RPC and Threads

Jinyang Li

These slides are based on lecture notes of 6.824

Labs are based on Go language

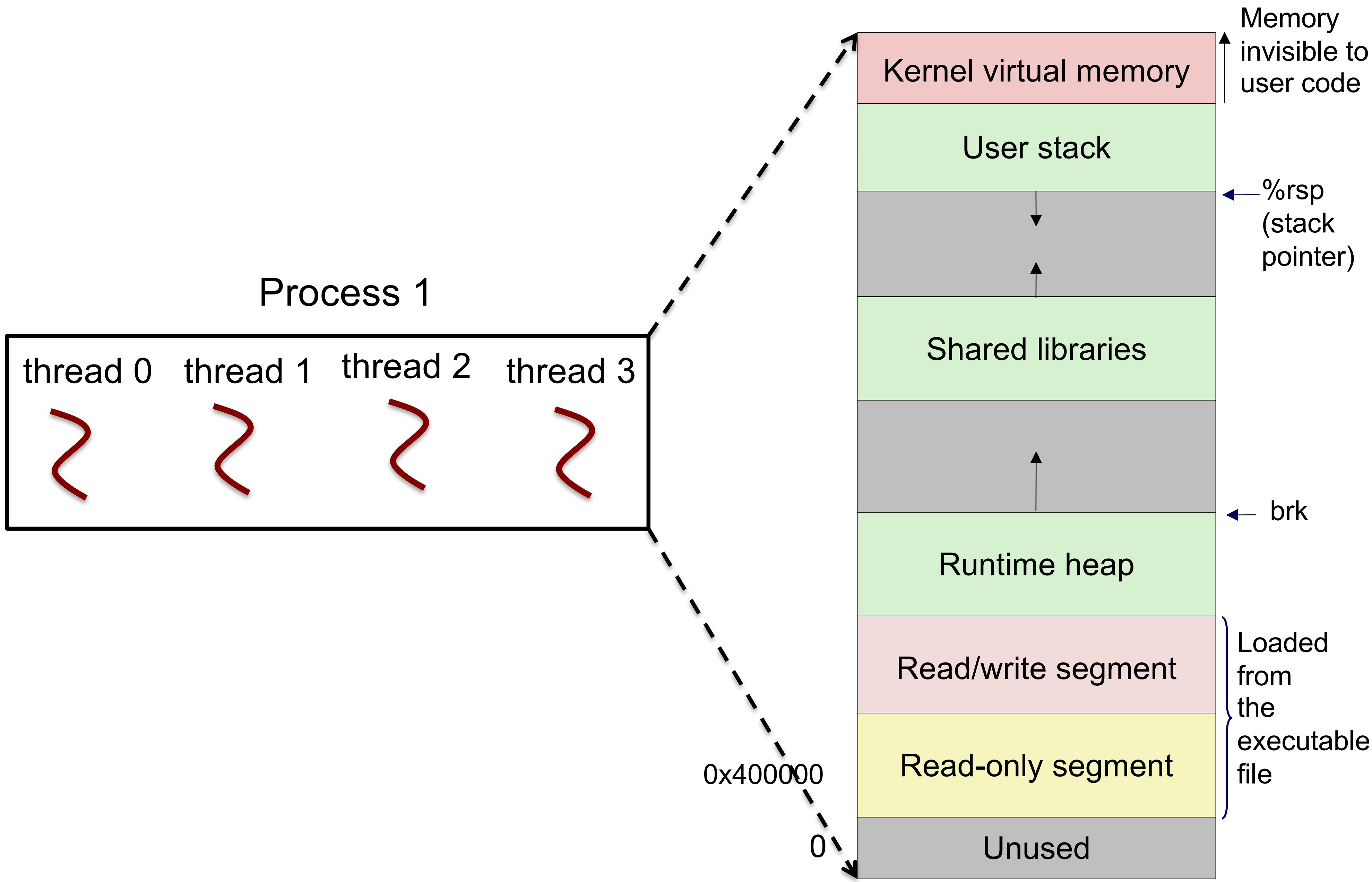
- Why Golang? (as opposed to the popular alternative: C++)
  - good support for concurrency
  - good support for RPC
  - garbage-collected (no use-after-free problems)
  - good and comprehensive library
- Notable systems built using Go
  - Dropbox's backend infrastructure
  - CoachroachDB

Threads

- Thread = “thread of execution”
  - allow one program to logically execute many things at once
  - Each thread has its own per-thread state:
    - program counter
    - registers
    - stack
  - All threads share memory (occupy same address space)

