# Scalable IO in Java

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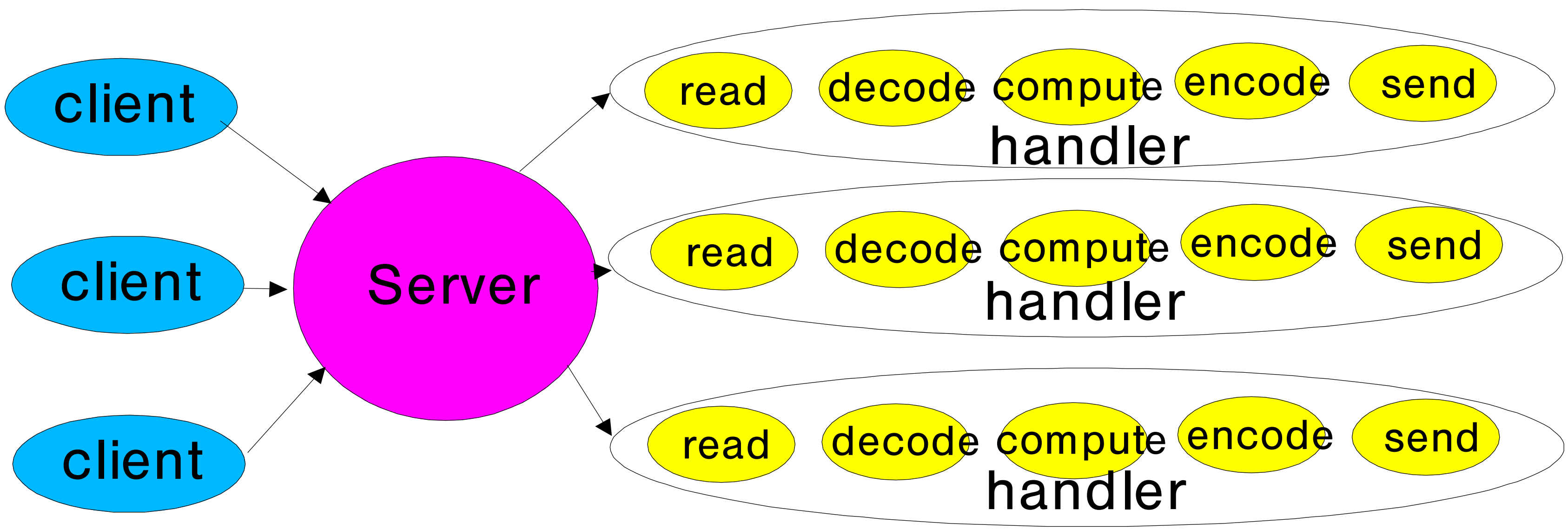
# Outline

- 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) { /* ... */ }
  }
}
```

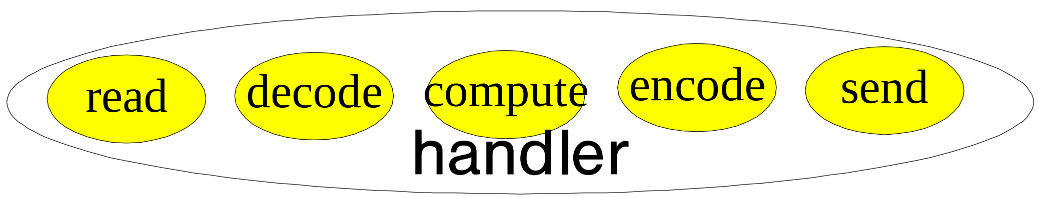
*Note: most exception handling elided from code examples*

