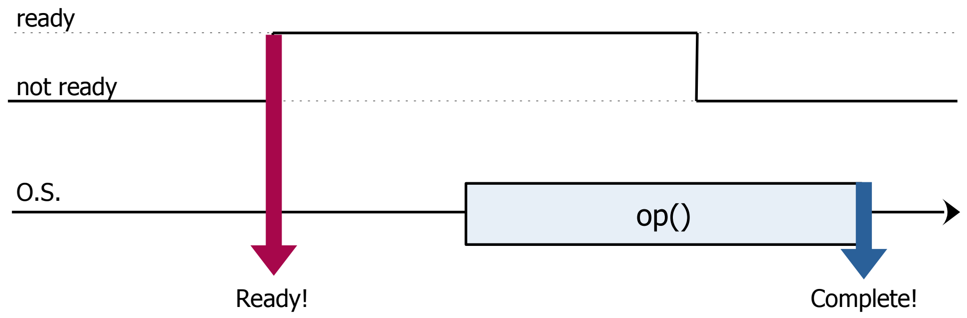
Event-driven I/O

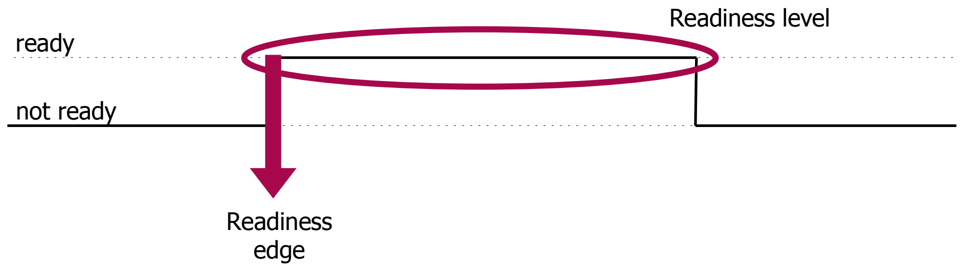
- Instead of waiting for each I/O event with a dedicated thread…
- …let the operating system explicitly notify the application of an I/O event

Design issues

- Completion vs readiness



- Level-triggered vs edge-triggered



Implementation issues

- Managing the event set
  - User vs. kernel-level
  - Examples: select()/poll() vs epoll()
- Control transfer
  - Blocking thread vs signals vs busy polling
  - Examples: select() vs SIGIO vs DPDK/SPDK

Case studies in Java

- Asynchronous sockets (NIO2)
- Selectors (NIO)

Asynchronous I/O

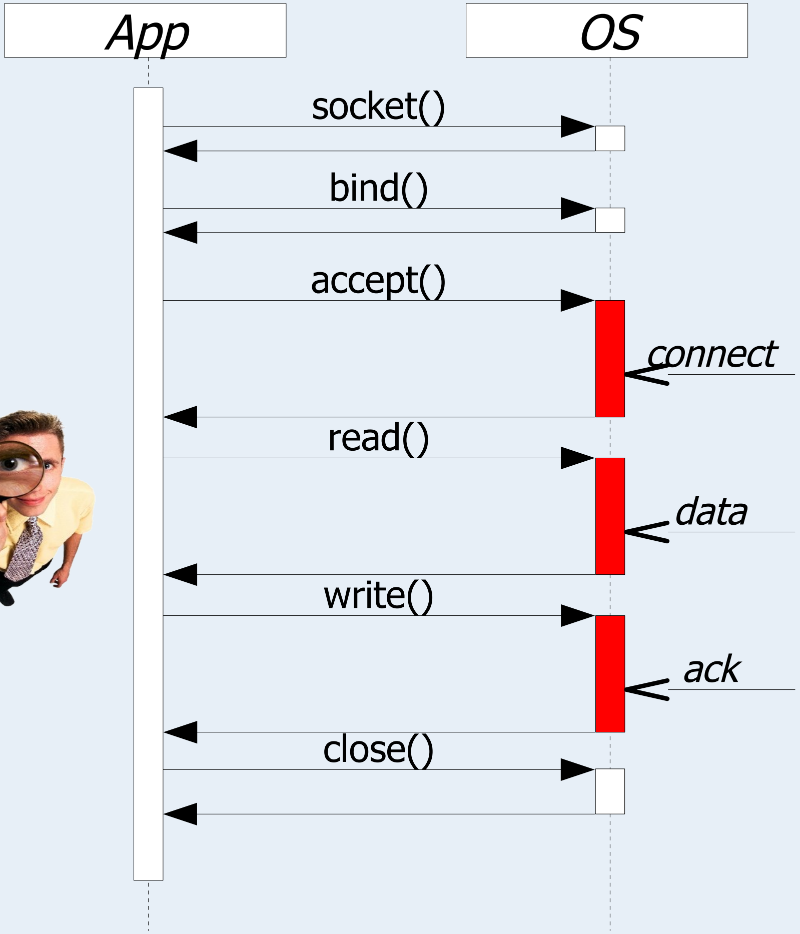
- For each blocking I/O operation, provide a callback to execute after the operation has completed
  - Completion event / edge-triggered
- General idea: Instead of:

