Effective Software

Lecture 7: Non-blocking I/O, C10K, efficient networking

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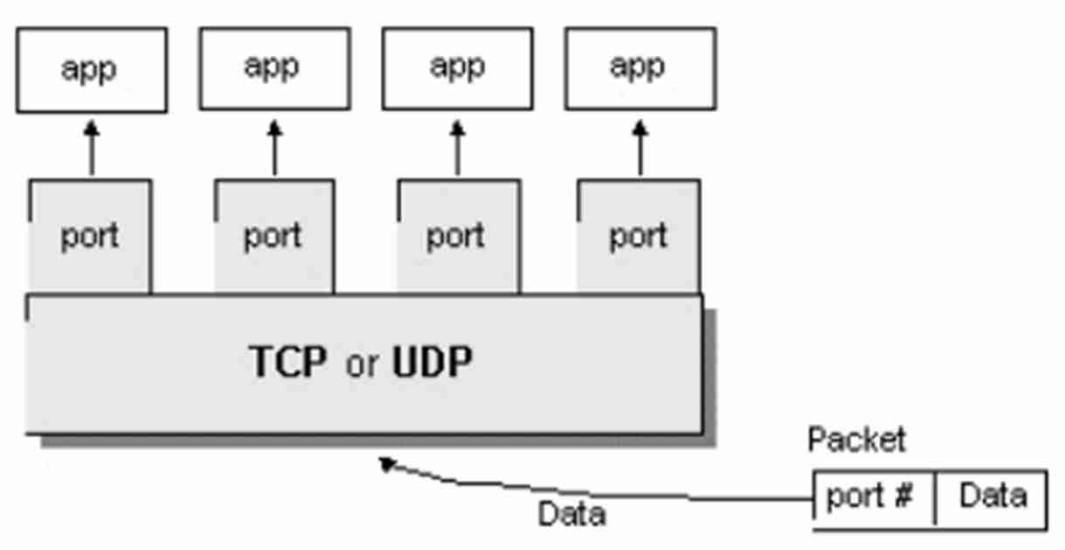
[1] Tanenbaum, A. S., Wetherall, D. J.: Computer Networks. Pearson, 2011.
[2] Kegel, D.: The C10K problem. http://www.kegel.com/c10k.html
[3] Hitchens, R.: Java NIO. O'Reilly, 2002.

Network Communication – OSI Model

7 – Application Interface to end user. Interaction directly with software application.		**Software App Layer** Directory services, email, network management, file transfer, web pages, database access.	FTP, HTTP, WWW, SMTP, TELNET, DNS, TFTP, NFS
6 – Presentation Formats data to be "presented" between application-layer entities.		**Syntax/Semantics Layer** Data translation, compression, encryption/decryption, formatting.	ASCII, JPEG, MPEG, GIF, MIDI
5 – Session Manages connections between local and remote application.		**Application Session Management** Session establishment/teardown, file transfer checkpoints, interactive login.	SQL, RPC, NFS
4 – Transport Ensures integrity of data transmission.	Segment	**End-to-End Transport Services** Data segmentation, reliability, multiplexing, connection-oriented, flow control, sequencing, error checking.	TCP, UDP, SPX, AppleTalk
3 – Network Determines how data gets from one host to another.	Packet	**Routing** Packets, subnetting, logical IP addressing, path determination, connectionless.	IP, IPX, ICMP, ARP, PING, Traceroute
2 – Data Link Defines format of data on the network.	Frame	**Switching** Frame traffic control, CRC error checking, encapsulates packets, MAC addresses.	Switches, Bridges, Frames, PPP/SLIP, Ethernet
1 – Physical Transmits raw bit stream over physical medium.	Bits	**Cabling/Network Interface** Manages physical connections, interpretation of bit stream into electrical signals	Binary transmission, bit rates, voltage levels, Hubs

Network Communication – Introduction



TCP		UDP	
FTP	20,21	DNS	53
SSH	22	BooTPS/DHCP	67
Telnet	23	TFTP	69
SMTP	25	SNMP	161
DNS	53		
HTTP	80		
POP3	110		
NTP	123		
IMAP4	143		
HTTPS	443		

