Scalable IO in Java

Doug Lea
State University of New York at Oswego
dl@cs.oswego.edu
http://gee.cs.oswego.edu

Outline

- Scalable network services
- Event-driven processing
- Reactor pattern
  - Basic version
  - Multithreaded versions
  - Other variants
- Walkthrough of java.nio nonblocking IO APIs

Network Services

- Web services, Distributed Objects, etc
- Most have same basic structure:

  Read request

  Decode request

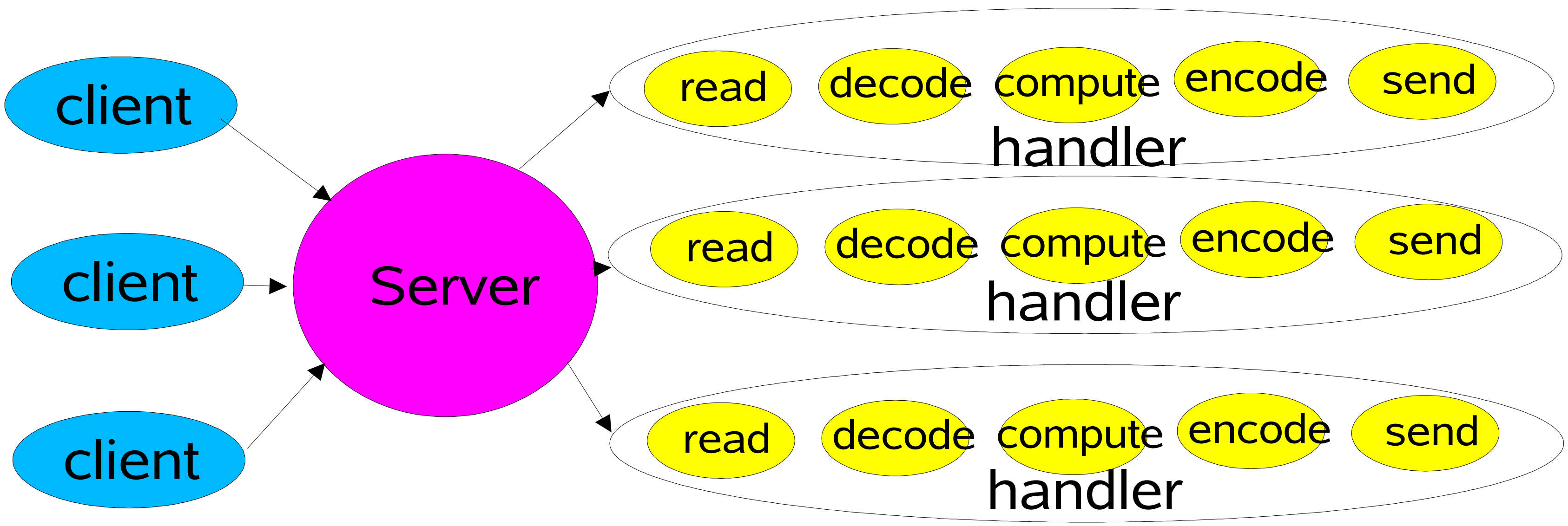
  Process service

  Encode reply

  Send reply
- But differ in nature and cost of each step

  XML parsing, File transfer, Web page generation, computational services, ...

Classic Service Designs



Each handler may be started in its own thread

Classic ServerSocket Loop

```
class Server implements Runnable {
  public void run() {
    try {
      ServerSocket ss = new ServerSocket(PORT);
      while (!Thread.interrupted())
        new Thread(new Handler(ss.accept())).start();
      // or, single-threaded, or a thread pool
    } catch (IOException ex) { /* ... */ }
  }

  static class Handler implements Runnable {
    final Socket socket;
    Handler(Socket s) { socket = s; }
    public void run() {
      try {
        byte[] input = new byte[MAX_INPUT];
        socket.getInputStream().read(input);
        byte[] output = process(input);
        socket.getOutputStream().write(output);
      } catch (IOException ex) { /* ... */ }
    }
    private byte[] process(byte[] cmd) { /* ... */ }
  }
}
```

Note: most exception handling elided from code examples

Scalability Goals

- Graceful degradation under increasing load (more clients)
- Continuous improvement with increasing resources (CPU, memory, disk, bandwidth)
- Also meet availability and performance goals
  - Short latencies
  - Meeting peak demand
  - Tunable quality of service
- Divide-and-conquer is usually the best approach for achieving any scalability goal