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

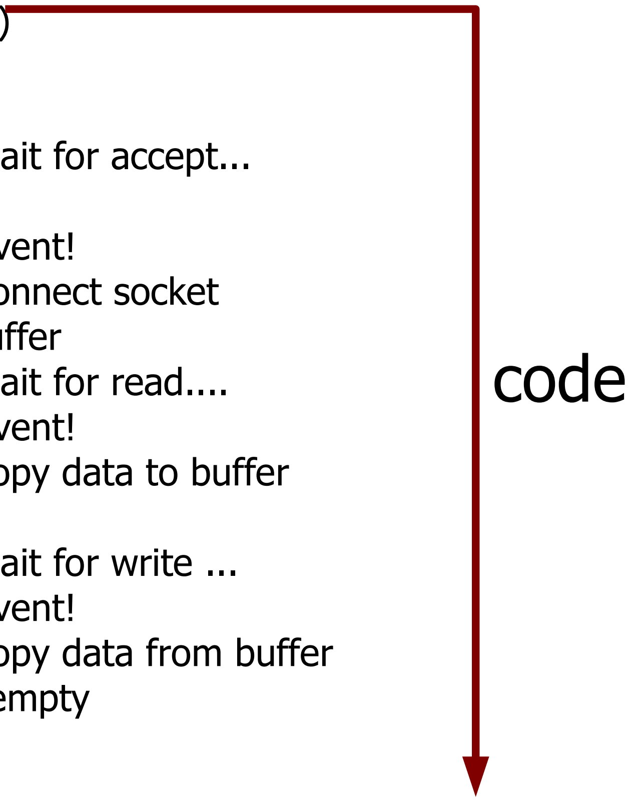
do:

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

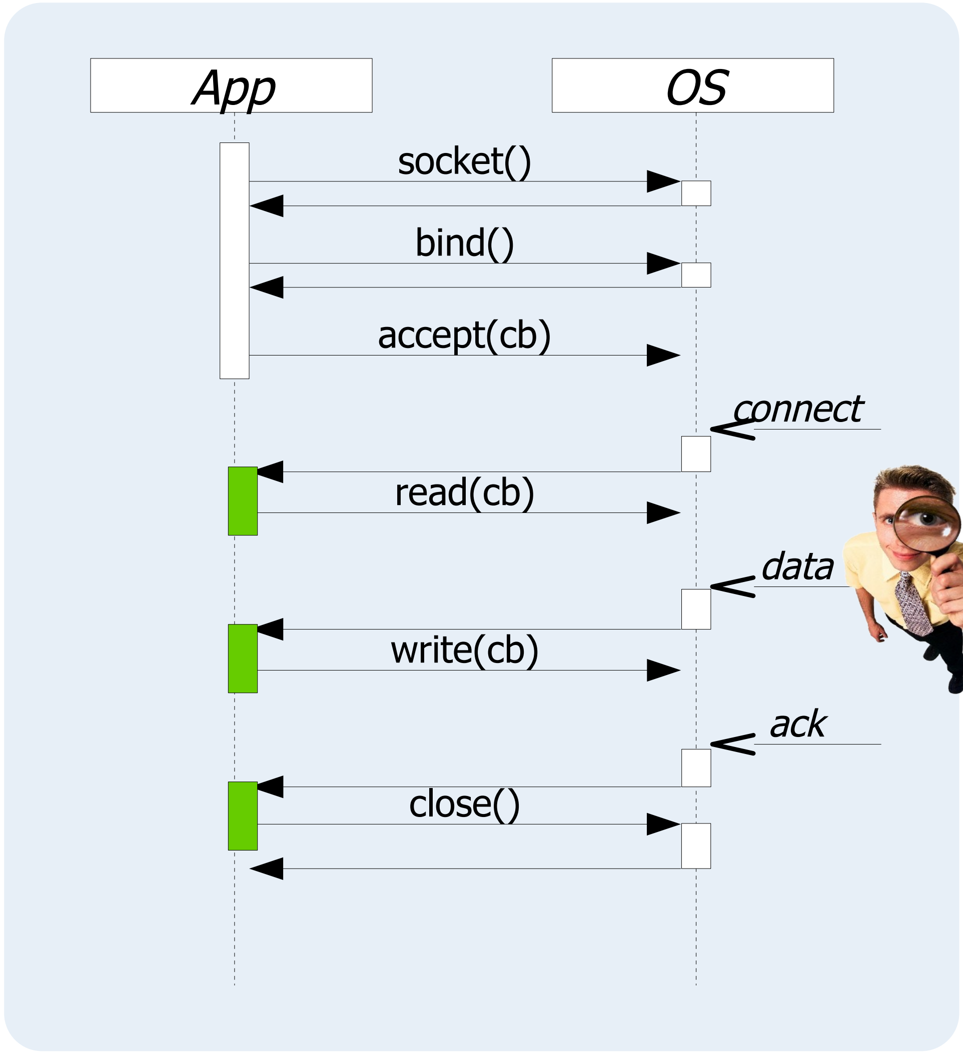
Threaded version

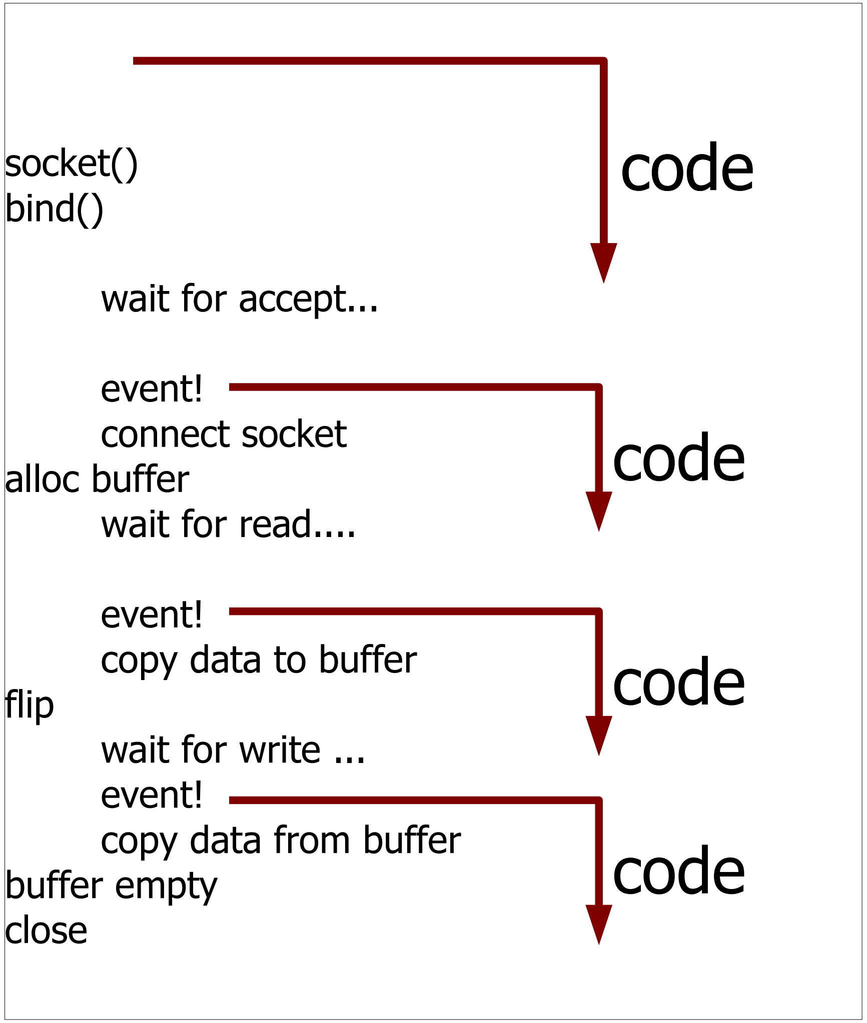


```
socket()

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
```