Golang refers to threads as goroutines

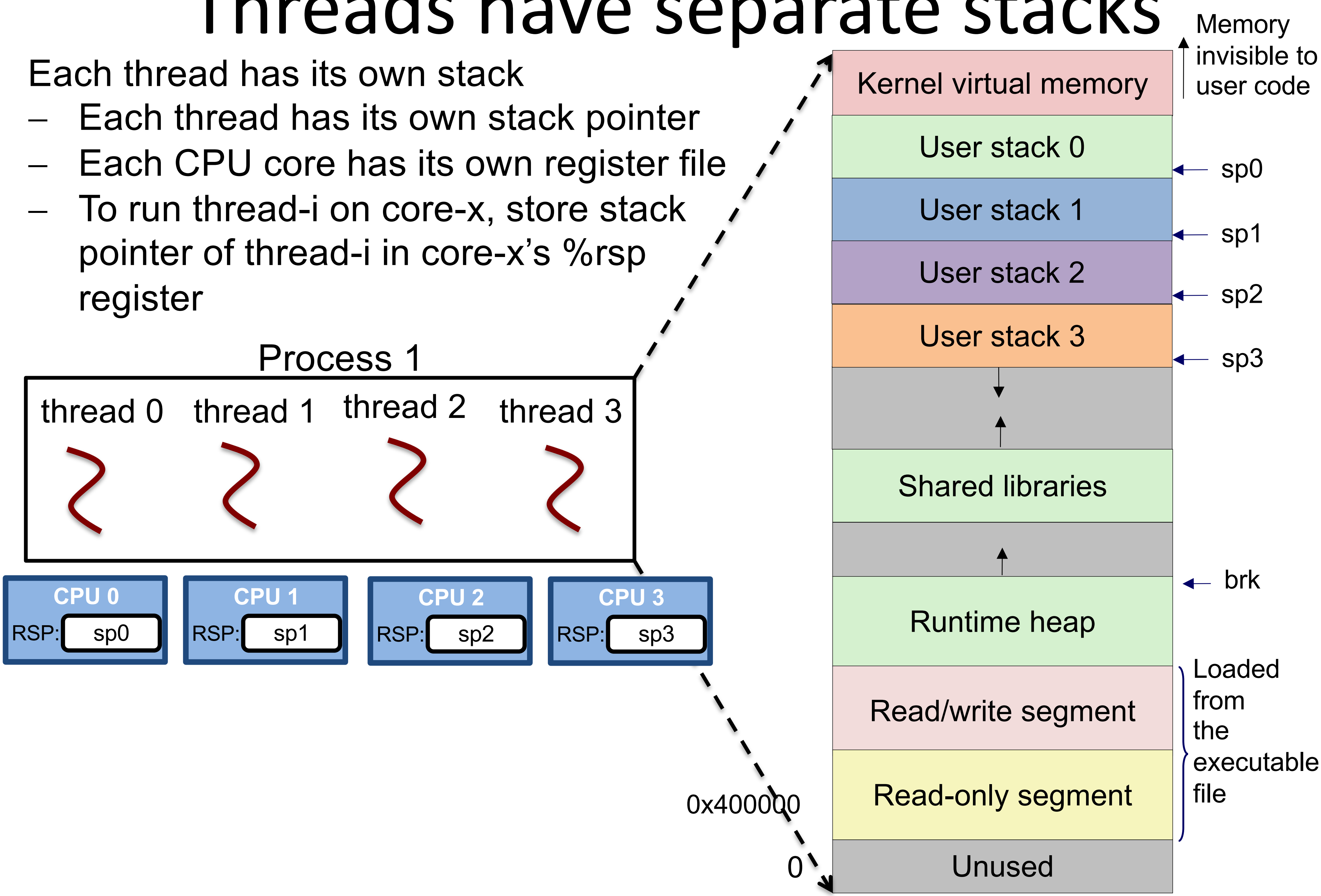
Threads share address space



Threads have separate stacks

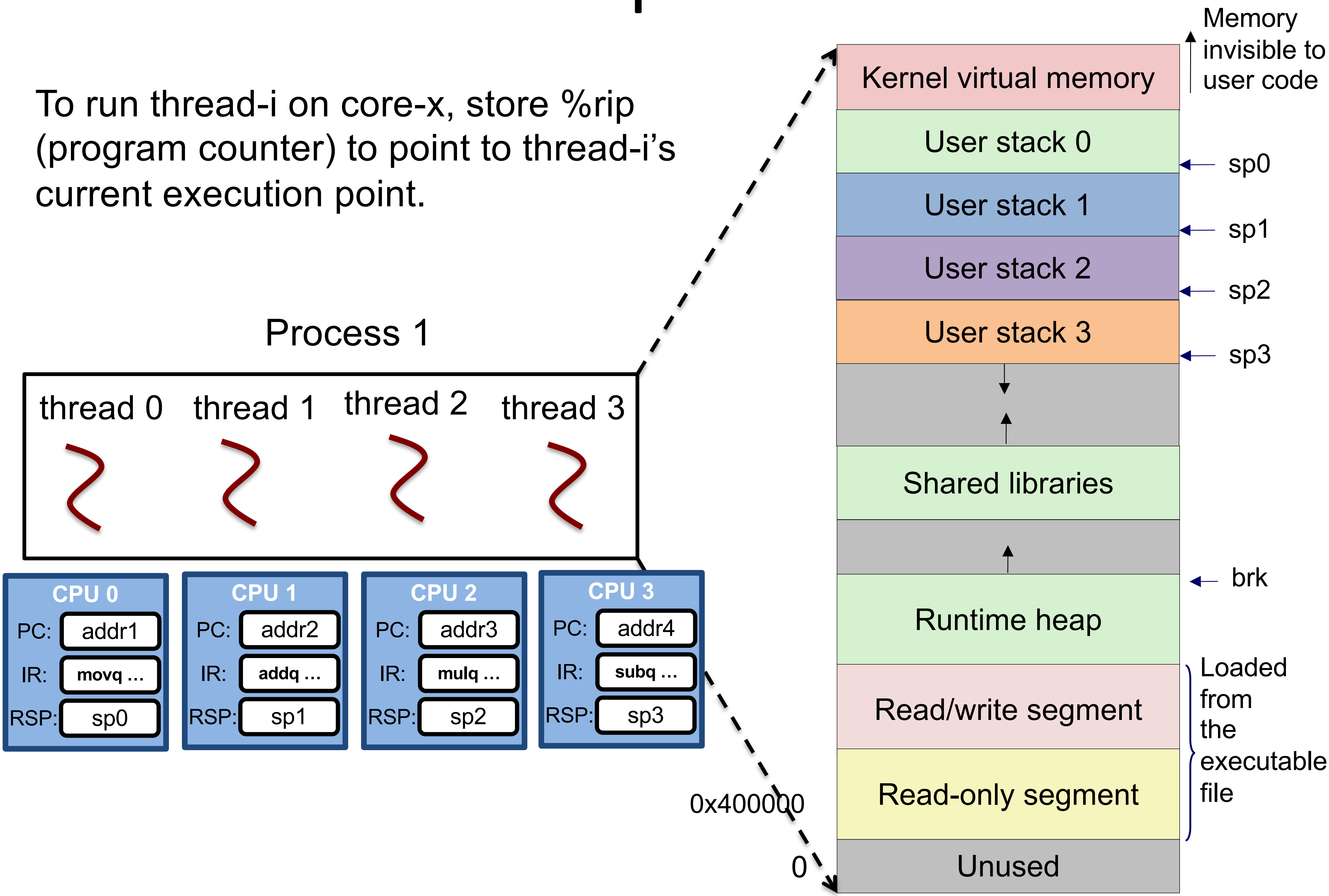
Each thread has its own stack

- Each thread has its own stack pointer
- Each CPU core has its own register file
- To run thread-i on core-x, store stack pointer of thread-i in core-x's %rsp register



Threads have separate control flow

To run thread-i on core-x, store %rip (program counter) to point to thread-i's current execution point.



Why threads and how many?

- Threads are created to exploit concurrency
  - I/O concurrency: while waiting for a response from another machine, process another request
  - Multicore: threads run parallel on many CPU cores
- Go encourages one to create many goroutines
  - many more than # of cores
  - Go runtime schedules threads on available cores
- Goroutines are more efficient than C++ threads
  - but still more expensive than function calls

Threading Challenges : races

- Races arise because of shared memory

```
var x int
for i := 0; i < 2; i++ {
      go func() {
            x++
      }()
}
```

Read x=0 into %rax

Incr %rax to 1

Write %rax=1 to x

Read x=0 into %rax
Incr %rax to 1
Write %rax=1 to x

go run –race main.go

Threading challenges: races

- Races due to shared memory

```
var x int
var mu sync.Mutex
for i := 0; i < 2; i++ {
      go func() {
            mu.Lock()
            defer mu.Unlock()
            x++
      }()
}
```