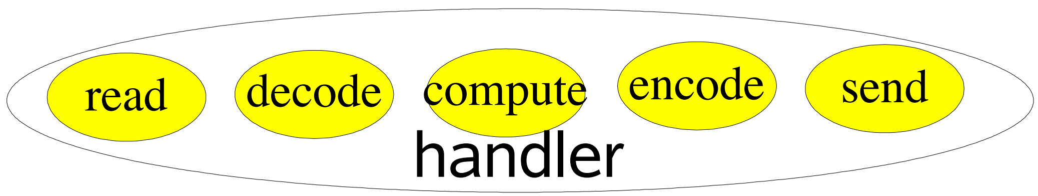
Divide and Conquer

" Divide processing into small tasks

  Each task performs an action without blocking

" Execute each task when it is enabled

  Here, an IO event usually serves as trigger



" Basic mechanisms supported in java.nio

  Non-blocking reads and writes

  Dispatch tasks associated with sensed IO events

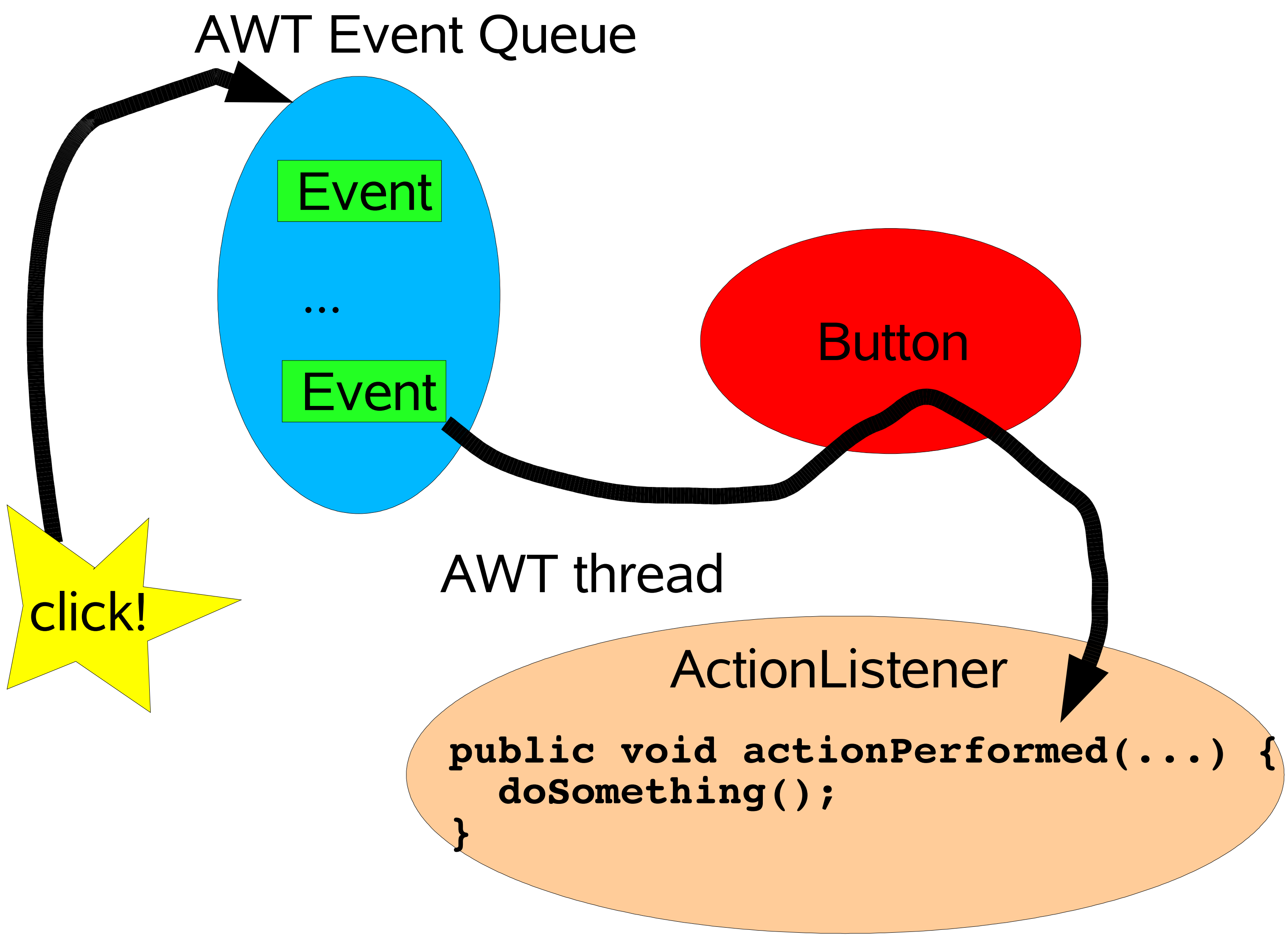
" Endless variation possible

  A family of event-driven designs

Event-driven Designs

- Usually more efficient than alternatives
  - Fewer resources
    - Don't usually need a thread per client
  - Less overhead
    - Less context switching, often less locking
  - But dispatching can be slower
    - Must manually bind actions to events
- Usually harder to program
  - Must break up into simple non-blocking actions
    - Similar to GUI event-driven actions
    - Cannot eliminate all blocking: GC, page faults, etc
  - Must keep track of logical state of service