Asynchronous version





socket()
bind()
wait for accept...
event!
connect socket
alloc buffer
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copy data to buffer
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copy data from buffer
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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

Blocking sockets

```
try {
        ByteBuffer buf=ByteBuffer.allocate(100);

        s.read(buf);
        buf.flip();

        r.write(buf);

} catch(IOException e) {
        report(e);
}
```

Translation to CompletionHandler

```
try {
	C c = codeBefore(...);

	R r = operation(...);

	codeAfter(c, r);

} catch(Exception e) {
	handleException(e);
}
```

```
C c = codeBefore(...);

asyncOperation(..., c, new CompletionHandler<R,C>() {
	public void sucess(R r, C c) {
		codeAfter(c, r);
	}
	public void failure(Exception e, C c) {
		handleException(e);
	}
});
```

Asynchronous sockets

```
ByteBuffer buf=ByteBuffer.allocate(100);

s.read(buf, null, new CompletionHandler() {
        public void completed(Integer result, Object a) {
                buf.flip();

                r.write(buf, ...);
        }
        public void failure(Throwable t, Object a) {
                report(t);
        }
);
```

Thread pools

- For non-blocking, short-lived events:
    - One pool thread for hardware thread
- While all threads are blocked, the application stops handling events

```
AsynchronousChannelGroup g =
        AsynchronousChannelGroup.withFixedThreadPool(...);

AsynchronousSocketChannel s =
        AsynchronousSocketChannel.open(g);

...     /* callbacks use g.shutdown() to exit */

g.awaitTermination(Long.MAX_VALUE, TimeUnit.SECONDS);
```

