Protocol Analysis

17-654/17-764

Analysis of Software Artifacts

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Take-Aways

- Protocols define temporal ordering of events
  - Can often be captured with state machines
- Protocol analysis needs to pay attention to
  - Interprocedural control flow
  - Aliasing of objects
- Disjoint sets and capabilities can handle aliasing correctly

Agenda

- Example protocols
  - Modeling protocols as state machines
- Protocol analysis approaches
  - Annotations vs. interprocedural analyses
- Aliasing challenges
  - Tracking aliases in methods and fields
- Protocol implementation checking

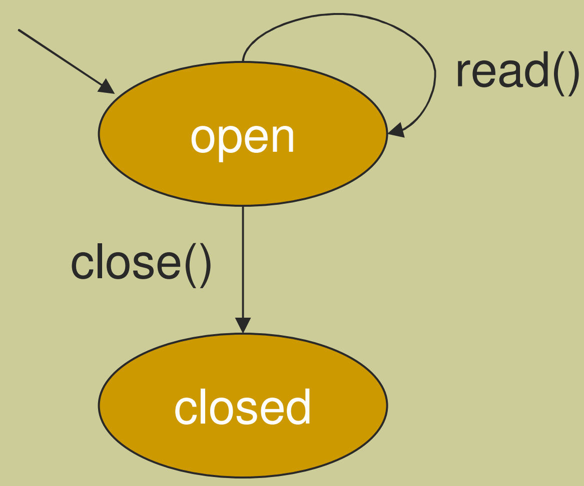
Streams can be read until they're closed

```
public interface InputStream {
    public int read();
    public void close();
}
```

Stream sample client

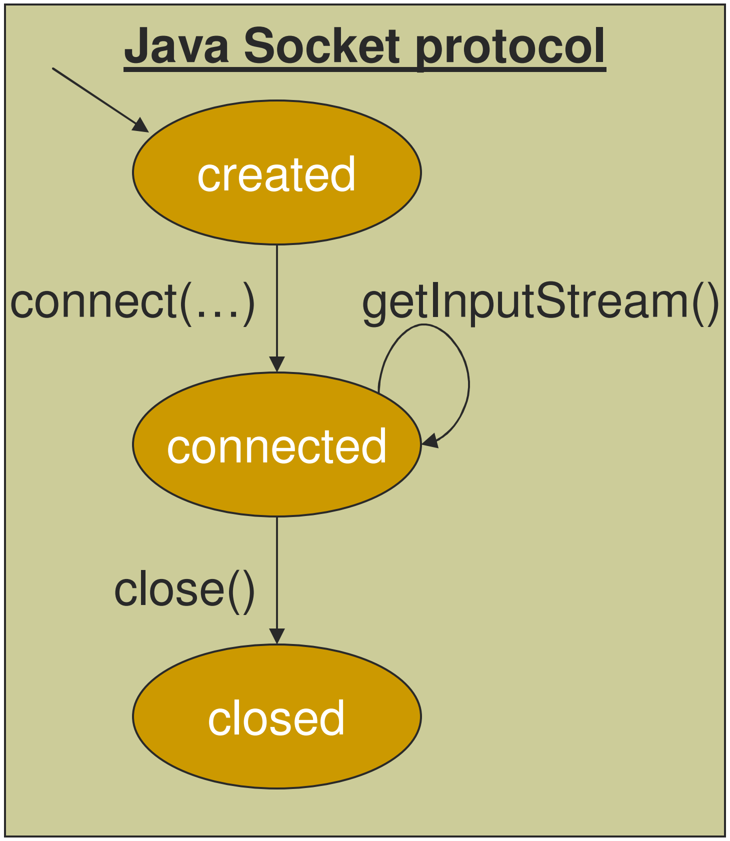
```
InputStream f = new FileInputStream(…);
int c = f.read();  // read first character
while(c >= 0) {
    // do something with c
    c = f.read();   // read next character
}
f.close();
```