# 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



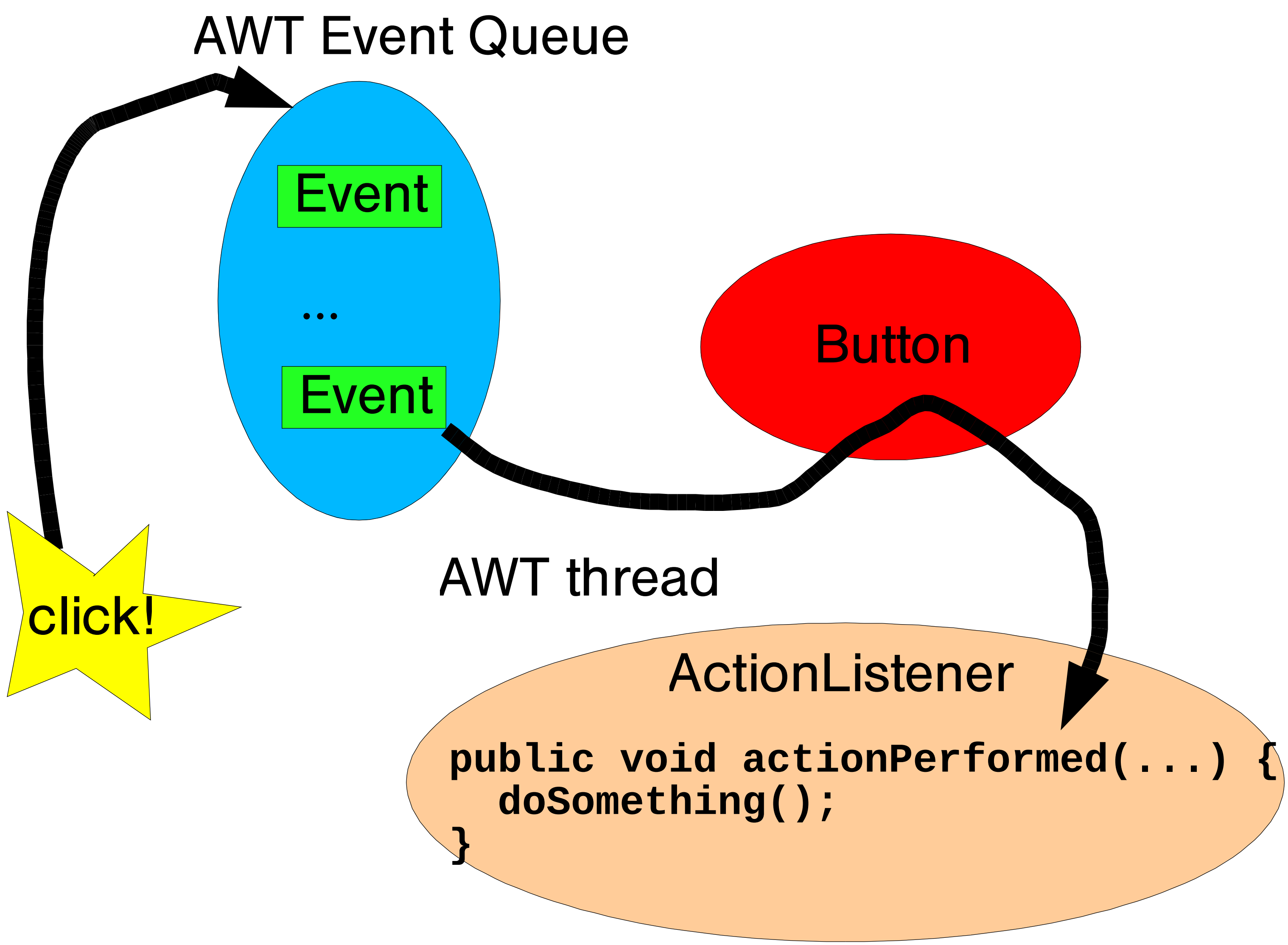

- Basic mechanisms supported in java.nio
  - Non-blocking reads and writes
  - Dispatch tasks associated with sensed IO events
- Endless variation possible
  - A family of event-driven designs

# 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





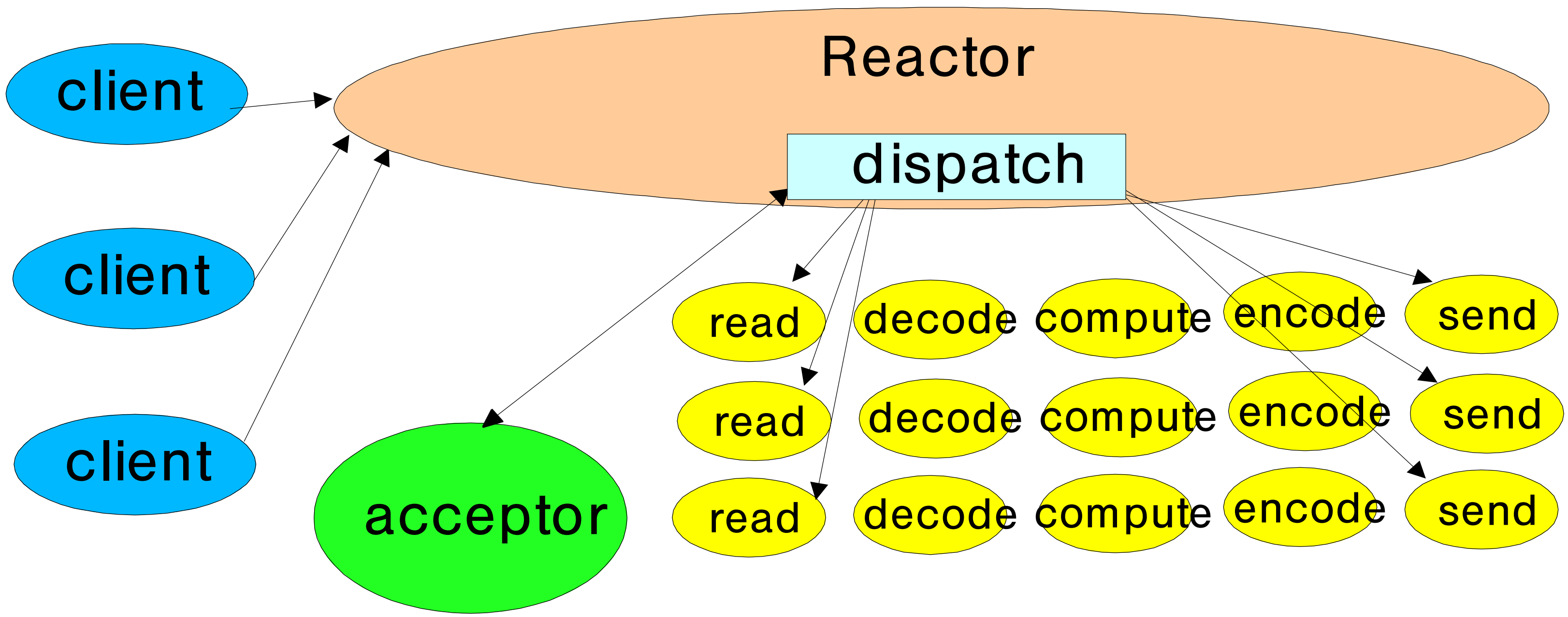