» **ports** – 16-bit number

» **IPv4** – 32-bit address

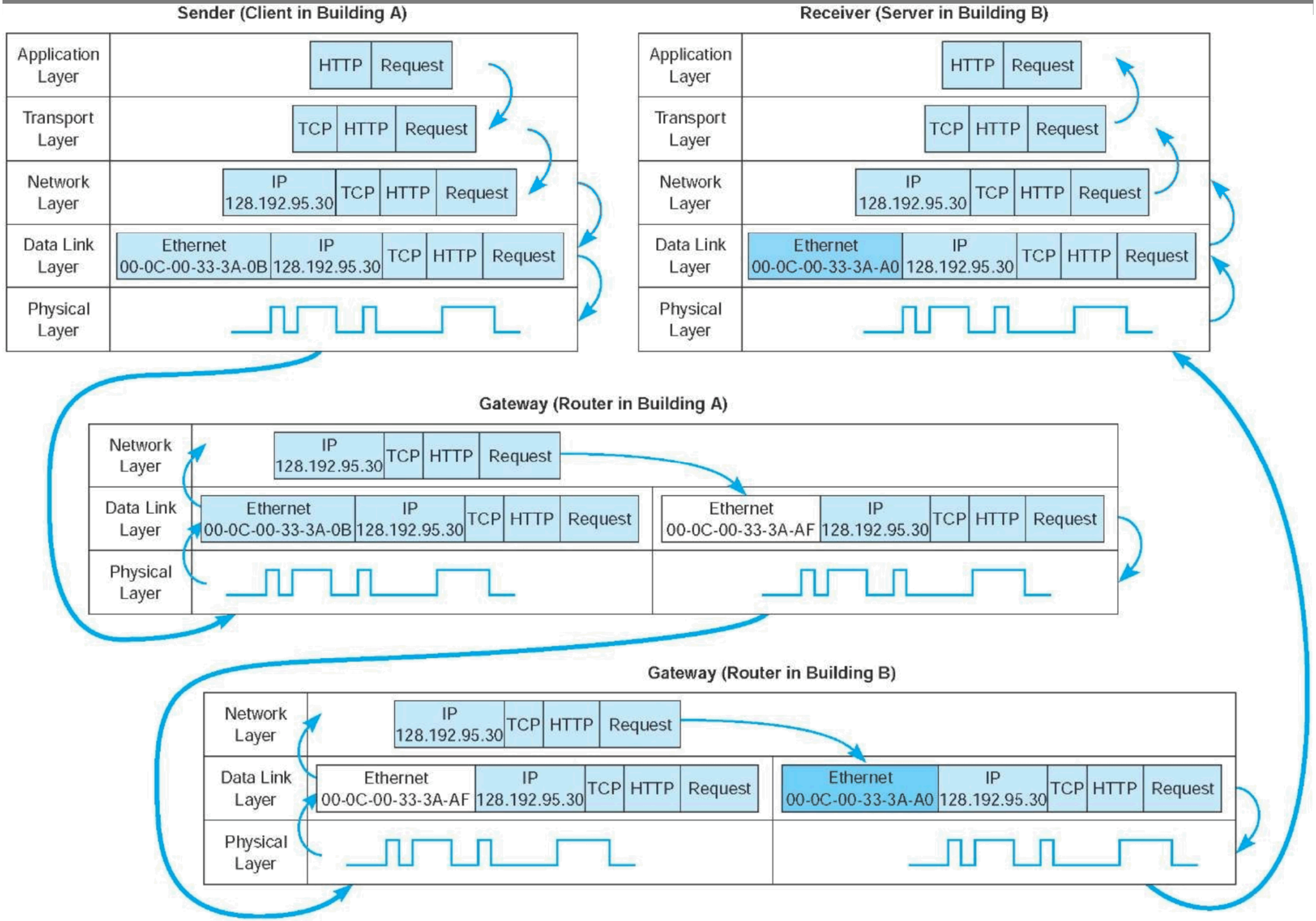
» **IPv6** – 128-bit address

- 48-bit or more routing prefix, 16-bit or less subnet id, 64-bit interface

http://[1fff:0:a88:85a3::ac1f]:8080/index.html

» TCP/UDP connection identification – **quad** – src IP, src port, dst IP, dst port

Network Communication – HTTP Example



C10k Problem

- handling a large number of clients (10 000s) at the same time (late 90s)
  - **concurrent connections at one server** requiring efficient scheduling
  - not related to requests per second
- sometime known as C1M or C10M problem (nowadays)
- approach
  - don't use **threading servers** like *Apache*
    - each connection handled by own thread/process (pooled but limited)
    - connection operations usually use **blocking** operations
    - thread scheduling doesn't scale (+cost for thread context switching)
    - thread scheduling used as packet scheduling
  - use **event-driven I/O servers** like *Nginx*
    - do packet scheduling yourself – single/multi-threaded event loop
    - using **non-blocking** (asynchronous) operations with **event interceptors**
    - **multi-core scalability** with controlled number of worker threads
    - reuse thread-based data structures, avoid locks (atomics, non-blocking)

Threads

» **processes** vs. **threads**

- both support concurrent execution
- one process has one or multiple threads
- threads share the same address space (data and code)
- context switching between threads is usually less expensive
- thread inter-communication is relatively efficient using shared memory

» **JVM**

- a thread executes sequence of code with own stack with frames

  t.getStackTrace()

- own local variables
- own method parameters

» thread creation by

- subclass of **java.lang.Thread**
- implementation of **java.lang.Runnable**

JAVA Thread Pool - ExecutorService

- concept of **thread pooling**
- suitable for execution of large number of asynchronous tasks
  - e.g. processing of requests in server
- reduce overhead with Thread creation for each task, context switching
- interface - java.util.concurrent.ExecutorService
  - shutdown(), shutdownNow(), awaitTermination
  - **execute**(Runnable r)
  - Future<?> **submit**(Runnable r), Future<T> **submit**(Callable<T> c)
- java.util.concurrent.Future<T>
  - boolean cancel(boolean mayInterruptIfRunning)
  - isCancelled(), isDone()
  - V get(), V get(long timeout, TimeUnit unit)
- java.util.concurrent.Executors (optionally with ThreadFactory)
  - **newSingleThreadExecutor**()
  - **newFixedThreadPool**(nThreads)
  - **newCachedThreadPool**() – default 60 seconds keep-alive

Non-Blocking I/O Approach

- **polling**
  - looping to regularly check status (readiness for I/O)
  - wastes CPU cycles
- **signals**
  - OS generated signals on I/O readiness
  - might leave state inconsistent in the process inconsistent
- **callbacks**
  - pointer to handler function
  - stack deepening issue (callback issuing I/O)
- **interrupts**
  - hardware interrupts in kernel mode
- **event-based**
  - select
  - poll
  - epoll