Stream protocol state machine

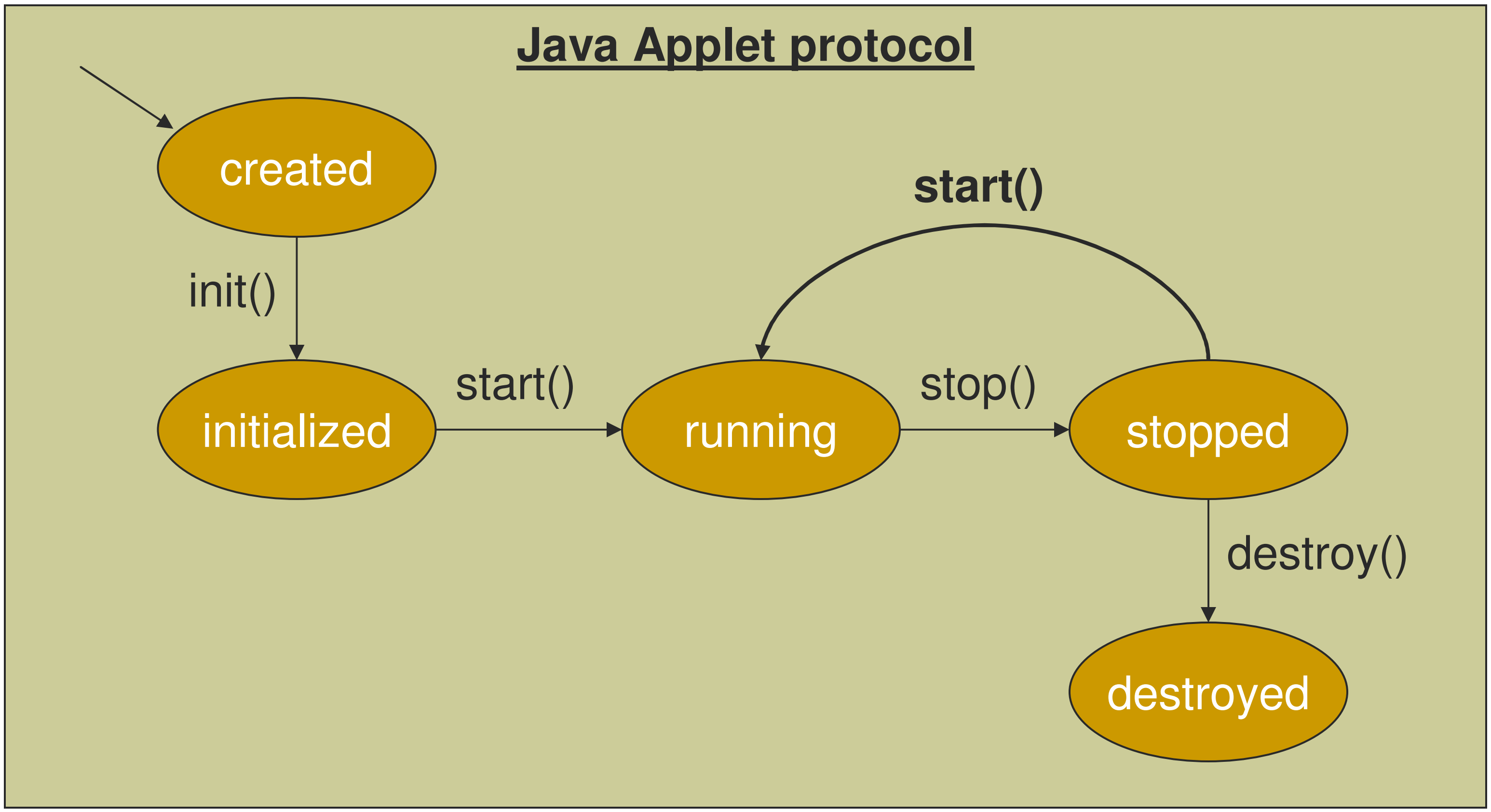


Sockets go through a well-defined sequence of states

```
@States({“created”, “connected”, “closed”})
public class Socket {
   @Creates(“created”)
   public Socket()

   @ChangesState(“created”, “connected”)
   public void connect(…)

   @InState(“connected”)
   public InputStream getInputStream()

   @InState(“connected”)
   public OutputStream getOutputStream()

   @ChangesState(“connected”, “closed”)
   public void close();
}
```