Event-driven IO uses similar ideas but in different designs

# 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.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();
  */
```

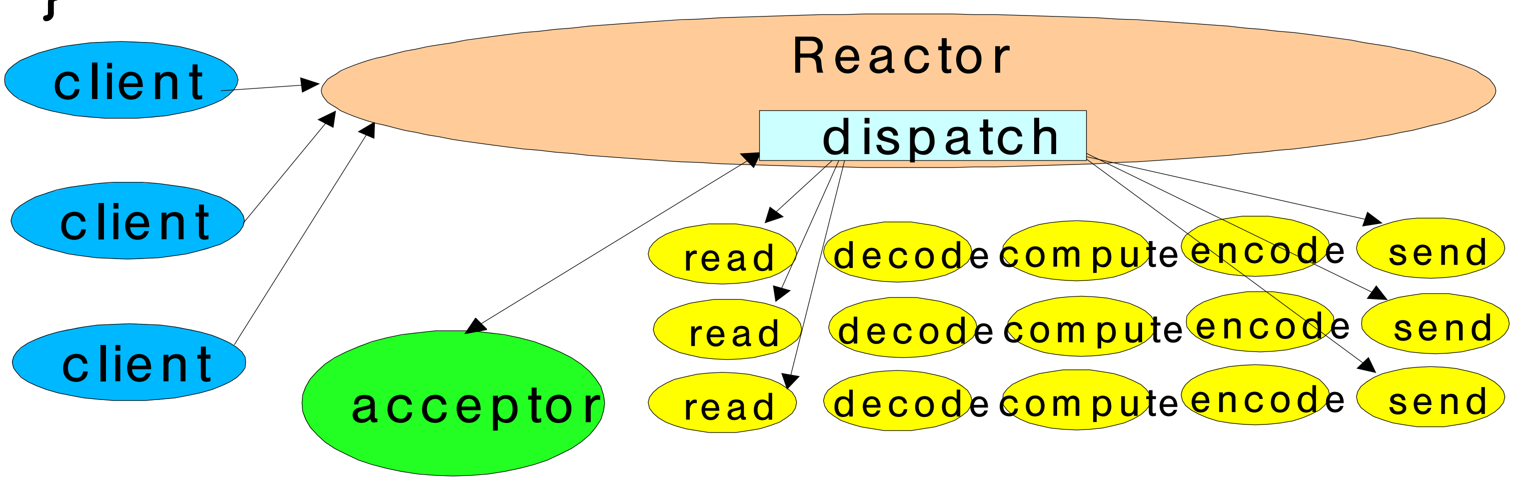
# Reactor 2: Dispatch Loop

```
// 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();
  }
```