Background: Events in AWT

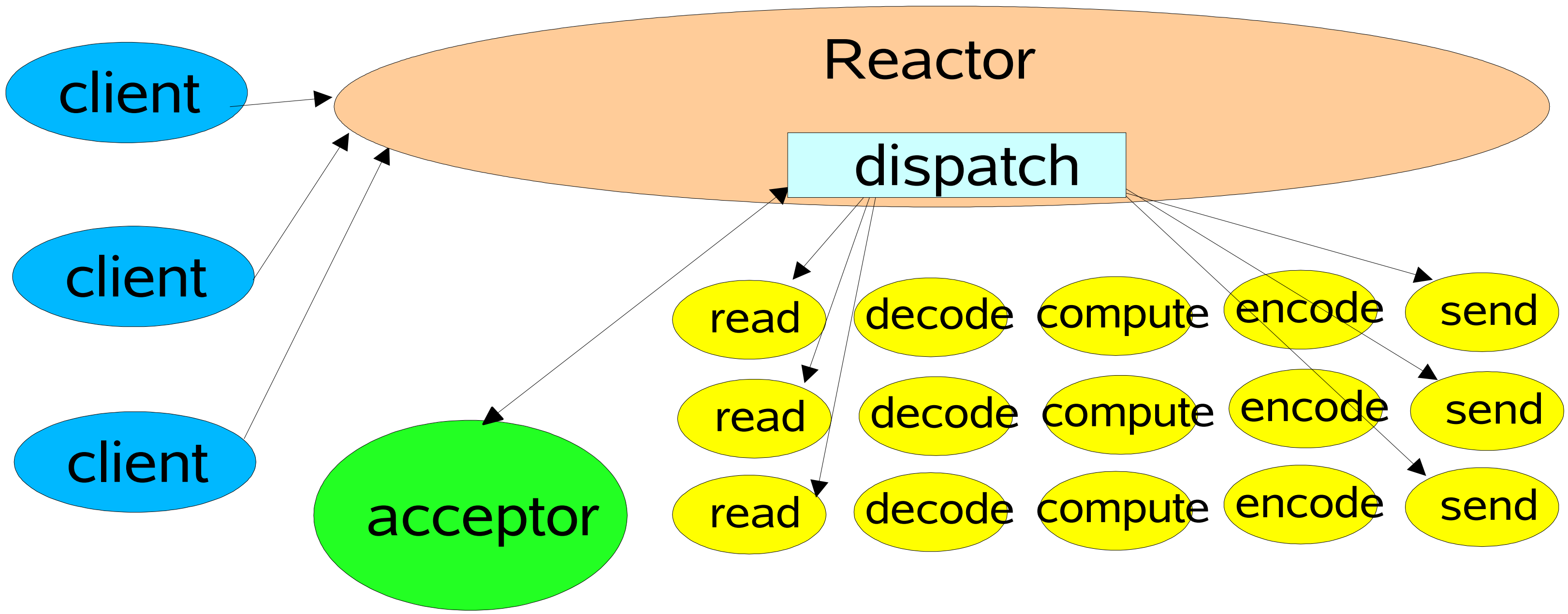


Event-driven IO uses similar ideas but in different designs

Reactor Pattern

- **Reactor** responds to IO events by dispatching the appropriate handler
  - Similar to AWT thread
- **Handlers** perform non-blocking actions
  - Similar to AWT ActionListeners
- Manage by binding handlers to events
  - Similar to AWT addActionListener
- See Schmidt et al, *Pattern-Oriented Software Architecture, Volume 2* (POSA2)
  - Also Richard Stevens's networking books, Matt Welsh's SEDA framework, etc

Basic Reactor Design



Single threaded version

java.nio Support

- **Channels**

  Connections to files, sockets etc that support non-blocking reads

- **Buffers**

  Array-like objects that can be directly read or written by Channels

- **Selectors**

  Tell which of a set of Channels have IO events

- **SelectionKeys**

  Maintain IO event status and bindings

Reactor 1: Setup

```
class Reactor implements Runnable {
  final Selector selector;
  final ServerSocketChannel serverSocket;

  Reactor(int port) throws IOException {
    selector = Selector.open();
    serverSocket = ServerSocketChannel.open();
    serverSocket.socket().bind(
                    new InetSocketAddress(port));
    serverSocket.configureBlocking(false);
    SelectionKey sk =
      serverSocket.register(selector,

SelectionKey.OP_ACCEPT);
    sk.attach(new Acceptor());
  }

  /*
   Alternatively, use explicit SPI provider:
    SelectorProvider p = SelectorProvider.provider();
    selector = p.openSelector();
    serverSocket = p.openServerSocketChannel();
  */
```