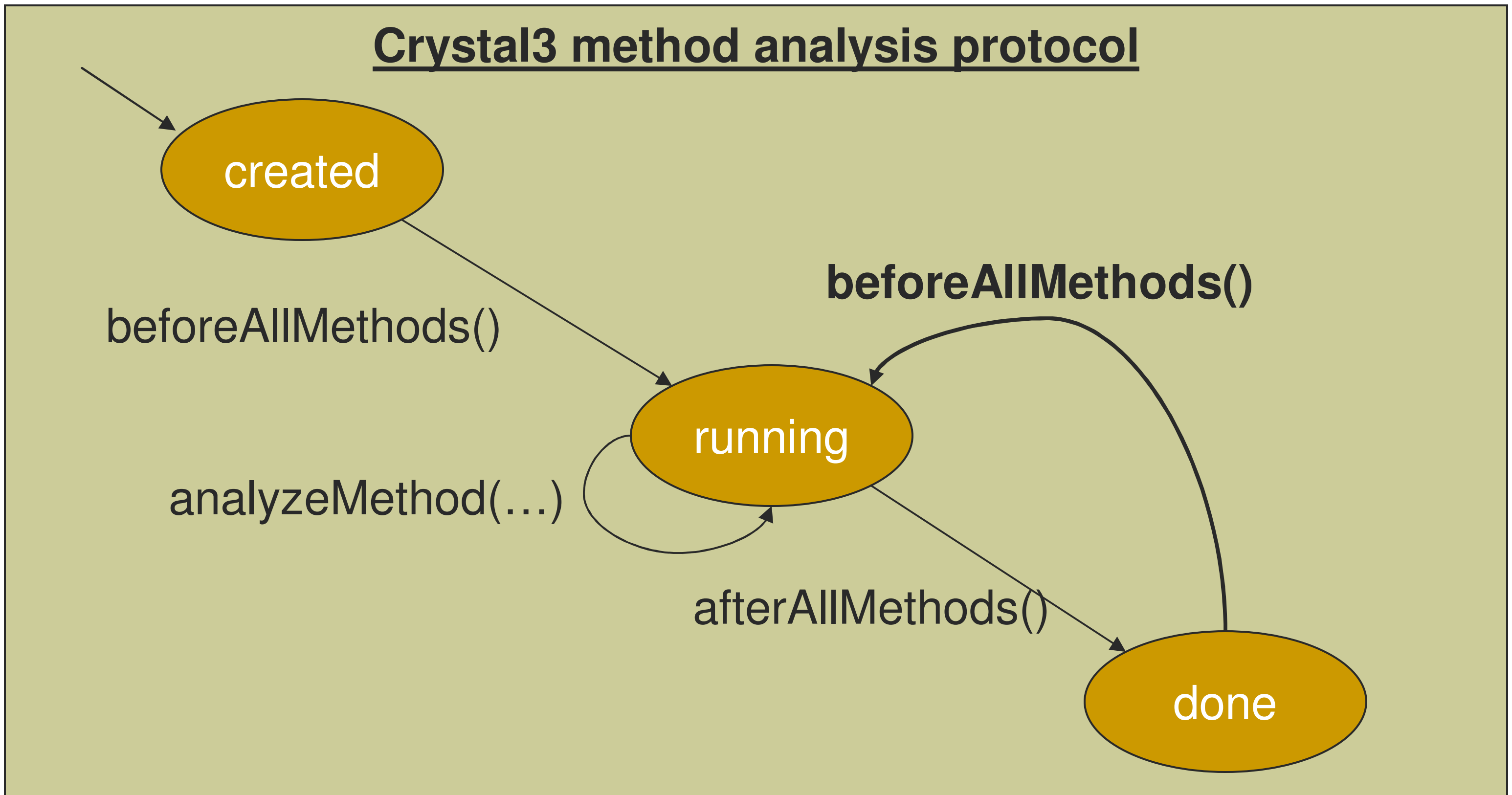


Java Applets have a funny back edge



Example based on: G. Fairbanks, D. Garlan & W. Scherlis. Design fragments make using frameworks easier. In *Proceedings of OOPSLA'06*, pp. 75-88. ACM Press, 2006.