# 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;
    // 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();
    }
  }
}
```

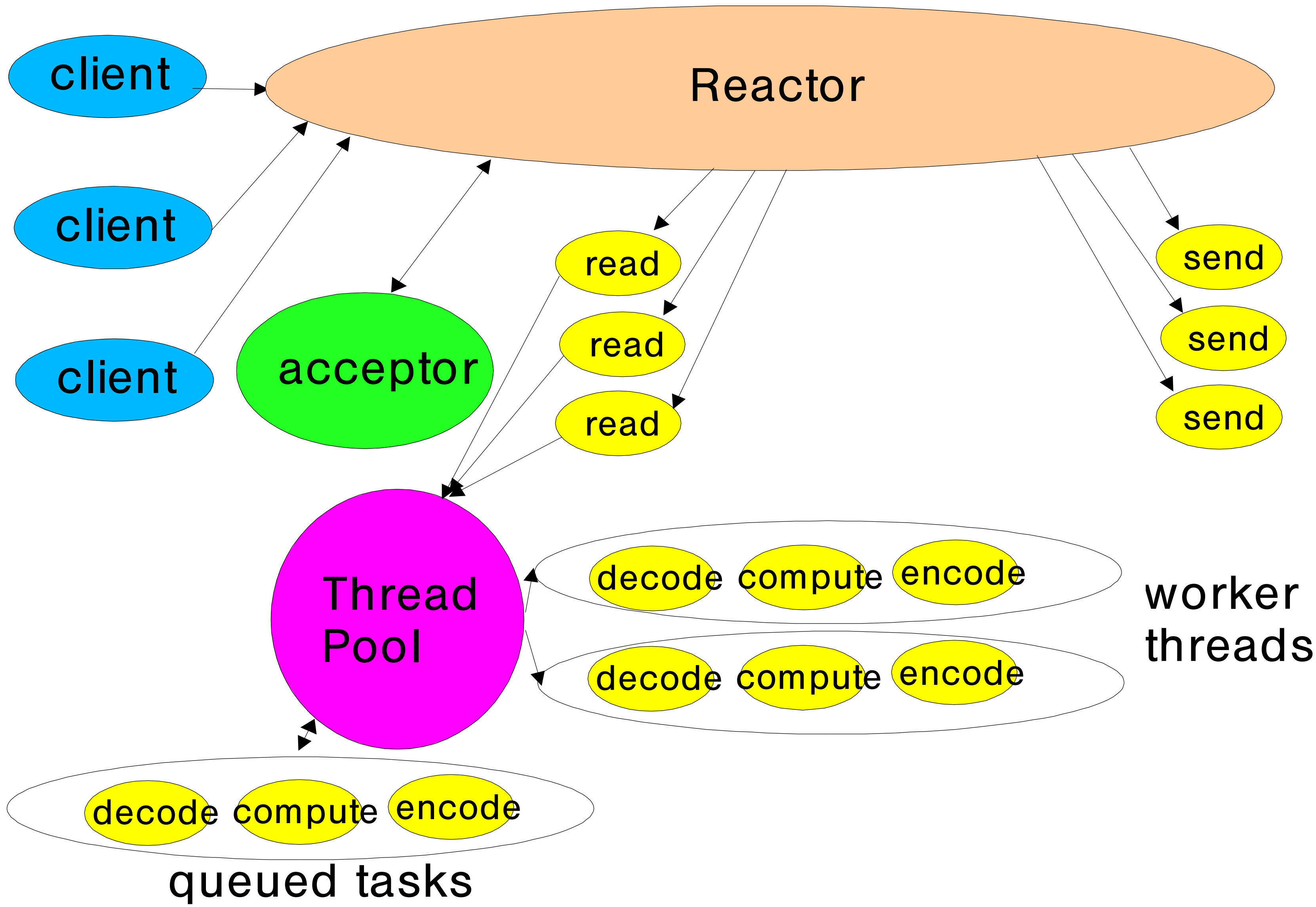
# Multithreaded Designs

- 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

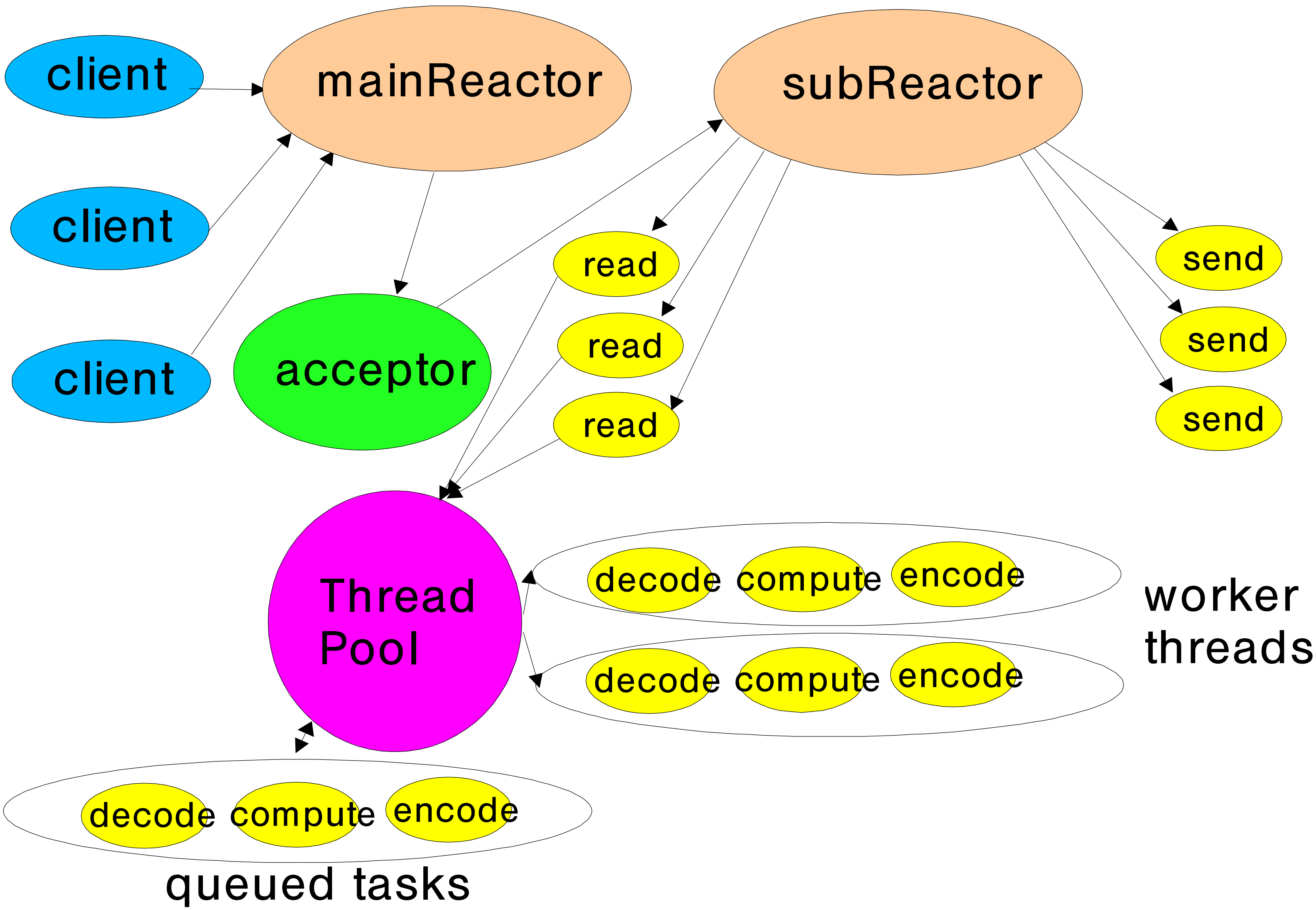
- A tunable worker thread pool
- Main method `execute(Runnable r)`
