Distributed Systems Paradigms

José Orlando Pereira
Fábio André Coelho

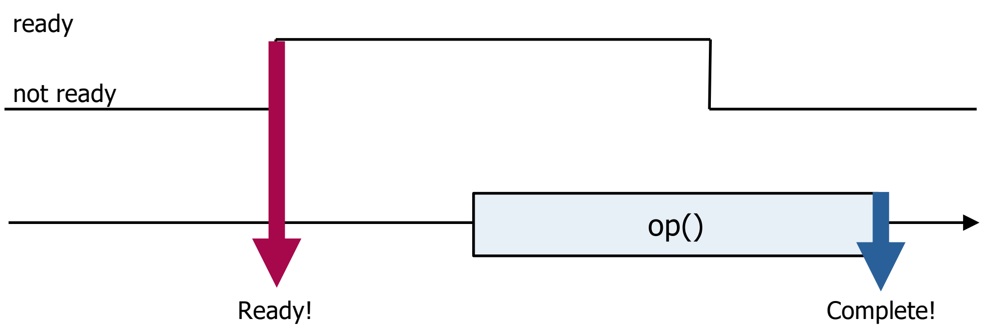
Aula 2

Departamento de Informática
Universidade do Minho

Event-driven I/O

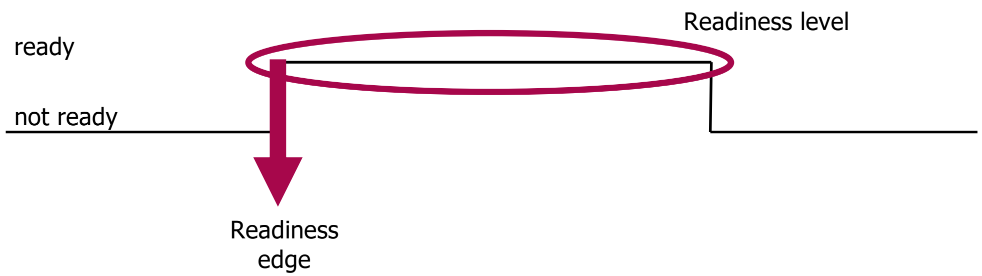
- Instead of waiting for each I/O event with a dedicated thread…
- …let the operating system explicitly notify the application of an I/O event

Design issues



- Readiness notification:
  - avoids pre-allocating buffers
  - two system calls and copying of data
- Completeness notification:
  - allows zero copy
  - pre-allocates buffers

Design issues



- Level-triggered:
  - easier for application to handle (does not need to remember past events)
  - needs synchronization with concurrent handlers
- Edge-triggered:
  - easier with concurrent handler threads
  - ignoring an event might result in a deadlock

Implementation issues

- User vs. kernel-level event set:
  - User level better for a few events / many changes to set
  - Kernel level better for many events / fewer changes to set
  - Examples: select()/poll() vs epoll()
- Control transfer
  - Blocking thread on a polling system call is the most useful for I/O bound applications
  - Signals also useful for other applications
  - Busy polling useful for dedicated hosts / low latency
  - Examples: select() vs SIGIO vs DPDK/SPDK

Case studies in Java

- Asynchronous sockets (NIO2)
- Selectors (NIO)

Asynchronous I/O

- For each blocking I/O operation, provide a callback to execute after the operation has completed
  - Completion event / edge-triggered
- General idea: Instead of:

```
read(buf); doSomething();
```

do:

```
read(buf, ()->{ doSomething(); })
```

Threaded version

App

socket()

bind()

accept()

read()

write()

close()

OS

connect

data

ack

socket()

bind()

wait for accept...

event!

connect socket

alloc buffer

wait for read....

event!

copy data to buffer

flip

wait for write ...

event!

copy data from buffer

buffer empty

close

code

Asynchronous version

App	*OS*			
socket()		socket() bind()		code
bind()				
accept(cb)			wait for accept...	
	connect		event! connect socket	code
rea (cb)		alloc buffer	wait for read....	
	data			
wri (cb)			event! copy data to buffer	code
	ack	flip	wait for write ...	
cl e()			event! copy data from buffer	code
		buffer empty close		

Inversion of Control (IoC)

- With threads:
  - The program controls flow
  - Calls into the framework for specific tasks
- With events:
  - The framework controls flow
  - Calls back the program for specific tasks