Crystal3 analyses have the same back edge



Unawareness of this back edge can lead to outdated error reports

Protocols constrain temporal ordering of events

- Protocols define restrictions on which methods can be called when
- Clients have to follow protocols in order to avoid runtime errors
- Protocols can often be modeled as **state machines**

Protocol documentation…

- Protocols are informally documented
  - Example: java.io.InputStream
    - Detailed Javadoc for every method
  - Example: java.net.Socket
    - Exceptions describe when methods *cannot* be called
- Not always complete and precise

…formalized in various ways

Formalization	**Socket example**
Annotations on classes and methods	@States({“created”, “connected”, “closed”}) **public class** Socket { @Creates(“created”) **public** Socket() @ChangesState(“created”, “connected”) **public void** connect(…) …
Regular expressions	connect (getInputStream | getOutputStream)* close
State machine defined in one place (similar to Metal)	created : connect(…) -> connected connected : getInputStream() -> connected | close() -> closed

We will use annotations on classes and methods

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Protocol analysis tracks states of variables

Code	**Post-state**
Socket sock = **new** Socket();	Created
sock.connect(**new** InetSocketAddress("www.cs.cmu.edu",80));	Connected
InputStream in = sock.getInputStream();	Connected
sock.close();	Closed

- What if *sock* is assigned to another variable?
- What if *sock* is assigned to a field?
- What if *sock* is passed to another method?

Calling other methods

```
public class SocketClient {

private String readSocket(Socket s) {
    InputStream in = s.getInputStream();
    … // read and return string
}
public String readRemoteData() {
    Socket sock = new Socket();
    sock.connect(new InetSocketAddress(
            "www.cs.cmu.edu",80));
    String result = readSocket(sock);
    sock.close();
    return result;
} }
```

Is this call ok?

Is this call ok?

Need to handle inter-procedural control flow

Interprocedural analysis techniques

- Need to handle inter-procedural control flow
  - Every method call could potentially affect analysis results
  - Need to figure out what happens in called methods
- Some possible approaches
  - Default assumptions
  - Interprocedural CFG
  - More annotations

Defaults too inflexible for protocol analysis

- Simple approach: **default assumptions**
  - Assumption about method parameters and result
  - Check that call and return sites respect the default
  - Example: Maybe-null assumption in null analysis (HW6)
    - Assume that method parameters may be null
    - Check methods with that assumption
    - All call and return sites automatically maybe-null
- No reasonable default for protocol analysis
  - “Any” state too imprecise (lots of false positives)
  - Optimistic assumption (a particular state) might be wrong a lot of the times

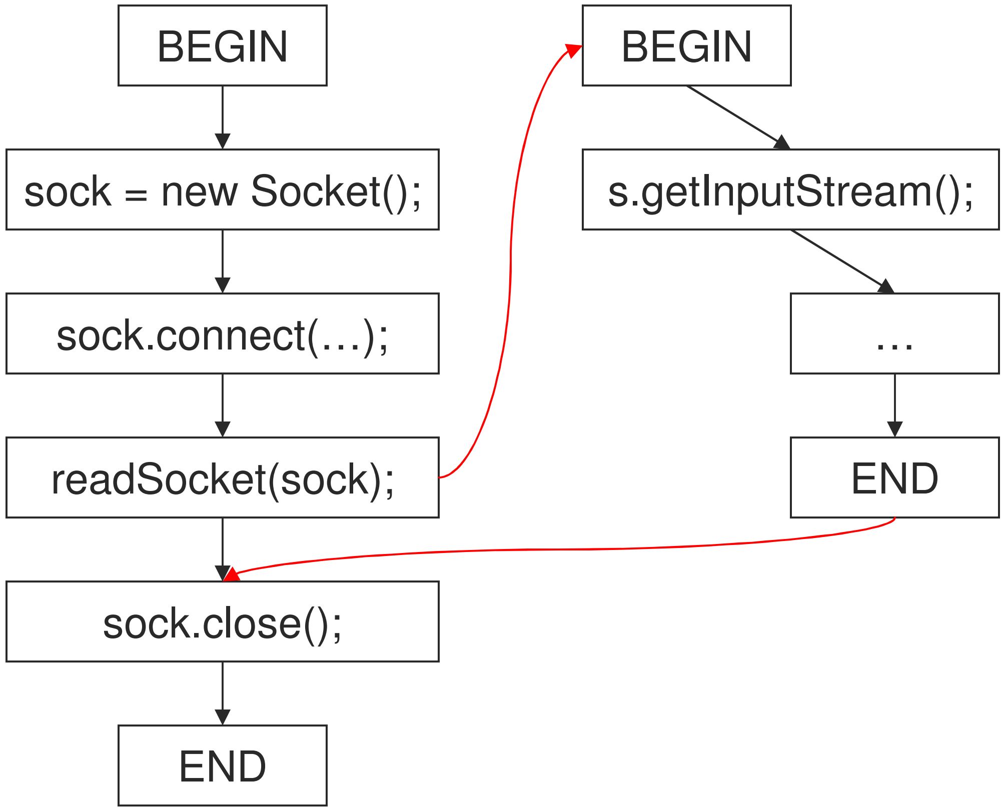
Interprocedural CFG "inlines" method calls