- Controls for:
  - The kind of task queue (any Channel)
  - Maximum number of threads
  - Minimum number of threads
  - "Warm" versus on-demand threads
  - Keep-alive interval until idle threads die
    - to be later replaced by new 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

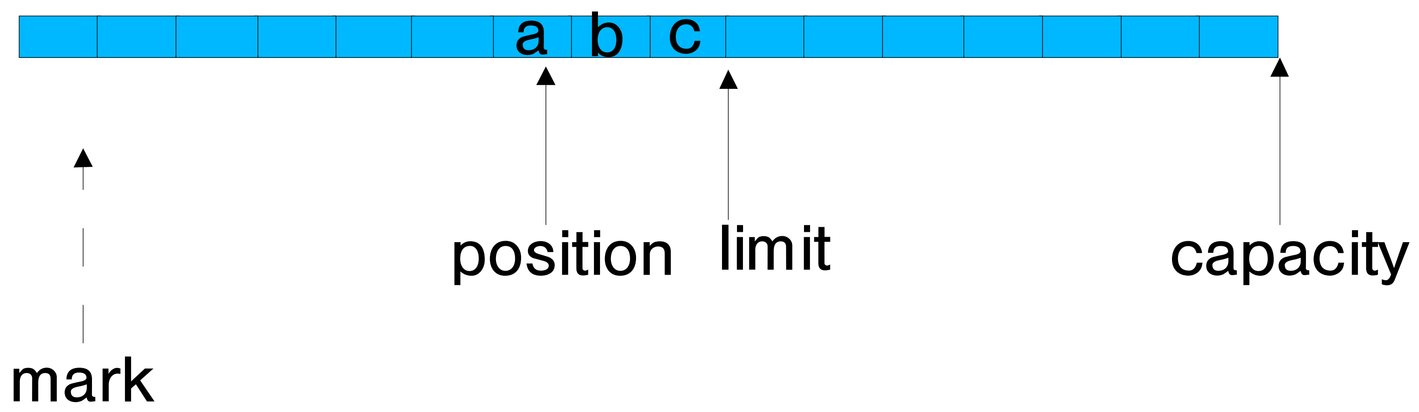
- Instead of a single service request,
  - Client connects
  - Client sends a series of messages/requests
  - Client disconnects
- Examples
  - Databases and Transaction monitors
  - Multi-participant games, chat, etc
- Can extend basic network service patterns
  - Handle many relatively long-lived clients
  - 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();
}
```