Event-Based I/O - select

» **select**

- defined in POSIX (Portable Operating System Interface)
- originally used for blocking I/O
- passed lists of descriptors cannot be reused in subsequent calls as they are modified by the system call
- not scalable – limited descriptors + iterate over to find the event

```
int
select(int nfds, fd_set *restrict readfds, fd_set *restrict writefds, fd_set *restrict errorfds,
struct timeval *restrict timeout);

void
FD_CLR(fd, fd_set *fdset);

void
FD_COPY(fd_set *fdset_orig, fd_set *fdset_copy);

int
FD_ISSET(fd, fd_set *fdset);

void
FD_SET(fd, fd_set *fdset);

void
FD_ZERO(fd_set *fdset);
```

Event-Based I/O - poll

» **poll**

- polled descriptors not limited
- descriptors can be reused
- better but you still need iterate over descriptors to find events

```
int
poll(struct pollfd fds[], nfds_t nfds, int timeout);
```

```
struct pollfd {
    int    fd;       /* file descriptor */
    short  events;   /* events to look for */
    short  revents;  /* events returned */
};
```

Event-Based I/O - epoll

- **epoll**
  - Linux only (e.g. Windows has IOCP – IO Completion Ports)
  - scalable
  - monitored events can be modified while polling (via syscall)
  - returns triggered events directly
- **API**
  - epoll_create & epoll_create1 – initialize epoll instance (kerne structure)
  - epoll_ctl – add/modify/remove descriptors to epoll instance
  - epoll_wait – wait for events up to timeout
- **modes**
  - **level triggered** – wait always returns if event is available
  - **event triggered** (EPOLLET) – readiness returned upon incoming event only
    (you have to process all pending events before next wait !)
- **events**
  - EPOLLIN, EPOLLOUT, EPOLLPRI
  - EPOLLRDHUP, EPOLLHUP
  - EPOLLERR

Epoll Usage

epoll structure:

```
typedef union epoll_data
{
  void        *ptr;
  int          fd;
  __uint32_t   u32;
  __uint64_t   u64;
} epoll_data_t;

struct epoll_event
{
  __uint32_t   events; /* Epoll events */
  epoll_data_t data;   /* User data variable */
};
```

initialization:

```
int epfd = epoll_create1(0);
...
struct epoll_event ev;
int client_sock;
...
ev.events = EPOLLIN | EPOLLPRI | EPOLLERR | EPOLLHUP;
ev.data.fd = client_sock;
int res = epoll_ctl(epfd, EPOLL_CTL_ADD, client_sock, &ev);
```

Epoll Event Loop

```
while (1) {
    // wait for something to do...
    int nfds = epoll_wait(epfd, events,
                                MAX_EPOLL_EVENTS_PER_RUN,
                                EPOLL_RUN_TIMEOUT);
    if (nfds < 0) die("Error in epoll_wait!");

    // for each ready socket
    for(int i = 0; i < nfds; i++) {
      int fd = events[i].data.fd;
      handle_io_on_socket(fd);
    }
}
```

JAVA Networking – TCP Client

» **Socket**

- client end-point of network TCP/IP connection
- is bound to particular destination IP and port
- each TCP/IP connection is uniquely identified by its two end-points
- provides input/output streams

```
try (
    Socket echoSocket = new Socket( host: "localhost",  port: 7);
    PrintWriter out = new PrintWriter(echoSocket.getOutputStream(),  autoFlush: true);
    BufferedReader in = new BufferedReader(new InputStreamReader(echoSocket.getInputStream()));
    BufferedReader stdIn = new BufferedReader(new InputStreamReader(System.in))
) {

    String userInput;

    while ((userInput = stdIn.readLine()) != null) {
        out.println(userInput);
        System.out.println("echo: " + in.readLine());
    }
}
```

JAVA Networking – TCP Server

» **ServerSocket**

- special socket representing listening TCP/IP end-point
- within constructor you specify the port, and optionally IP where it has to be bound
- wait for establishing connection using method Socket **accept**()

JAVA Networking – TCP Server - Example

threading server example – each handler runs in own thread with blocking I/O

```
ExecutorService clientRunner = Executors.newCachedThreadPool();
try (
        ServerSocket serverSocket = new ServerSocket( port: 7)
) {
    while (true) {
        final Socket s = serverSocket.accept();
        clientRunner.execute(() -> {
            try (
                    BufferedReader in = new BufferedReader(new InputStreamReader(s.getInputStream()));
                    PrintWriter out = new PrintWriter(s.getOutputStream(), autoFlush: true)
            ) {
                String line;
                while (s.isConnected()) {
                    if ((line = in.readLine()) != null) {
                        out.println(line);
                    }
                }
            } catch (IOException e) {
                e.printStackTrace();
            }
        });
    }
} catch (Exception e) {
    e.printStackTrace();
} finally {
    clientRunner.shutdownNow();
}
```

JAVA Networking - UDP

» **DatagramPacket**

- independent, self-contained message sent over the network
- like packet
  - InetAddress address, int port – destination
  - byte data[], int length, int offset
  - SocketAddress sa – sender