Interprocedural CFG

- Pretend that called methods are part of current method
- Every method appears once

Problem: scalability

- One big CFG for the entire program



Interprocedural CFG hard to use at scale

Assume and Check Annotations

```
String readSocket(
        @InState("connected") Socket s) {
    InputStream in = s.getInputStream();
    … }
```

- Annotations
  - Starting dataflow value for all parameters
  - Dataflow value for result
- Verification
  - Initial info: starting value for parameters
  - Verify result $\sqsubseteq$ $\text{annotation}_{\text{result}}$
    - Ending value for result obeys annotation
  - Verify arg $\sqsubseteq$ $\text{annotation}_{\text{arg}}$
    - Actual arguments obey annotations on formal parameter

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Looks familiar? Aliasing is a problem that you can easily have

	t1	t2	t3
SimpleProtocolTest t1 = **new** SimpleProtocolTest();	a	--	--
SimpleProtocolTest t2 = **new** SimpleProtocolTest();	a	a	--
SimpleProtocolTest t3 = t1;	a	a	a
t1.aToB(); // t1 alias t3 in b, t2 in a	b	a	a
t1 = t2; // t3 in b, t1 alias t2 in a	a	a	a
t1.aToB();	b	a	a
t3.bToC();	b	a	ERR
t2.inB(); // t1 alias t2 in b, t3 in c	b	ERR	

Spurious warnings

Aliasing = multiple names for the same thing

Track local aliases as disjoint sets (aka equivalence classes)

- Track aliased variables as disjoint sets
  - Lattice information
    - $A = \{ S1, \ldots, Sn \}$
    - S1, …, Sn disjoint sets of variables
  - Copy instructions x = y
    - Get y's aliases $S \in A$ where $y \in S$
    - Add x to S (and remove it from any other set)
  - Object allocations x = new C(…)
    - Remove x from existing sets
    - $A = A \cup \{ x \}$ (i.e., add new set with just x)
    - (Need to also set initial state for x)
- Track state for each disjoint set
  - Method calls x = y.m(…)
    - Get y's aliases $S = \{ y1, \ldots, yn \}$ where $y \in S$
    - Update S's state according to m's spec

Disjoint sets correctly handle local aliases in example

	aliasing	**t1**	**t2**	**t3**
SimpleProtocolTest t1 = **new** SimpleProtocolTest();	{t1}	a	--	--
SimpleProtocolTest t2 = **new** SimpleProtocolTest();	{t1}, {t2}	a	a	--
SimpleProtocolTest t3 = t1;	{t1,t3}, {t2}	a	a	a
t1.aToB(); // t1 alias t3 in b, t2 in a	{t1,t3}, {t2}	b	a	b
t1 = t2; // t3 in b, t1 alias t2 in a	{t1,t2}, {t3}	a	a	b
t1.aToB();	{t1,t2}, {t3}	b	b	b
t3.bToC();	{t1,t2}, {t3}	b	b	c
t2.inB(); // t1 alias t2 in b, t3 in c	{t1,t2}, {t3}	b	b	c

States of aliased variables are updated correctly

Calling other methods can affect fields

```
public class AliasingFun() {
@InState("b") private SimpleProtocolTest t2;

private void callField() {
    t2.inB();
}
public void aliasingFun() {
    SimpleProtocolTest t1 = …
    t1.aToB();
    internal(t1);
    t1.bToC();
    callField();
    …
}
```

```
private void internal(@InState("b") SimpleProtocolTest t) {
    t2 = t;
}
```

Our approach so far does not issue any warnings

Field annotation makes this call go through

t2 is actually in "c" when called

This call violates t2's annotation

t2 aliases t **and t1**

Fields hold on to objects beyond duration of methods

Aliasing through fields different from local variables

- Aliasing in local variables affects current method only
  - We can handle that with disjoint sets
- Fields hold on to objects
  - Assignment to field in one method can affect other methods
  - Changing state of local variable can inadvertently change state of field
- Other situations with similar problems?