Polled I/O

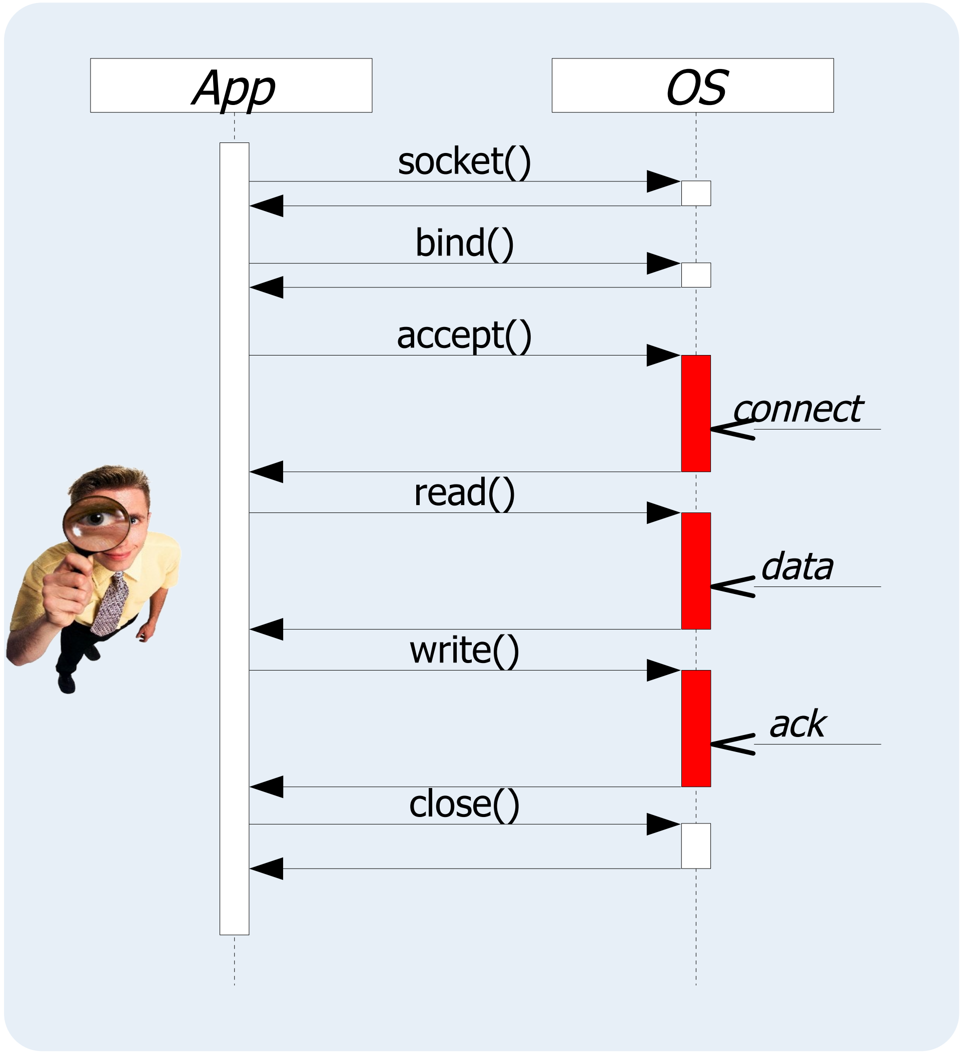
- Explicitly inform the application of which I/O channels are ready (and won’t blo\ck)
  - Readiness event / level-triggered
- General idea: Instead of:

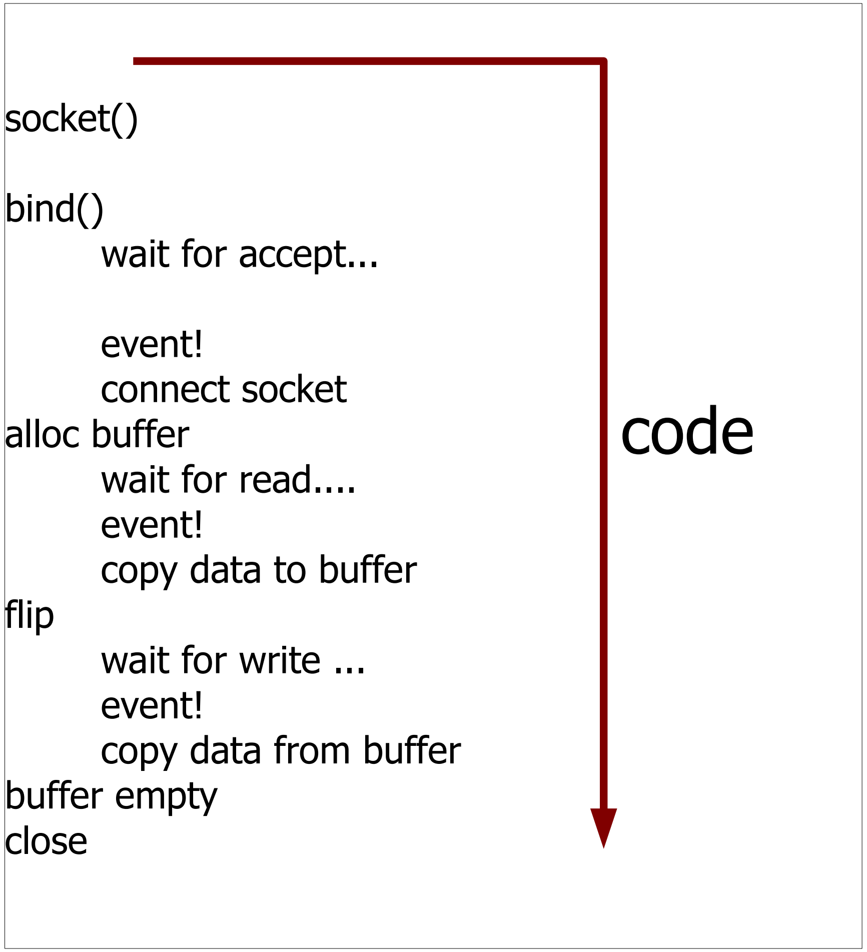
```
read(buf); doSomething();
```

- do:

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

Threaded version

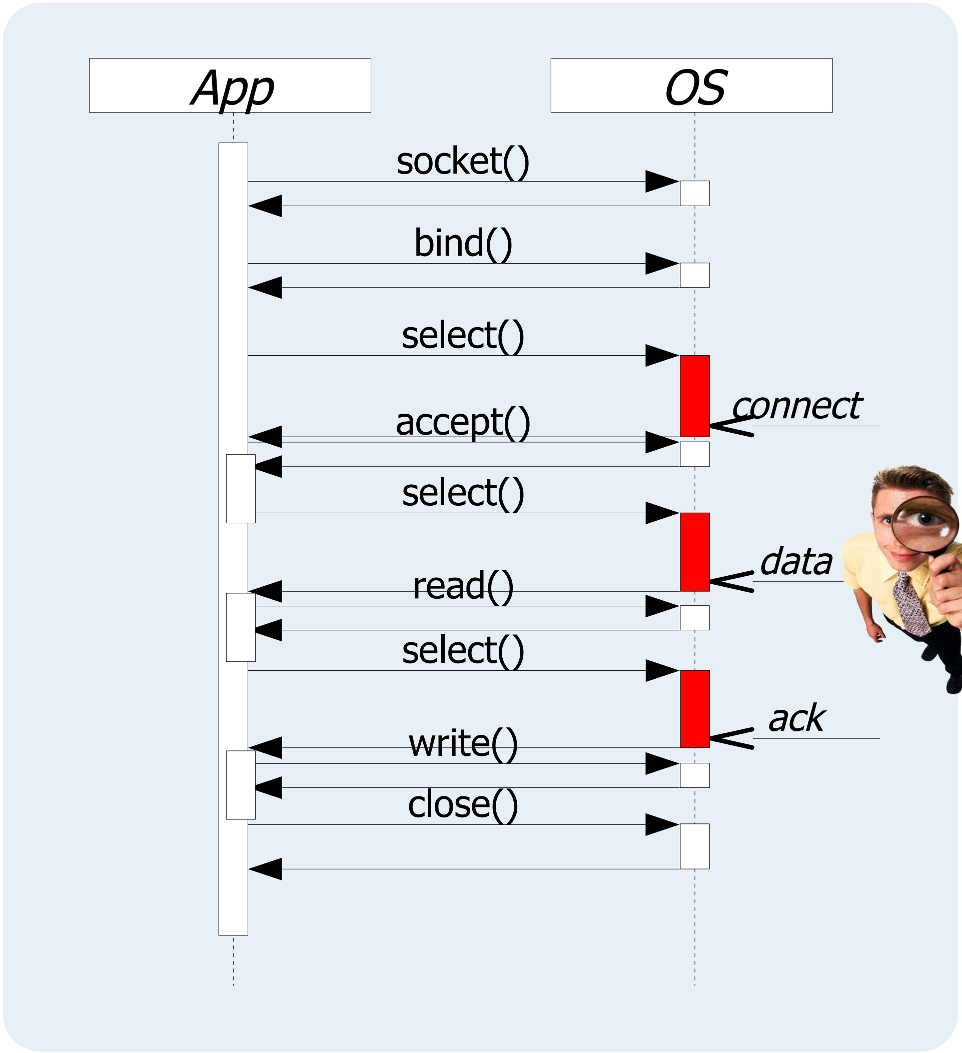


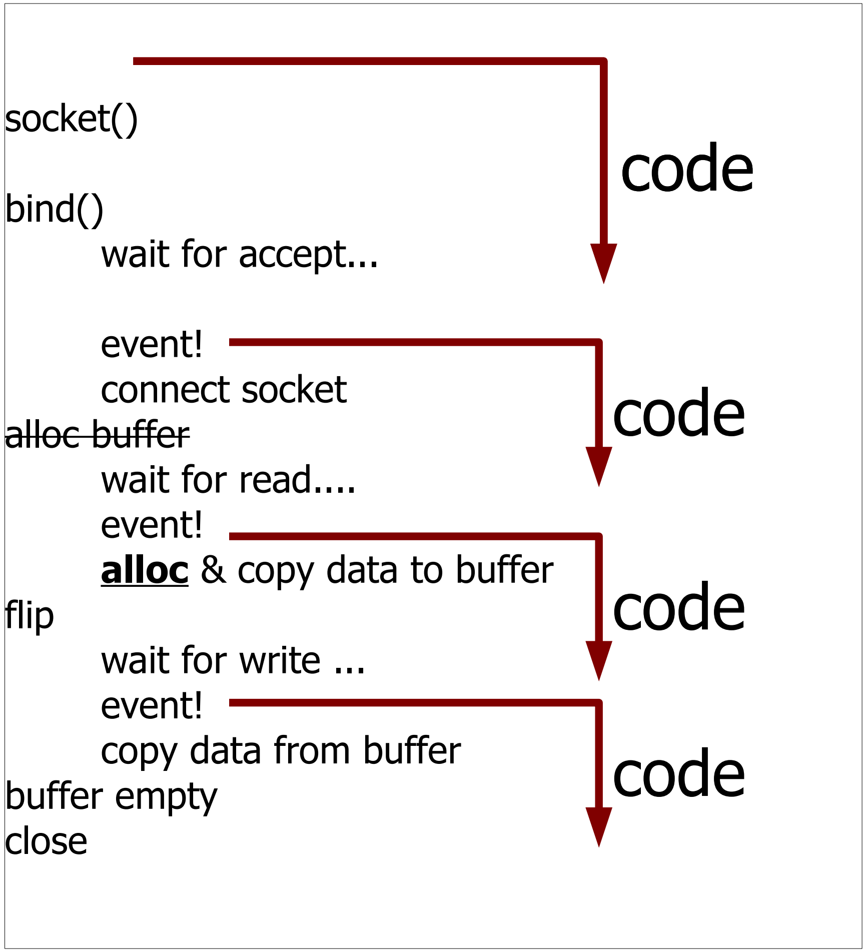

```
socket()

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
```

Polled version





socket()

bind()
        wait for accept...

        event!
        connect socket
~~alloc buffer~~
        wait for read....
        event!
        alloc & copy data to buffer
flip
        wait for write ...
        event!
        copy data from buffer
buffer empty
close

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: ...) {
                        key.attach(buf.duplicate());
                        key.interestOps( ... | 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.interestOps(SelectionKey.OP_READ);
}
```

Polled I/O + Object oriented

- Encapsulate context data + event-handling code

```
public class ChatSession implements Handler {
        private ByteBuffer stored; // possibly a queue...

        public ChatSession(SelectionKey key) {
                // initialization
        }

        public void handleRead(ByteBuffer in) throws IOException {
                // store input
        }
        public void handleWrite() throws IOException {
                // write from stored
        }
}
```

Polled I/O + Object oriented

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

        if (s!=null) {
                s.configureBlocking(false);
                SelectionKey nkey=s.register(sel, SelectionKey.OP_READ);
                nkey.attach(new ChatSession(...));
        }
} else if (key.isReadable()) {
        Handler h=(Handler)key.attachment();
        ByteBuffer buf = ByteBuffer.allocate(100);
        ((SocketChannel)key.channel()).read(buf);
        handler.handleRead(buf);
} else if (key.isWritable()) {
        Handler handler=(Handler)key.attachment();
        handler.handleWrite();
}
```