» **DatagramSocket**

- sending or receiving point for a packet delivery service
- can be bound to any available port (using default constructor)
- connect(InetAddress,int) – can sent or receive packets only specified host, if not set in DatagramPacket automatically fill
- send(DatagramPacket p), receive(DatagramPacket p) – blocking IO

» **MulticastSocket**

- additional capabilities for joining/leaving multicast groups, loopback
- multicast IP (IGMP – Internet Group Management Protocol)

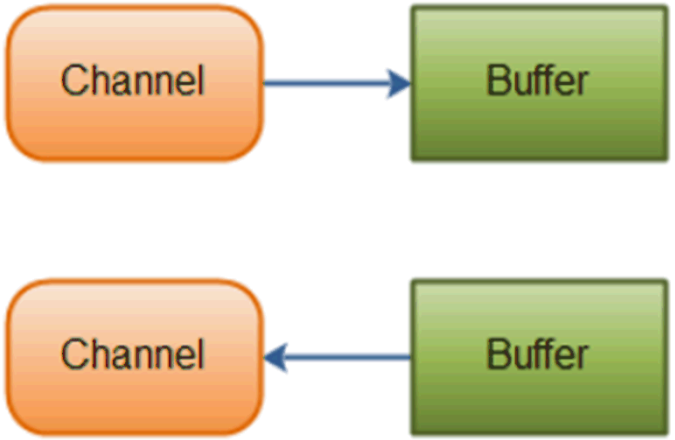
  224.0.0.0 – 239.255.255.255

JAVA Networking - NIO

» **scalable I/O** – asynchronous I/O requests and polling

» high-speed **block-oriented** binary and character I/O working – including mapping files to the memory, using channels and selectors