Asynchronous I/O

- Avoids having a dedicated thread for each event source
- However:
  - Requires captive memory for idle I/O channels
  - Hides threading policy within the framework

- Available in Java with NIO2 AsynchronousSockets

Polled I/O

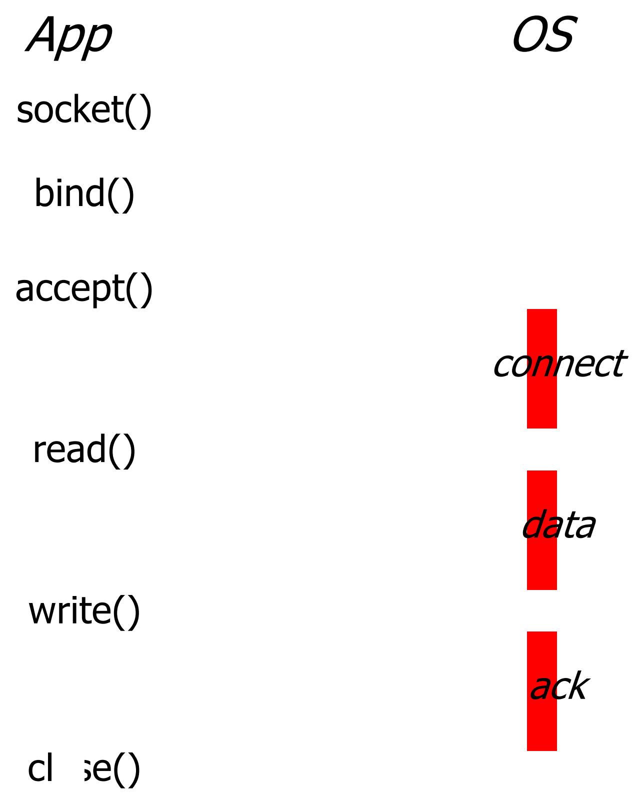
- Explicitly inform the application of which I/O channels are ready (and won't block)
  - Readiness event / level-triggered
- General idea: Instead of:

```
read(buf); doSomething();
```

- do:

```
for(key: select())
    read(buf); doSomething();
```

Threaded version



socket()

bind()

wait for accept...

