  send(srv, write_msg);
  Msg end_write(END_WRITE);
  send(srv, end_write);
}
```

```
class RWServer : public ActiveObject {
  Msg msg; // Message buffer
public:
  ...
  // Control flow
  void action() {
    while (true) {
      receive(ANY, msg); // receive msg.
      switch (msg.type()) {
      case START_READ:  startRead();  break;
      case DO_READ:     doRead();     break;
      case END_READ:    endRead();    break;
      case START_WRITE: startWrite(); break;
      case DO_WRITE:    doWrite();    break;
      case END_WRITE:   endWrite();   break;
      default: msg.type(ERROR); reply(msg);
      }
    }
  }
};
```

Duality – Active Objects

- Reader–writer synchronization with message exchange
  - Actual read/write operations happen concurrently in a child process

The ‘request’ message must be copied because it could be overwritten while the child process is being executed.

```
void RWServer::doRead() {
  Msg copy=msg;
  if (fork()==0) {
    // actual read op.
    copy.set(...) // reply
    reply(copy);
  }
  else {
  } // Parent proc.: nothing
}
```

```
void RWServer::doWrite() {
  Msg copy=msg;
  if (fork()==0) {
    // actual write op.
    // (uses 'copy')
    reply(copy);
  }
  else {
  } // Parent process: nothing
}
```

The server process can immediately wait for more requests.

Duality – Active Objects

- Reader–writer synchronization with message exchange

```
void RWServer::startRead() {
  ar++;
  if (aw>0)
    read.copy_enqueue(msg);
  else {
    rr++; reply(msg);
  }
}

void RWServer::endRead() {
  ar--; rr--;
  if (rr==0 && aw>0) {
    Msg wmsg=write.dequeue();
    ww++; reply(wmsg);
  }
  reply(msg);
}
```

```
void RWServer::startWrite() {
  aw++;
  if (ww>0 || rr>0)
    write.copy_enqueue(msg);
  else {
    ww++; reply(msg);
  }
}

void RWServer::endWrite() {
  aw--; ww--;
  if (aw>0) {
    Msg wmsg=write.dequeue();
    ww++; reply(wmsg);
  }
  else while (rr < ar) {
    Msg rmsg=read.dequeue();
    rr++; reply(rmsg);
  }
  reply(msg);
}
```

Duality – Discussion

- Is there a **fundamental difference** between IPC via shared memory and IPC via messages?
  - or more provocatively: Which is better – **microkernels or monoliths**?
- Example: Reader–writer monitor vs. server:
  - Monitor: 2 potential waiting points
    - Client is delayed for mutual exclusion
    - Client is potentially further delayed due to a condition variable
  - Server: 2 potential waiting points
    - Reply is delayed because the server serves other requests
    - Reply is potentially further delayed if the request must be enqueued in a waiting queue
- Conclusion: Synchronization and concurrency identical!

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Summary

- Two central IPC-mechanism classes:
  - IPC via shared memory
  - Message-based IPC
- Mechanisms of both classes exist in real-world OSs
  - However, language mechanisms like monitors and path expressions usually cannot be used in OS development
- Neither class is generally better regarding synchronization behavior and degree of concurrency
  - Advantages and disadvantages lie in other properties (see slides 8 and 24)

Bibliography

[1] C. A. R. Hoare, *Monitor – An Operating System Structuring Concept*, Communications of the ACM 17, 10, S. 549-557, 1974

[2] R. H. Campbell and A. N. Habermann, *The Specification of Process Synchronization by Path Expressions*, Lecture Note in Computer Science 16, Springer, 1974

[3] K. Li, *Shared Virtual Memory on Loosely Coupled Multiprocessors*, PhD Thesis, Yale University, 1986