» Channel is like a block device working with Buffers

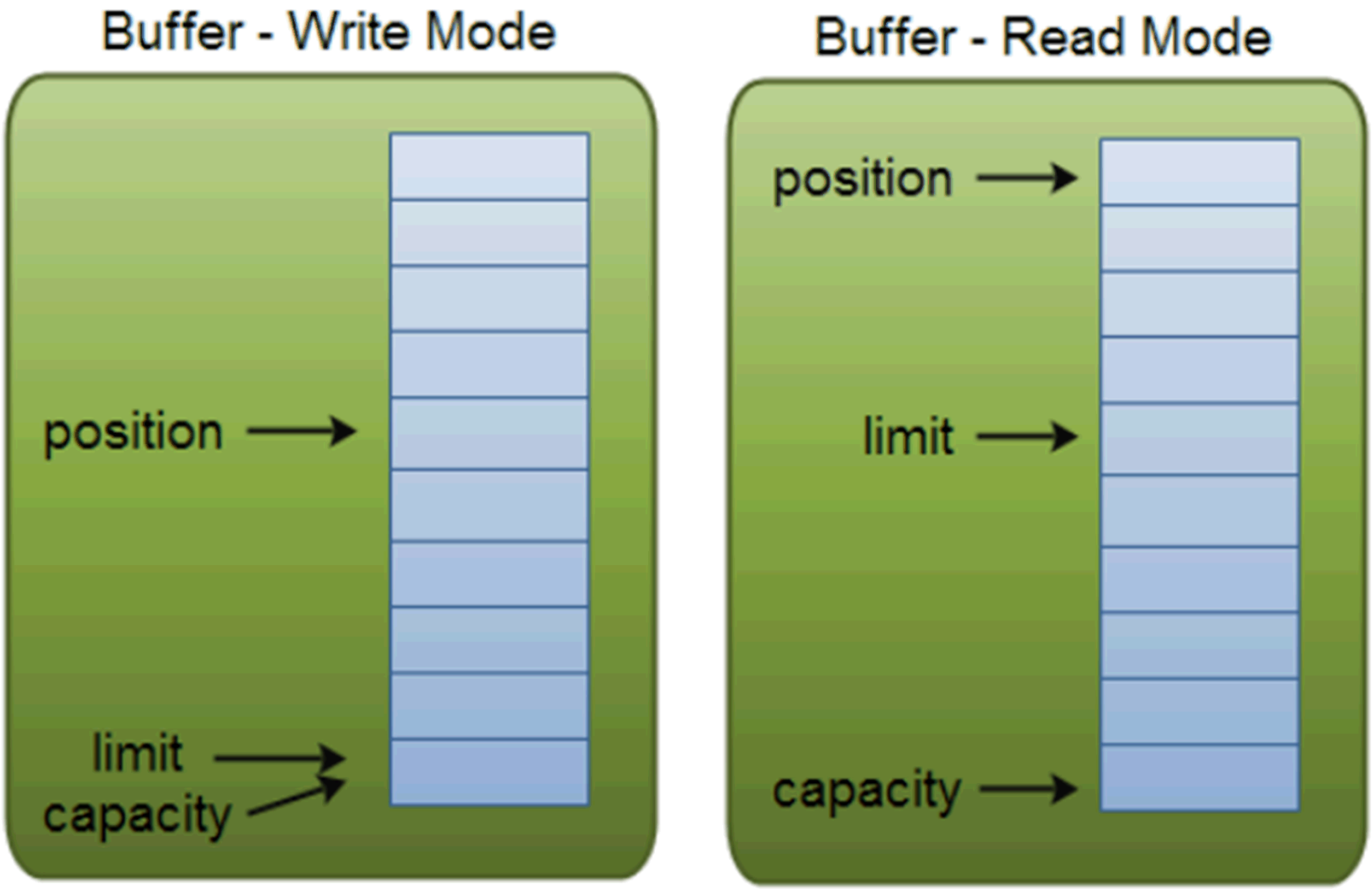


JAVA – NIO - Buffer

» java.nio.Buffer

- **linear, finite sequence of elements** of a specific primitive type
  - ByteBuffer, CharBuffer, DoubleBuffer, FloatBuffer, IntBuffer, LongBuffer, ShortBuffer, MappedByteBuffer {FileChannel.map(…)}
- not thread safe, **multi mode** for the same buffer (both read & write)
- key properties – 0 <= mark <= position <= limit <= capacity
  - capacity – numbers of elements, never changing !
  - limit – index of the first element that should not be read or written
  - position – index of the next element to be read or written
  - mark – index to which its position is set after reset()
- clear() – position=0, limit=capacity => ready for channel read (put)
- flip() – limit=position, position=0 => ready for channel write (get)
- rewind() – limit unchanged, position=0 => ready for re-reading
- mark() – mark = position
- reset() – position=mark

JAVA – NIO - Buffer



» write mode – channel.read(buf); buf.put(…);

» read mode – channel.write(buf); … buf.get();

JAVA – NIO - Buffer

» java.nio.Buffer

- isReadOnly() – can be read-only
- hasArray() – is backed by an accessible array (array())
- equals(), compareTo() – compare remainder sequence

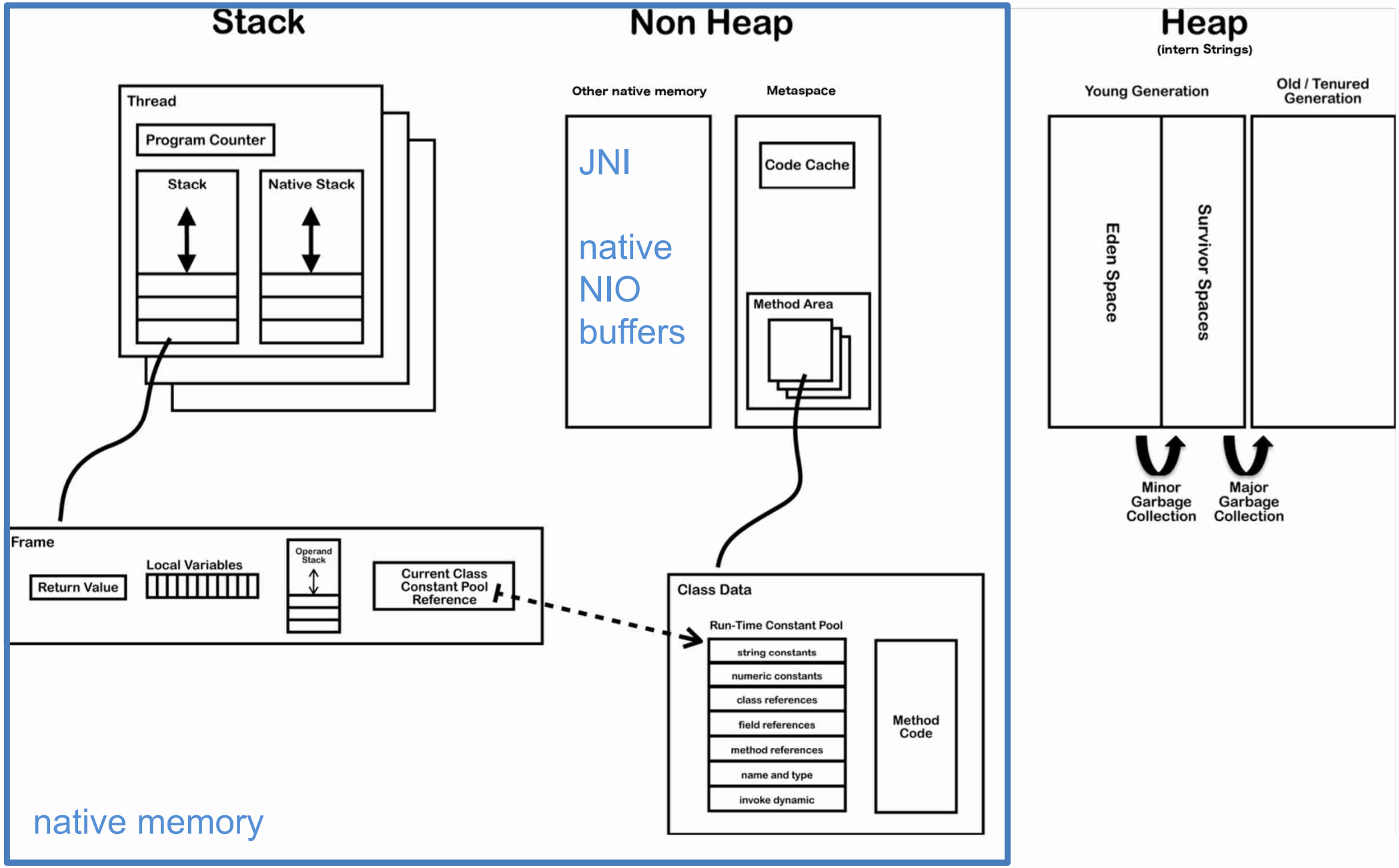
- can be **allocated to native memory** (see next slide)