Reactor 2: Dispatch Loop

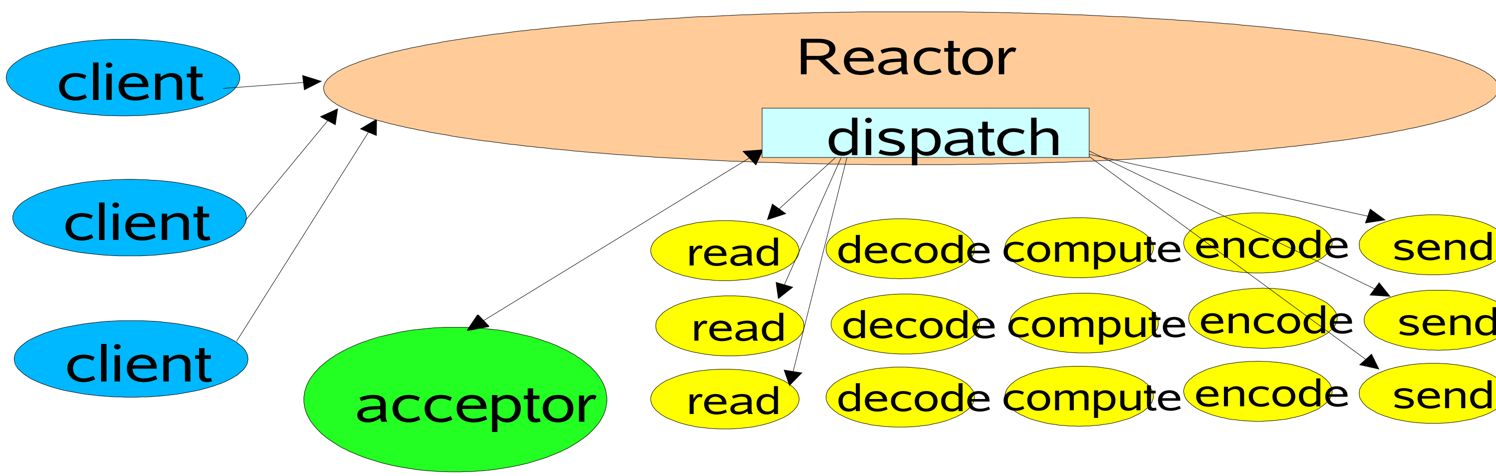
```
// class Reactor continued
  public void run() {  // normally in a new
Thread
    try {
      while (!Thread.interrupted()) {
        selector.select();
        Set selected = selector.selectedKeys();
        Iterator it = selected.iterator();
        while (it.hasNext())
          dispatch((SelectionKey)(it.next());
        selected.clear();
      }
    } catch (IOException ex) { /* ... */ }
  }

  void dispatch(SelectionKey k) {
    Runnable r = (Runnable)(k.attachment());
    if (r != null)
      r.run();
  }
```

http://gee.cs.oswego.edu

Reactor 3: Acceptor

```
// class Reactor continued
   class Acceptor implements Runnable { // inner
     public void run() {
       try {
         SocketChannel c = serverSocket.accept();
         if (c != null)
           new Handler(selector, c);
       }
       catch(IOException ex) { /* ... */ }
     }
   }
}
```



Reactor 4: Handler setup

```
final class Handler implements Runnable {
  final SocketChannel socket;
  final SelectionKey sk;
  ByteBuffer input = ByteBuffer.allocate(MAXIN);
  ByteBuffer output = ByteBuffer.allocate(MAXOUT);
  static final int READING = 0, SENDING = 1;
  int state = READING;

  Handler(Selector sel, SocketChannel c)
   throws IOException {
    socket = c; c.configureBlocking(false);
    // Optionally try first read now
    sk = socket.register(sel, 0);
    sk.attach(this);
    sk.interestOps(SelectionKey.OP_READ);
    sel.wakeup();
  }

  boolean inputIsComplete()  { /* ... */ }
  boolean outputIsComplete() { /* ... */ }
  void process()             { /* ... */ }
```

Reactor 5: Request handling

```
// class Handler continued
   public void run() {
    try {
      if      (state == READING) read();
      else if (state == SENDING) send();
    } catch (IOException ex) { /* ... */ }
  }
  void read() throws IOException {
    socket.read(input);
    if (inputIsComplete()) {
       process();
       state = SENDING;
       // Normally also do first write now
       sk.interestOps(SelectionKey.OP_WRITE);
    }
  }
  void send() throws IOException {
    socket.write(output);
    if (outputIsComplete()) sk.cancel();
  }
}
```

Per-State Handlers

- A simple use of GoF State-Object pattern
  - **Rebind** appropriate handler as attachment

```
class Handler  { // ...

  public void run() { // initial state is reader
    socket.read(input);
    if (inputIsComplete()) {
      process();
      sk.attach(new Sender());
      sk.interest(SelectionKey.OP_WRITE);
      sk.selector().wakeup();
    }
  }

  class Sender implements Runnable {
    public void run(){ // ...
      socket.write(output);
      if (outputIsComplete()) sk.cancel();
    }
  }
}
```