Capabilities track whether an object is accessible

- **Capabilities**: Access objects only if not stored in a field
- Exactly one capability for each object
  - Can call methods only if capability available
    - x.m(…) only valid if caller has capability for x
  - Capability created with **new**
  - Field assignments x.f = y
    - “Capture” capability for y
- Annotate methods with capabilities
  - @Captured if capability needed but not returned
  - @Borrowed if capability needed and returned

Capabilities correctly handle field assignments and method calls

```
public class AliasingFun() {
@InState("b") private SimpleProtocolTest t;

private void callField() {
    t.inB();
}
public void aliasingFun() {
    SimpleProtocolTest t1 = new SimpleProtocolTest();
    t1.aToB();
    internal(t1);
    t1.bToC();
    callField();
    …
}
```

```
private void internal(@Borrowed SimpleProtocolTest t) {
}
private void internal(@Captured SimpleProtocolTest t) {
    t2 = t;
}
```

Error: No capability for t1

Disjoint sets and capabilities can handle aliasing correctly

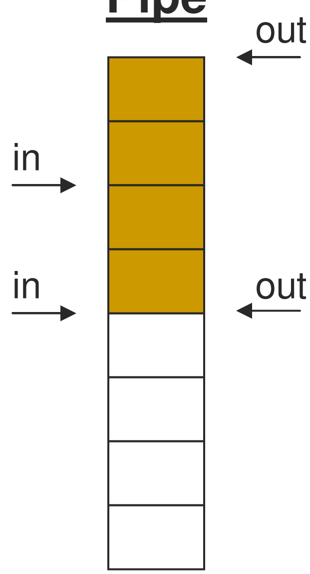
- Track disjoint sets of local aliases
  - Handle copies between local variables
- One capability for each object
  - Handle assignments to fields
- Capability annotations on methods
  - Handle aliasing during method calls

F. Smith, D. Walker & G. Morrisett. Alias types. In *European Symposium on Programming*, pages 366-381. Springer, 2000.
R. DeLine & M. Fähndrich. Enforcing high-level protocols in low-level software. In *ACM Conference on Programming Language Design and Implementation*, pages 59-69, 2001.

Capabilities are sometimes not enough

- Source calls receive(byte) to deposit characters
- ReceivedLast() signals no more characters

Pipe



- Reader calls read() to retrieve characters
- Reader calls close() to close the pipe
- Unsafe to call close() before source finished

within eof closed

read() returns -1

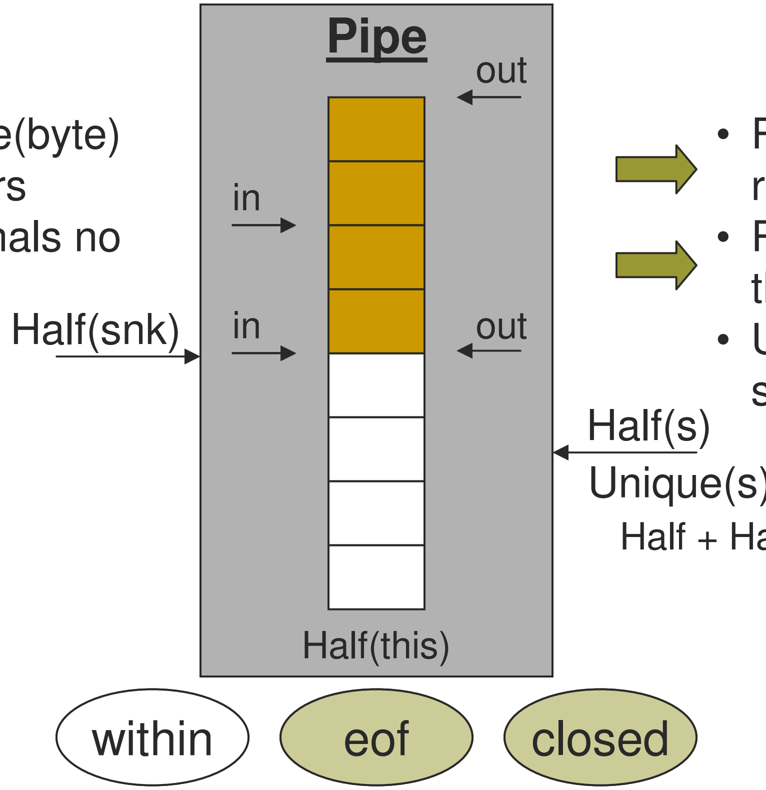
Pipe is modified through two independent aliases