- **typical usage**

1. Write data into the Buffer
2. Call `buffer.flip()`
3. Read data out of the Buffer
4. Call `buffer.clear()` or `buffer.compact()`

Note: compact() – bytes between position and limit are copied to the beginning of the buffer and prepare for writing again

JVM – Memory Layout – Native Memory

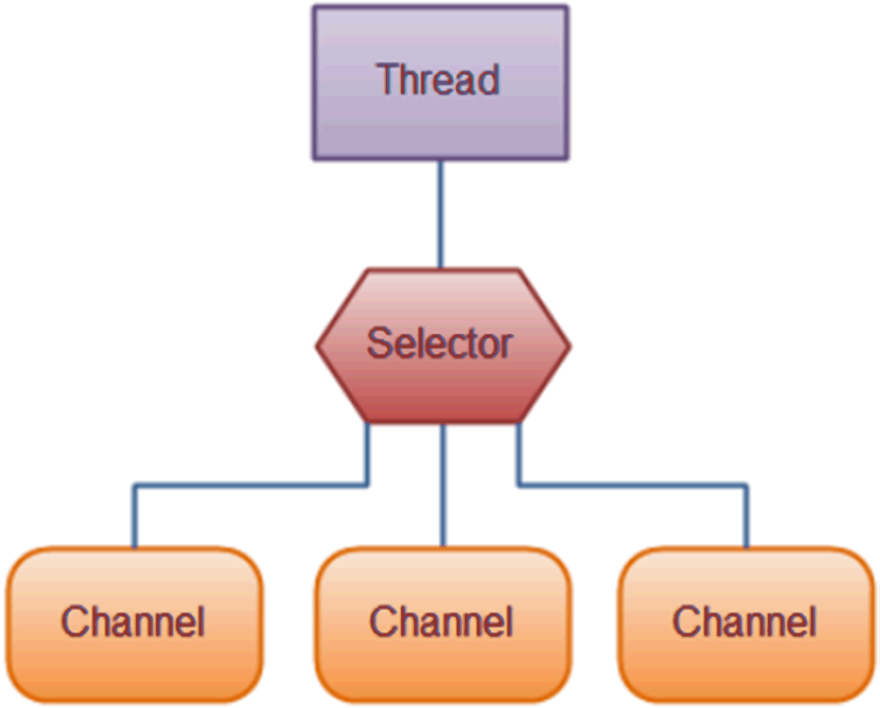


JVM – NIO - Direct Buffers

- **ByteBuffer.allocateDirect**(…)
- stored out of JAVA heap in **native memory**
- allow native code and Java code to **share data without copying**
  - useful for file and socket
    - the same memory is passed to kernel during calls
- multiple buffers can share native memory
  - slice()/duplicate() – independent position, limit, mark, shared content
  - asReadOnlyBuffer() – read only view of shared content
- tuning/tracking
  - -XX:MaxDirectMemorySize=N (default unlimited)
  - -XX:NativeMemoryTracking=off|summary|detail
  - -XX:+PrintNMTStatistics

<u>Note</u>: usage of heap buffers implies content copy out/in Java heap space due to possible relocations by GC

JAVA Networking - NIO – Channel, Selector



» **one thread** works with **multiple channels at the same time**
  - **epoll-based** if OS support epoll

» **Channel** – cover UDP+TCP network IO, file IO
  - FileChannel – from Input/OutputStream or RandomAccessFile
  - DatagramChannel
  - MulticastChannel
  - SocketChannel
  - ServerSocketChannel

JAVA – NIO – Channel

» **Channel**

- read/write at the same time (streams are only one-way)
- always read/write from/to a **buffer**

» **FileChannel**

- only **blocking**
- support – direct buffers, mapped files, locking
- bulk transfers between channels
  - no copy at all, direct transfer e.g. to socket
  - **transferFrom**(sourceChannel, int pos, int count)
  - **transferTo**(int pos, int count, dstChannel)

JAVA – NIO – Channel

» **SocketChannel** – client end-point of TCP/IP

- can be configured as non-blocking before connecting
- SocketChannel socket.getChannel();
- SocketChannel SocketChannel.open();
- sch.connect(…)

- write(…) and read(…) may return without having written/read anything for non-blocking channel

» **ServerSocketChannel** – server end-point of TCP/IP

- can be configured as non-blocking
- can be created directly using open() or from ServerSocket
- accept() – returns SocketChannel in the same mode

JAVA – NIO – Selector

» **Selector**

- Selector Selector.open();
- only channels in **non-blocking** mode can be registered

  channel.configureBlocking(false);

  SelectionKey channel.register(selector, SelectionKey.OP_READ);
- FileChannel doesn't support non-blocking mode

» **SelectionKey** – events you can listen for (can be combined together)

- OP_CONNECT
- OP_ACCEPT
- OP_READ
- OP_WRITE

» events are filled by channel which is ready with operation

JAVA – NIO – Selector

» **SelectionKey** – returned from register method

- interest set – your configured ops
- ready set – which ops are ready, sk.isReadable(), sk.isWritable(), …
- channel
- selector
- optional attached object – sk.attach(Object obj);
  Object sk.attachment()

SelectionKey channel.register(selector, ops, attachmentObj);