- defer is executed when the enclosing function returns
- Try to always put mu.Unlock in defer

go run –race main.go

Threading challenges: coordination

- Mechanism: Go channel
  - For passing information between goroutines
  - can be unbuffered or have a bounded-size buffer
  - Several threads can send/receive on same channel
    - Go runtime uses locks internally
  - Sending is blocked
    - when buffered channel is full
    - when no thread is ready to receive from unbuffered channel
  - Receiving is blocked
    - when channel is empty
  - Channel is closed to indicate the end
    - receiving from a closed channel returns error

Threading challenges: coordination

- Mechanism: Waitgroup
  - Used for waiting for a collection of threads to finish
  - Supports 3 methods:
    - Add(int x): add x (threads) to the collection
    - Done(): called when one thread has finished
    - Wait: blocks until all threads in the collection has finished

Channels and Waitgroups

```
func main() {

    workChan := make(chan int) //unbuffered channel
    go func() {
        for i := 1; i <= 20; i++ {
            workChan <- i
        }
    }()

   for i := 0; i < 5; i++ {
      go func() {
         for {
            n :=<- workChan
            f := computeFactorial(n)
            fmt.Printf("n=%d, f=%d\n", n, f)
         }
   }()

}
```

use
ve
from channel

Channels and WaitGroups

```
func main() {

    workChan := make(chan int, 20) //buffer size 20
    for i := 1; i <= 20; i++ {
        workChan <- i
    }

    var wg sync.WaitGroup
    for i := 0; i < 5; i++ {
        wg.Add(1)
        go func() {
            defer wg.Done()
            for {
                n :=<- workChan

                f := computeFactorial(n)
                fmt.Printf(“n=%d, f=%d\n”, n, f)
            }
    }()
    wg.Wait()
}
```

Channels and WaitGroups

```
func main() {

    workChan := make(chan int, 20) //buffer size 20
    for i := 1; i <= 20; i++ {
        workChan <- i
    }
    close(workChan)
    var wg sync.WaitGroup
    for i := 0; i < 5; i++ {
        wg.Add(1)
        go func() {
            defer wg.Done()
            for {
                n, ok :=<- workChan
                if !ok { //alternative: for n:= range workChan
                    break
                }
                f := computeFactorial(n)
                fmt.Printf("n=%d, f=%d\n", n, f)
            }
    }()
    wg.Wait()
}
```

RPC

- A key piece of infrastructure when building DS
- RPC's goals:
  - easier to program than raw sockets
  - hide details of client/server communication
- Ideal RPC interface

```
Client:

z = fn(x, y)
```

```
Server:

fn(x, y) {
    ...
    return z
}
```

Example: KV service (Server-side)

```
import “net/rpc”
type PutArgs struct {
      Key string
      Value string
}
type PutReply struct {
      Err Err
}
type KV struct {
      mu sync.Mutex
      keyvalue map[st
}
func (kv *KV) Put(args *PutArgs, reply *PutReply) error {
      kv.mu.Lock()
      defer kv.mu.Unlock()
      kv.keyvalue[args.Key] = args.Value
      reply.Err = OK
      return nil
}
```

- RPC handlers have a certain signature (two arguments, second being a pointer, return type error)
- RPC handlers must be exported (First letter capitalized)

```
func (kv *KV) get(key string) string {
   …
}
```

Example: starting RPC server

```
func startServer() {
      rpcs := rpc.NewServer()
      kv := KV{keyvalue: make(map[string]string)}
      rpcs.Register(&kv)
      l, e := net.Listen("tcp", ":8888")
      go func() {
            for {
                  conn, err := l.Accept()
                  if err == nil {
                        go rpcs.ServeConn(conn)
                  } else {
                        break
                  }
            }
            l.close()
       }()
}
```