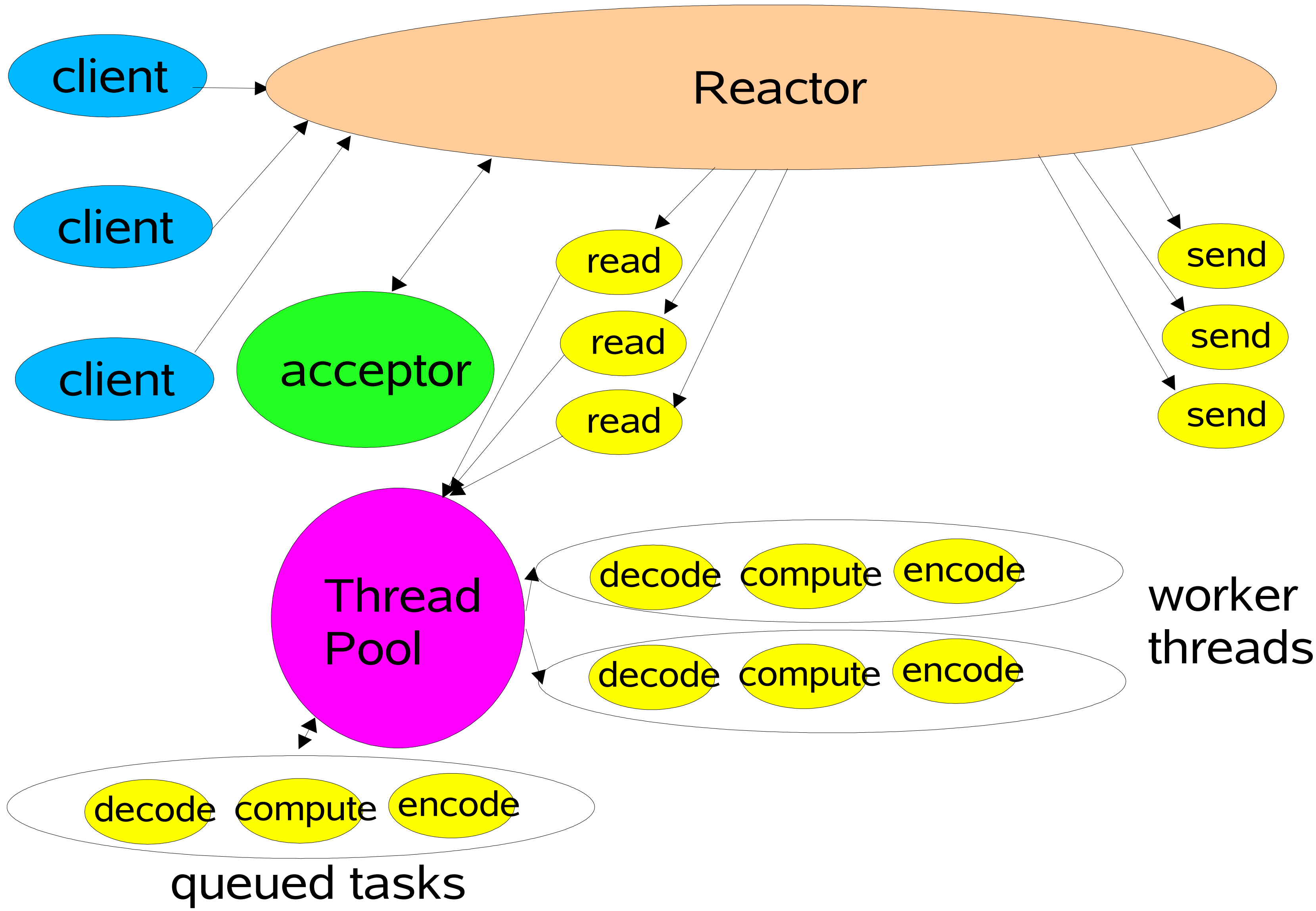
Multithreaded Designs

- Strategically add threads for scalability
  - Mainly applicable to multiprocessors
- Worker Threads
  - Reactors should quickly trigger handlers
    - Handler processing slows down Reactor
  - Offload non-IO processing to other threads
- Multiple Reactor Threads
  - Reactor threads can saturate doing IO
  - Distribute load to other reactors
    - Load-balance to match CPU and IO rates

Worker Threads

- Offload non-IO processing to speed up Reactor thread
  - Similar to POSA2 Proactor designs
- Simpler than reworking compute-bound processing into event-driven form
  - Should still be pure nonblocking computation
    - Enough processing to outweigh overhead
- But harder to overlap processing with IO
  - Best when can first read all input into a buffer
- Use thread pool so can tune and control
  - Normally need many fewer threads than clients

Worker Thread Pools



Handler with Thread Pool

```
class Handler implements Runnable {
  // uses util.concurrent thread pool
  static PooledExecutor pool = new PooledExecutor(...);
  static final int PROCESSING = 3;
  // ...

  synchronized void read() { // ...
    socket.read(input);
    if (inputIsComplete()) {
      state = PROCESSING;
      pool.execute(new Processer());
    }
  }

  synchronized void processAndHandOff() {
    process();
    state = SENDING; // or rebind attachment
    sk.interest(SelectionKey.OP_WRITE);
  }

  class Processer implements Runnable {
    public void run() { processAndHandOff(); }
  }
}
```