JAVA – NIO – Selector

» Selector with registered one or more channels

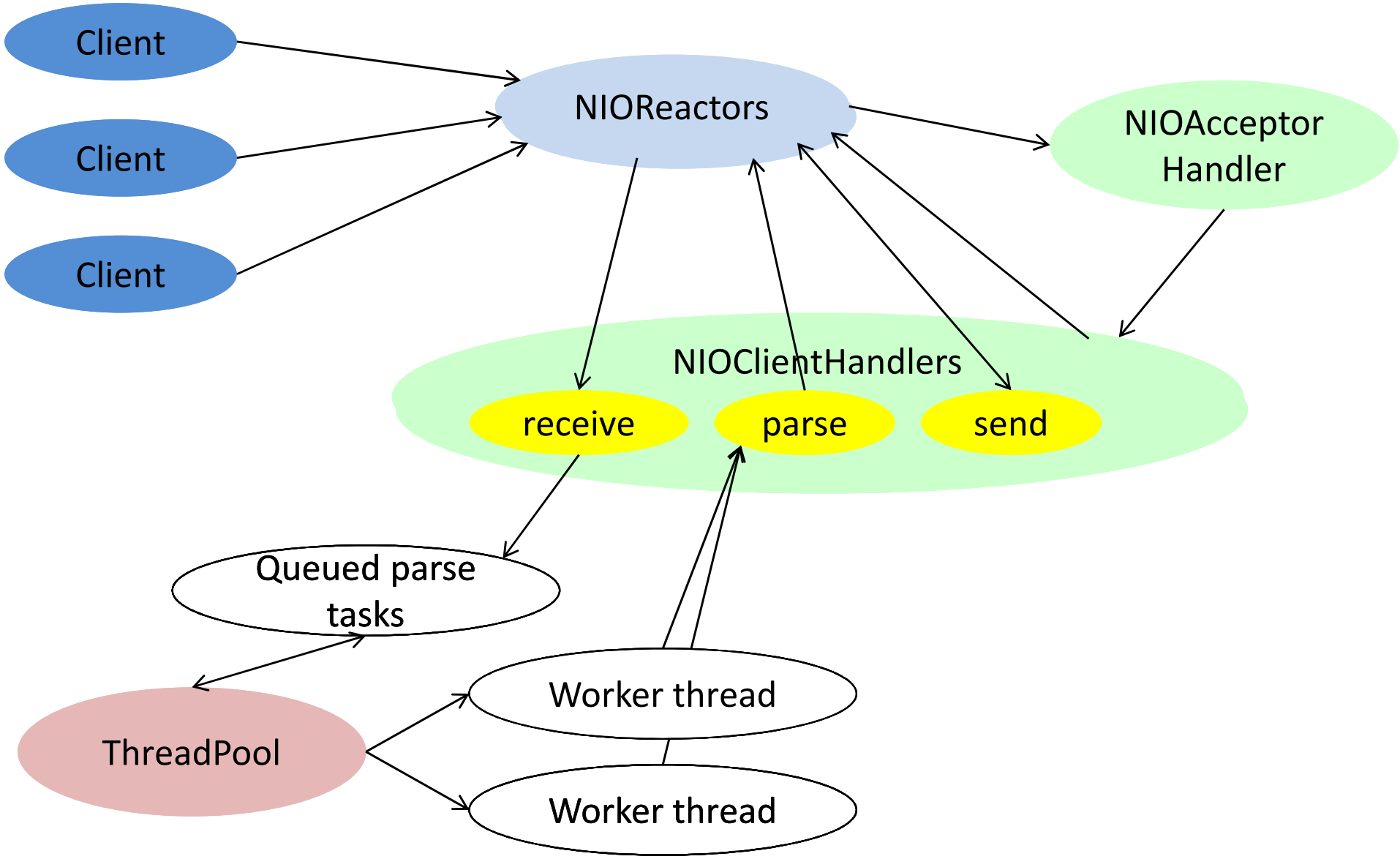
- int **select**() – blocks until at least one channel is ready
- int select(long timeout) – with timeout milliseconds
- int selectNow() – doesn't block at all, returns immediately

return the number of channels which are ready from the last call

Set<SelectionKey> selector.selectedKeys();

- **wakeUp**() – different thread can "wake up" thread blocked in select()
- **close**() – invalidates selector, channels are not closed

JAVA – NIO Server – Using Multiple Reactors



JAVA – NIOServer Example

```java
public class NIOServer {
    final static int MSG_SIZE = 1_000_000;
    private final static NIOReactor[] reactors;
    static ExecutorService workers = Executors.newWorkStealingPool();
    static BufferPool bufferPool = new BufferPool();

    static {
        reactors = new NIOReactor[4];
        try {
            for (int i=0; i<reactors.length; i++) {
                    reactors[i] = new NIOReactor();
            }
        } catch (IOException e) {
            e.printStackTrace();
        }
    }

    public static void startNIOServer(int port) throws IOException {
        reactors[0].register(NIOAcceptorHandler.getNIOAcceptorHandler(reactors, port));
    }

    static class BufferPool {...}
}
```

JAVA – NIOReactor Example

```java
class NIOReactor implements Runnable {
    private final Selector s = Selector.open();
    private final ConcurrentLinkedQueue<NIOHandler> toRegister = new ConcurrentLinkedQueue<>();

    NIOReactor() throws IOException {
        Thread t = new Thread( target: this);
        t.setDaemon(true);
        t.start();
    }

    void register(NIOHandler target) {
        toRegister.add(target);
        s.wakeup();
    }

    @Override
    public void run() {
        try {
            while (true) {
                s.select();
                for (SelectionKey key : s.selectedKeys()) {
                    if (key.attachment() != null) ((NIOHandler) key.attachment()).run();
                }
                s.selectedKeys().clear();
                NIOHandler t;
                while ((t=toRegister.poll()) != null) {
                    t.setSelectionKey(t.getSelectableChannel().register(s, t.getInitialSelectableOps(), t));
                }
            }
        } catch (Exception e) {
            e.printStackTrace();
        }
    }
}
```