event!
connect socket

alloc buffer

wait for read....
event!
copy data to buffer

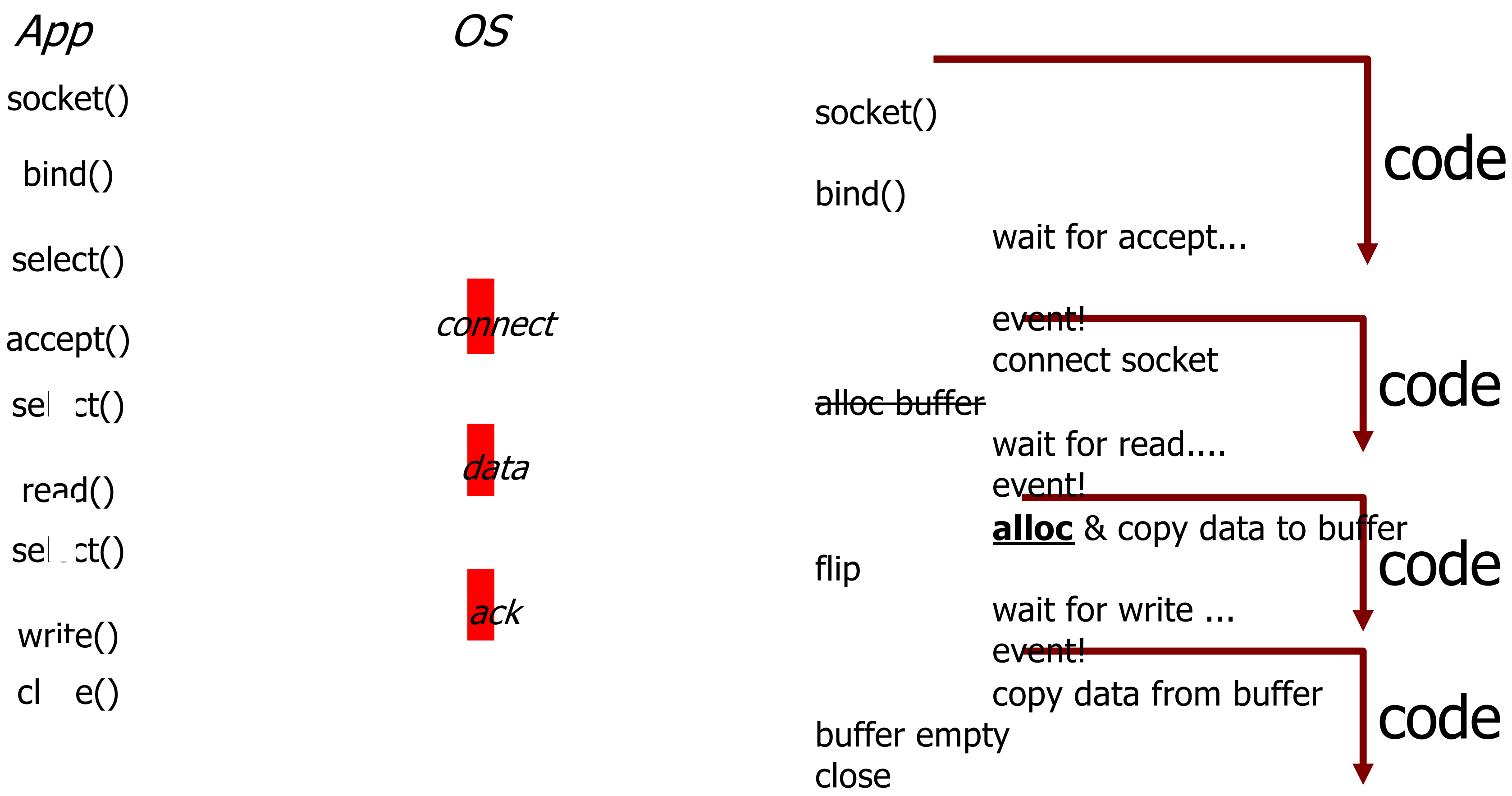
flip

wait for write ...
event!
copy data from buffer

buffer empty
close

code

Polled version



Polled I/O

- Avoids having a dedicated thread for each event source
- Avoids captive memory for idle I/O channels
- Makes threading policy explicit
- However:
  - Requires additional system calls (and copies)

- Polled I/O in Java with NIO Selectors

Polled I/O in Java

- Main loop:

```
Selector sel=SelectorProvider.provider().openSelector();

while(true) {
        sel.select();
        for(Iterator<SelectionKey> i=sel.selectedKeys().iterator();
i.hasNext(); ) {
                SelectionKey key = i.next();

                // i/o

                i.remove();
        }
}
```

Polled I/O in Java

- Register interest in server socket:

```
ServerSocketChannel ss=ServerSocketChannel.open();
ss.bind(new InetSocketAddress(12345));
ss.configureBlocking(false);
ss.register(sel, SelectionKey.OP_ACCEPT);
```

- Handle connection event:

```
if (key.isAcceptable()) {
        SocketChannel s=ss.accept();

        s.configureBlocking(false);

        s.register(sel, SelectionKey.OP_READ);
}
```

Polled I/O in Java

```
if (key.isReadable()) {
        ByteBuffer buf=ByteBuffer.allocate(100);
        SocketChannel s=(SocketChannel)key.channel();

        int r=s.read(buf);
        if (r<0) {
                key.cancel();
                s.close();
        } else {
                buf.flip();
                for(Socket r: ..) {
                        r.write(buf);
                        buf.rewind();
                }
        }
}
```

What if write blocks?

Polled I/O in Java

- Need to poll before writing
- Bytes read must be saved until writing is possible
- Signal interest on writing

```
if (key.isReadable()) {
        ...
        } else {
                buf.flip();
                for(SelectionKey k: ...) {
                        k.attach(buf.duplicate());
                        k.interestOpsOr(SelectionKey.OP_WRITE);
                }
        }
}
```

What if multiple writes pending?