Permissions for shared access

- Permissions generalize capabilities
  - Permission required for all object access
  - Many permissions to the same object can exist
  - But keep track of how many permissions there are
- Unique(x) is the only existing permission for object referenced by x
  - Similar to capability for x
- Half(x) is one of two permissions for x
  - Half(x) + Half(x) = Unique(x)

Permissions in pipe example

- Source calls receive(byte) to deposit characters
- ReceivedLast() signals no more characters



- Reader calls read() to retrieve characters
- Reader calls close() to close the pipe
- Unsafe to call close() before source finished

Half + Half => Unique

read() returns -1

Change to eof with Half permission
Unique permission needed to close the pipe

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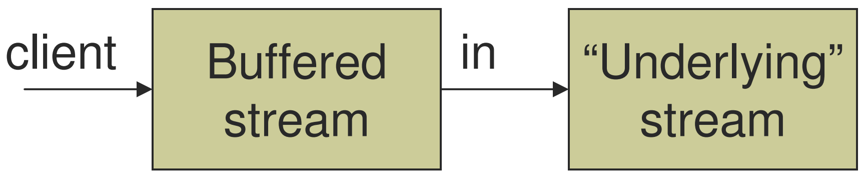
Implementation checking tracks changes to fields

- So far we looked at clients
  - Code calling methods on sockets etc.
  - Assumed that declared protocol was right
- Checking protocol implementations
  - Does *this* change state as declared?
  - **State changes = field manipulations**
    - Protocols ensure that “something” happened already (or has not happened yet)
    - “Something” can (only) be recorded in fields

State invariants define states in terms of fields

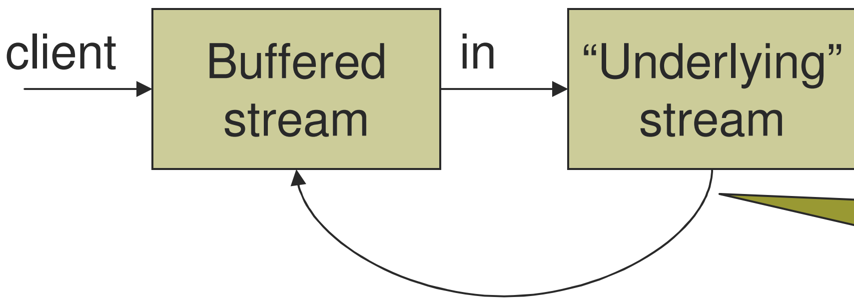



```
public class BufferedInputStream {
    private InputStream in;
    private byte[] buffer;
    private int pos, count;
    // open: in instate (within | eof) &&
              buffer != null &&
              0 ≤ pos ≤ count &&
              count ≤ buffer.length
    // closed: in == null && buffer == null
}
```

- **State invariants** constrain fields…
  - Constraints on field values
    - E.g., greater than zero or non-null
  - Expected state of referenced object
    - E.g., underlying stream should be “within” or “eof”
- …but only while in a particular state

close() will change fields accordingly

Don’t forget aliasing…!



What happens when the underlying stream calls back to the buffer?

public class BufferedInputStream {
    private InputStream in;
    private byte[] buffer;
    private int pos, count;
    // open: *in* **instate** (within | eof) &&
            buffer != **null** &&
            $0 \leq$ *pos* $\leq$ *count* &&
            count $\leq$ *buffer*.length
    // closed: *in* == **null** && *buffer* == **null**

As it turns out, such a re-entrant callback can violate *count*’s invariant, leading to an access to *buffer* outside its bounds.