JAVA – NIOHandler Example

```java
abstract class NIOHandler implements Runnable {
    private final SelectableChannel selectableChannel;
    private final int initialSelectableOps;
    private SelectionKey selectionKey = null;

    NIOHandler(SelectableChannel selectableChannel, int initialSelectableOps) {
        this.selectableChannel = selectableChannel;
        this.initialSelectableOps = initialSelectableOps;
    }

    SelectableChannel getSelectableChannel() {
        return selectableChannel;
    }

    int getInitialSelectableOps() {
        return initialSelectableOps;
    }

    SelectionKey getSelectionKey() {
        return selectionKey;
    }

    void setSelectionKey(SelectionKey selectionKey) {
        this.selectionKey = selectionKey;
    }
}
```

JAVA – NIOAcceptorHandler Example

```java
class NIOAcceptorHandler extends NIOHandler {
    private final NIOReactor[] reactors;
    private final ServerSocketChannel ssch;
    private int roundRobin = 0;

    static NIOAcceptorHandler getNIOAcceptorHandler(NIOReactor[] reactors, int port) throws IOException {
        ServerSocketChannel ssch = ServerSocketChannel.open();
        ssch.socket().bind(new InetSocketAddress(port));
        ssch.configureBlocking( block: false);
        return new NIOAcceptorHandler(reactors, ssch, SelectionKey.OP_ACCEPT);
    }

    private NIOAcceptorHandler(NIOReactor[] reactors, ServerSocketChannel ssch, int selectableOps) {
        super(ssch, selectableOps);
        this.reactors = reactors;
        this.ssch = ssch;
    }

    @Override
    public void run() {
        try {
            SocketChannel sch = ssch.accept();
            if (sch != null) {
                reactors[roundRobin].register(new NIOClientHandler(sch));
                roundRobin = (roundRobin+1)%reactors.length;
            }
        } catch (IOException ex) {
            ex.printStackTrace();
        }

    }
}
```

JAVA – NIOClientHandler Example

```
class NIOClientHandler extends NIOHandler {
    private final SocketChannel socketChannel;
    private ByteBuffer readBuf;
    private ByteBuffer writeBuf = null;

    NIOClientHandler(SocketChannel socketChannel) throws IOException {
        super(socketChannel, SelectionKey.OP_READ);
        this.socketChannel = socketChannel;
        readBuf = NIOServer.bufferPool.getBuffer();
        socketChannel.configureBlocking( block: false);
    }

    @Override
    public void run() {
        try {
            if (getSelectionKey().isReadable()) read();
            else if (getSelectionKey().isWritable()) write( setWriteInterest: false);
        }
        catch (IOException ex) {
            ex.printStackTrace();
        }
    }

    private void read() throws IOException {...}

    private void process() {...}

    private void write(boolean setWriteInterest) throws IOException {...}
}
```

JAVA – NIOClientHandler Example

```java
private void read() throws IOException {
    if (socketChannel.read(readBuf) == -1) {
        getSelectionKey().cancel();
        socketChannel.close();
    } else if (readBuf.remaining() == 0) {
        getSelectionKey().interestOps(0);
        getSelectionKey().selector().wakeup();
        NIOServer.workers.execute(this::process);
    }
}

private void process() {
    try {
        readBuf.flip();
        writeBuf = NIOServer.bufferPool.getBuffer();

        // DO processing and prepare data in writeBuf
        writeBuf.put(readBuf);
        writeBuf.flip();

        NIOServer.bufferPool.releaseBuffer(readBuf);
        readBuf = null;
        write( setWriteInterest: true);
    } catch (IOException e) {
        e.printStackTrace();
    }
}
```

JAVA - NIOClientHandler Example

```java
private void write(boolean setWriteInterest) throws IOException {
    if (socketChannel.write(writeBuf) == -1) {
        getSelectionKey().cancel();
        socketChannel.close();
    } else if (writeBuf.remaining() > 0) {
        if (setWriteInterest) {
            getSelectionKey().interestOps(SelectionKey.OP_WRITE);
        }
    } else {
        readBuf = writeBuf;
        readBuf.clear();
        writeBuf = null;
        getSelectionKey().interestOps(SelectionKey.OP_READ);
    }
    if (setWriteInterest) {
        getSelectionKey().selector().wakeup();
    }
}
```

JAVA - NIOClientHandler Example

```java
private void write(boolean setWriteInterest) throws IOException {
    if (socketChannel.write(writeBuf) == -1) {
        getSelectionKey().cancel();
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    } else if (writeBuf.remaining() > 0) {
        if (setWriteInterest) {
            getSelectionKey().interestOps(SelectionKey.OP_WRITE);
        }
    } else {
        readBuf = writeBuf;
        readBuf.clear();
        writeBuf = null;
        getSelectionKey().interestOps(SelectionKey.OP_READ);
    }
    if (setWriteInterest) {
        getSelectionKey().selector().wakeup();
    }
}
```