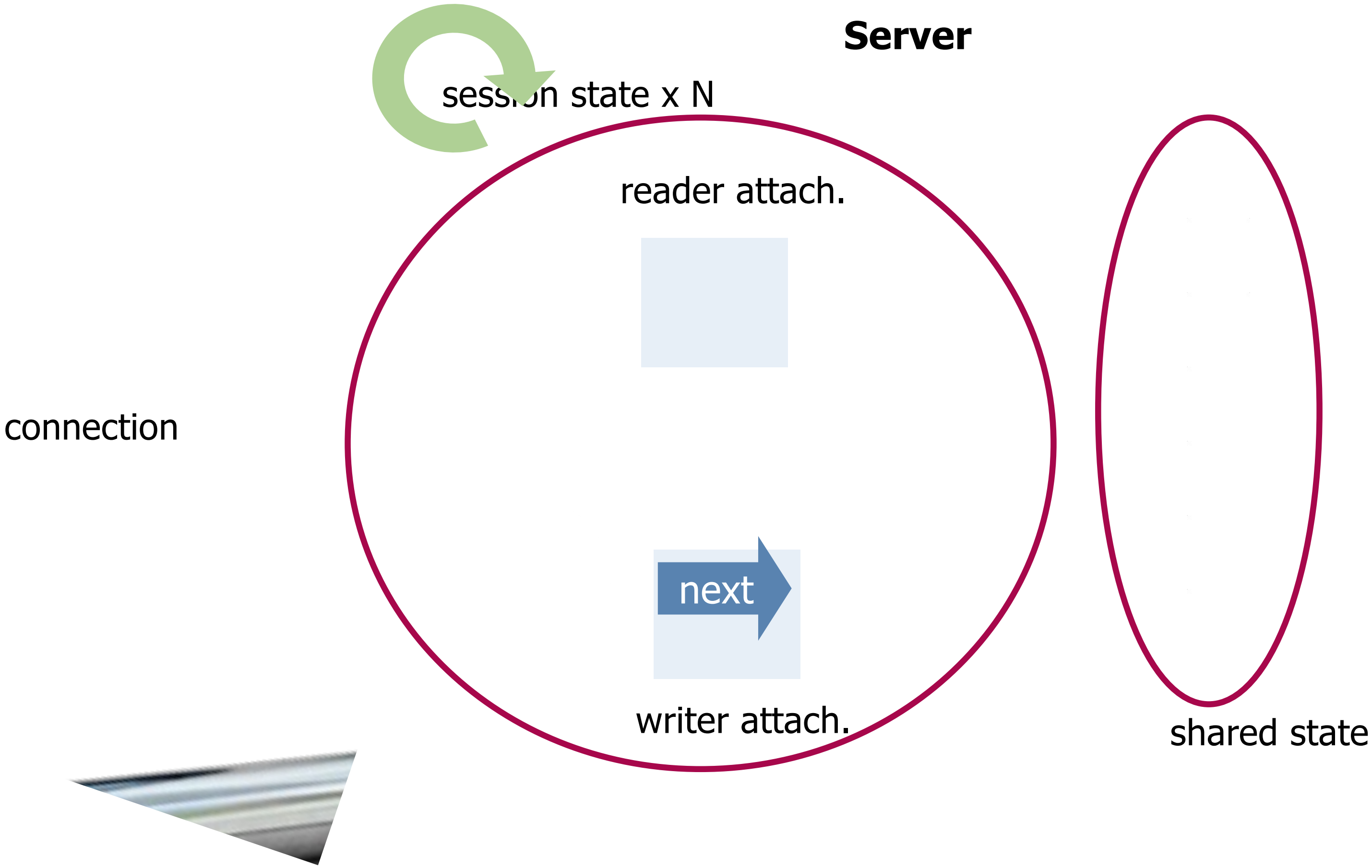
Polled I/O in Java

- Get bytes attached to key
- Reset interest to reading

```
if (key.isWritable()) {
        SocketChannel s=(SocketChannel)key.channel();
        ByteBuffer buf=(ByteBuffer)key.attachment();

        s.write(buf);
        key.interestOpsAnd(~SelectionKey.OP_WRITE);
}
```

Server architecture



Summary

- Memory:
  - No data copying by reference aliasing
  - Reduced allocation by avoiding captive buffers
- Event-driven programs:
  - A single shallow stack
  - Minimal context switching
  - Explicit scheduling and queuing (can be purged)

References

- Michael Kerrisk. *The Linux Programming Interface - A Linux and UNIX® System Programming Handbook.* No Starch Press, 2010.
  - **Chap. 63.**
- Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau. *Operating Systems: Three Easy Pieces.* Arpaci-Dusseau Books, 2018.
  - **Chap. 33:** https://pages.cs.wisc.edu/~remzi/OSTEP/threads-events.pdf