Coordinating Tasks

- Handoffs
  - Each task enables, triggers, or calls next one
  - Usually fastest but can be brittle
- Callbacks to per-handler dispatcher
  - Sets state, attachment, etc
  - A variant of GoF Mediator pattern
- Queues
  - For example, passing buffers across stages
- Futures
  - When each task produces a result
  - Coordination layered on top of join or wait/notify

Using PooledExecutor

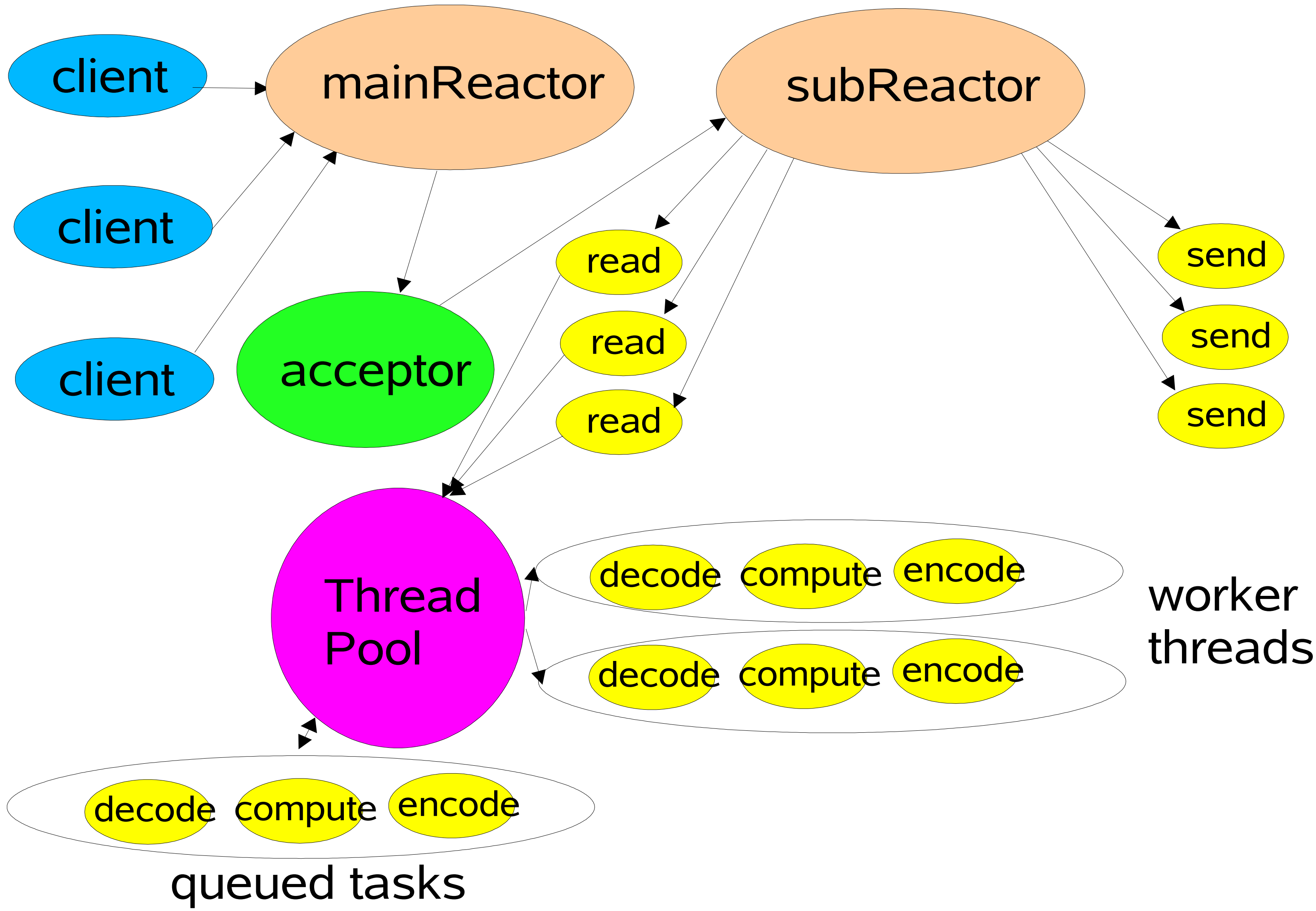
- A tunable worker thread pool
- Main method **`execute(Runnable r)`**
- Controls for:
  - The kind of task queue (any Channel)
  - Maximum number of threads
  - Minimum number of threads
  - "Warm" versus on-demand threads
  - Keep-alive interval until idle threads die
    - to be later replaced by new ones if necessary
  - Saturation policy
    - block, drop, producer-runs, etc

Multiple Reactor Threads

- Using Reactor Pools
    - Use to match CPU and IO rates
    - Static or dynamic construction
        - Each with own Selector, Thread, dispatch loop
    - Main acceptor distributes to other reactors

```
Selector[] selectors; // also create threads
int next = 0;
class Acceptor { // ...
  public synchronized void run() { ...
    Socket connection = serverSocket.accept();
    if (connection != null)
      new Handler(selectors[next], connection);
    if (++next == selectors.length) next = 0;
  }
}
```

Using Multiple Reactors



Using other java.nio features

- Multiple Selectors per Reactor
  - To bind different handlers to different IO events
  - May need careful synchronization to coordinate
- File transfer
  - Automated file-to-net or net-to-file copying
- Memory-mapped files
  - Access files via buffers
- Direct buffers
  - Can sometimes achieve zero-copy transfer
  - But have setup and finalization overhead
  - Best for applications with long-lived connections

Connection-Based Extensions

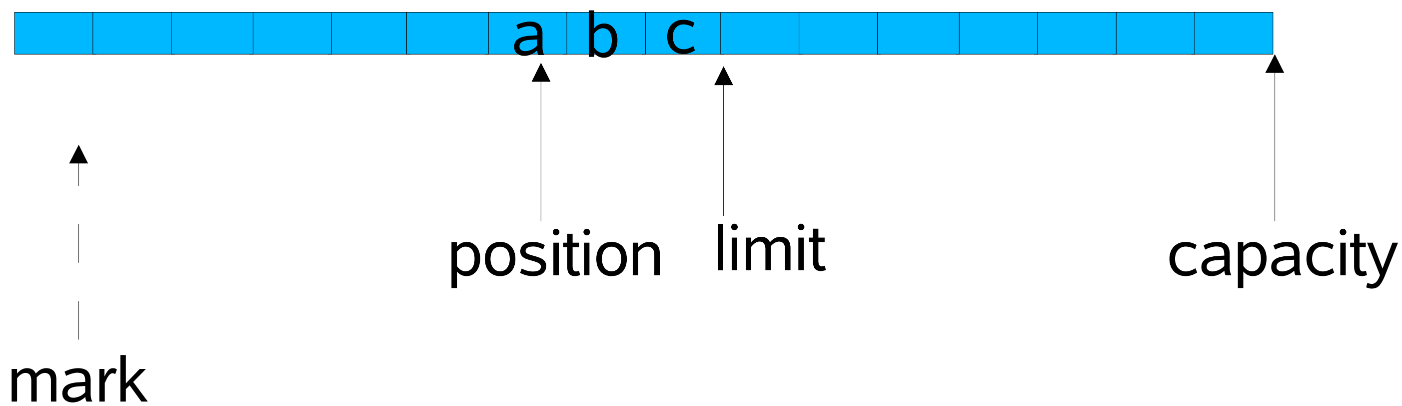
- Instead of a single service request,
  - Client connects
  - Client sends a series of messages/requests
  - Client disconnects
- Examples
  - Databases and Transaction monitors
  - Multi-participant games, chat, etc
- Can extend basic network service patterns
  - Handle many relatively long-lived clients
  - Track client and session state (including drops)
  - Distribute services across multiple hosts

API Walkthrough

- Buffer
- ByteBuffer
  - (CharBuffer, LongBuffer, etc not shown.)
- Channel
- SelectableChannel
- SocketChannel
- ServerSocketChannel
- FileChannel
- Selector
- SelectionKey

Buffer

```
abstract class Buffer {
  int     capacity();
  int     position();
  Buffer  position(int newPosition);
  int     limit();
  Buffer  limit(int newLimit);
  Buffer  mark();
  Buffer  reset();
  Buffer  clear();
  Buffer  flip();
  Buffer  rewind();
  int     remaining();
  boolean hasRemaining();
  boolean isReadOnly();
}
```



ByteBuffer (1)


```
abstract class ByteBuffer extends Buffer {
  static ByteBuffer allocateDirect(int capacity);
  static ByteBuffer allocate(int capacity);
  static ByteBuffer wrap(byte[] src, int offset, int len);
  static ByteBuffer wrap(byte[] src);

  boolean      isDirect();
  ByteOrder    order();
  ByteBuffer   order(ByteOrder bo);
  ByteBuffer   slice();
  ByteBuffer   duplicate();
  ByteBuffer   compact();
  ByteBuffer   asReadOnlyBuffer();
  byte         get();
  byte         get(int index);
  ByteBuffer   get(byte[] dst, int offset, int length);
  ByteBuffer   get(byte[] dst);
  ByteBuffer   put(byte b);
  ByteBuffer   put(int index, byte b);
  ByteBuffer   put(byte[] src, int offset, int length);
  ByteBuffer   put(ByteBuffer src);
  ByteBuffer   put(byte[] src);
  char         getChar();
  char         getChar(int index);
  ByteBuffer   putChar(char value);
  ByteBuffer   putChar(int index, char value);
  CharBuffer   asCharBuffer();
```

ByteBuffer (2)

```
   short          getShort();
   short          getShort(int index);
   ByteBuffer     putShort(short value);
   ByteBuffer     putShort(int index, short value);
   ShortBuffer    asShortBuffer();
   int            getInt();
   int            getInt(int index);
   ByteBuffer     putInt(int value);
   ByteBuffer     putInt(int index, int value);
   IntBuffer      asIntBuffer();
   long           getLong();
   long           getLong(int index);
   ByteBuffer     putLong(long value);
   ByteBuffer     putLong(int index, long value);
   LongBuffer     asLongBuffer();
   float          getFloat();
   float          getFloat(int index);
   ByteBuffer     putFloat(float value);
   ByteBuffer     putFloat(int index, float value);
   FloatBuffer    asFloatBuffer();
   double         getDouble();
   double         getDouble(int index);
   ByteBuffer     putDouble(double value);
   ByteBuffer     putDouble(int index, double value);
   DoubleBuffer   asDoubleBuffer();
}
```

Channel

```
interface Channel {
  boolean isOpen();
  void    close() throws IOException;
}

interface ReadableByteChannel extends Channel {
  int     read(ByteBuffer dst) throws IOException;
}

interface WritableByteChannel  extends Channel {
  int     write(ByteBuffer src) throws IOException;
}

interface ScatteringByteChannel extends ReadableByteChannel {
  int     read(ByteBuffer[] dsts, int offset, int length)
            throws IOException;
  int     read(ByteBuffer[] dsts) throws IOException;
}

interface GatheringByteChannel extends WritableByteChannel {
  int     write(ByteBuffer[] srcs, int offset, int length)
            throws IOException;
  int     write(ByteBuffer[] srcs) throws IOException;
}
```

SelectableChannel

```
abstract class SelectableChannel implements Channel {
  int           validOps();
  boolean       isRegistered();

  SelectionKey keyFor(Selector sel);
  SelectionKey register(Selector sel, int ops)
                   throws ClosedChannelException;

  void          configureBlocking(boolean block)
                   throws IOException;
  boolean       isBlocking();
  Object        blockingLock();
}
```

SocketChannel

```
abstract class SocketChannel implements ByteChannel ... {
  static SocketChannel open() throws IOException;

  Socket  socket();
  int     validOps();
  boolean isConnected();
  boolean isConnectionPending();
  boolean isInputOpen();
  boolean isOutputOpen();

  boolean connect(SocketAddress remote) throws IOException;
  boolean finishConnect() throws IOException;
  void    shutdownInput() throws IOException;
  void    shutdownOutput() throws IOException;

  int     read(ByteBuffer dst) throws IOException;
  int     read(ByteBuffer[] dsts, int offset, int length)
              throws IOException;
  int     read(ByteBuffer[] dsts) throws IOException;

  int     write(ByteBuffer src) throws IOException;
  int     write(ByteBuffer[] srcs, int offset, int length)
              throws IOException;
  int     write(ByteBuffer[] srcs) throws IOException;
}
```

ServerSocketChannel

```
abstract class ServerSocketChannel extends ... {
  static ServerSocketChannel open() throws IOException;

  int            validOps();
  ServerSocket   socket();
  SocketChannel accept() throws IOException;
}
```

FileChannel

```
abstract class FileChannel implements ... {
  int  read(ByteBuffer dst);
  int  read(ByteBuffer dst, long position);
  int  read(ByteBuffer[] dsts, int offset, int length);
  int  read(ByteBuffer[] dsts);
  int  write(ByteBuffer src);
  int  write(ByteBuffer src, long position);
  int  write(ByteBuffer[] srcs, int offset, int length);
  int  write(ByteBuffer[] srcs);
  long position();
  void position(long newPosition);
  long size();
  void truncate(long size);
  void force(boolean flushMetaDataToo);
  int  transferTo(long position, int count,
                  WritableByteChannel dst);
  int  transferFrom(ReadableByteChannel src,
                    long position, int count);
  FileLock lock(long position, long size, boolean shared);
  FileLock lock();
  FileLock tryLock(long pos, long size, boolean shared);
  FileLock tryLock();
  static final int MAP_RO, MAP_RW,  MAP_COW;
  MappedByteBuffer map(int mode, long position, int size);
}
```

NOTE: ALL methods throw IOException

Selector

```
abstract class Selector {
  static Selector open() throws IOException;
  Set  keys();
  Set  selectedKeys();
  int  selectNow() throws IOException;
  int  select(long timeout) throws IOException;
  int  select() throws IOException;
  void wakeup();
  void close() throws IOException;
}
```

SelectionKey

```
abstract class SelectionKey {
  static final int  OP_READ,    OP_WRITE,
                    OP_CONNECT, OP_ACCEPT;
  SelectableChannel channel();
  Selector          selector();
  boolean           isValid();
  void              cancel();
  int               interestOps();
  void              interestOps(int ops);
  int               readyOps();
  boolean           isReadable();
  boolean           isWritable();
  boolean           isConnectable();
  boolean           isAcceptable();
  Object            attach(Object ob);
  Object            attachment();
}
```