Server handles each connection and request in a separate thread

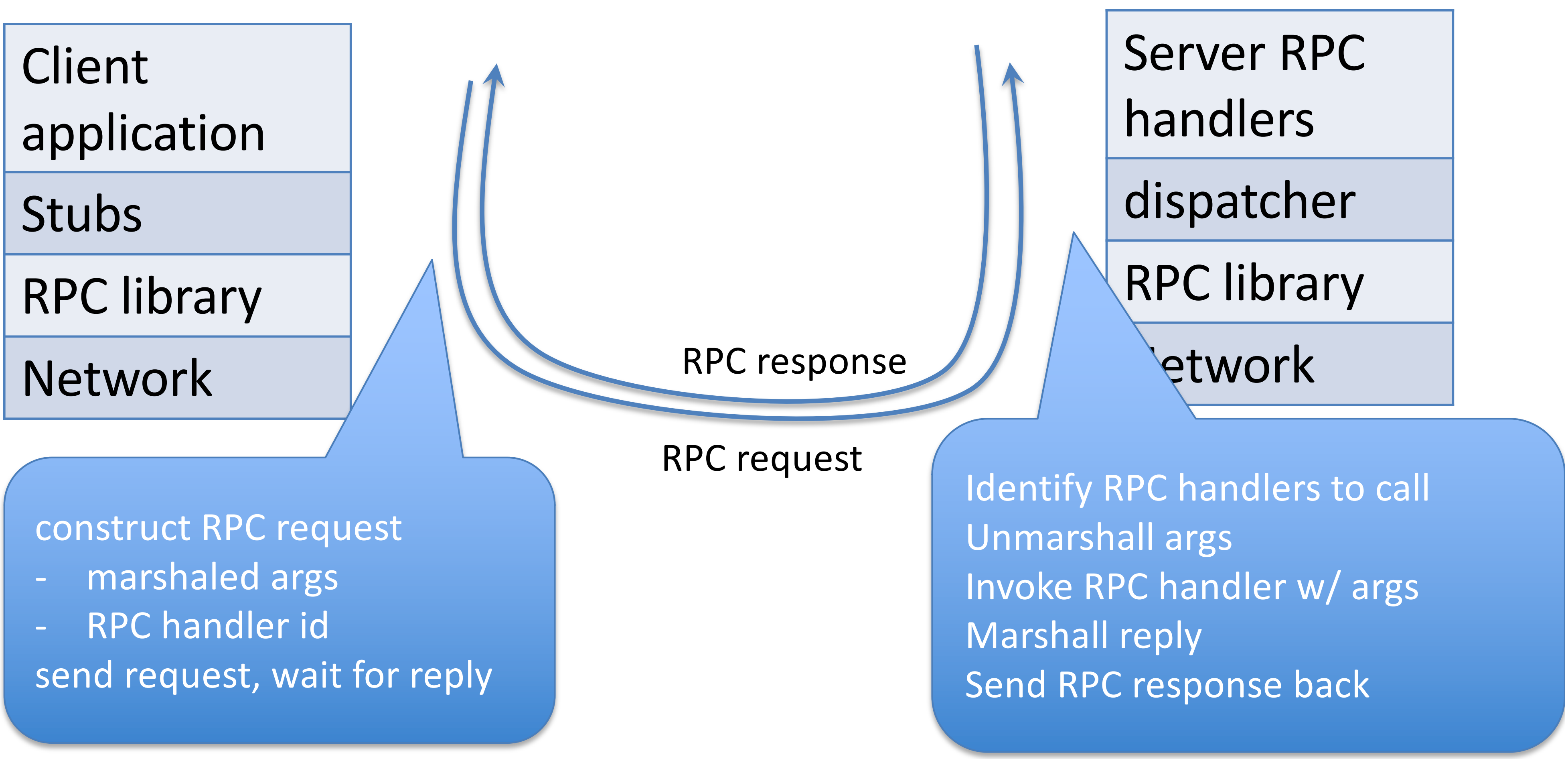
Example: client-side

```
type KVClient struct {
     clt *rpc.Client
}

func NewKVClient() *KVClient {
     clt, err := rpc.Dial("tcp", ":8888")
     return &KVClient{clt: clt}
}

func (c *KVClient) Put(key string, value string) {
     args := &PutArgs{Key: key, Value: val}
     reply := PutReply{}
     err := c.clt.call("KV.Put", args, &reply)
}
```

Example: putting it together

```
func main() {
      startServer()
      client := NewKVClient()
      client.Put("nyu", "New York University")
      client.Put("cmu", "Carnegie Mellon University")
      fmt.Printf("Get value=%s\n", client.Get("nyu"))
}
```

RPC software structure



Details of RPC library

- Which server function to call?
  - In Go RPC, it's specified in Call("KV.Put", ...)
- Marshalling: format data structure into byte stream
  - Go RPC forbids channels, functions, object references in RPC args/reply
- Binding: how does client know which server to talk to?
  - Go RPC: client supplies server host name
  - (rpcbind) A name service maps service names to some server host

RPC challenge

- What to do about failures?
  - lost packets, broken network, slow server, crashed server
- What does a failure look like to the client RPC library?
  - Client does not see a response from the server
  - Client cannot distinguish between the 2 scenarios:
    - Server has never seen/processed request
    - Server has processed request, but reply is lost

RPC behavior under failure: at-least-once?

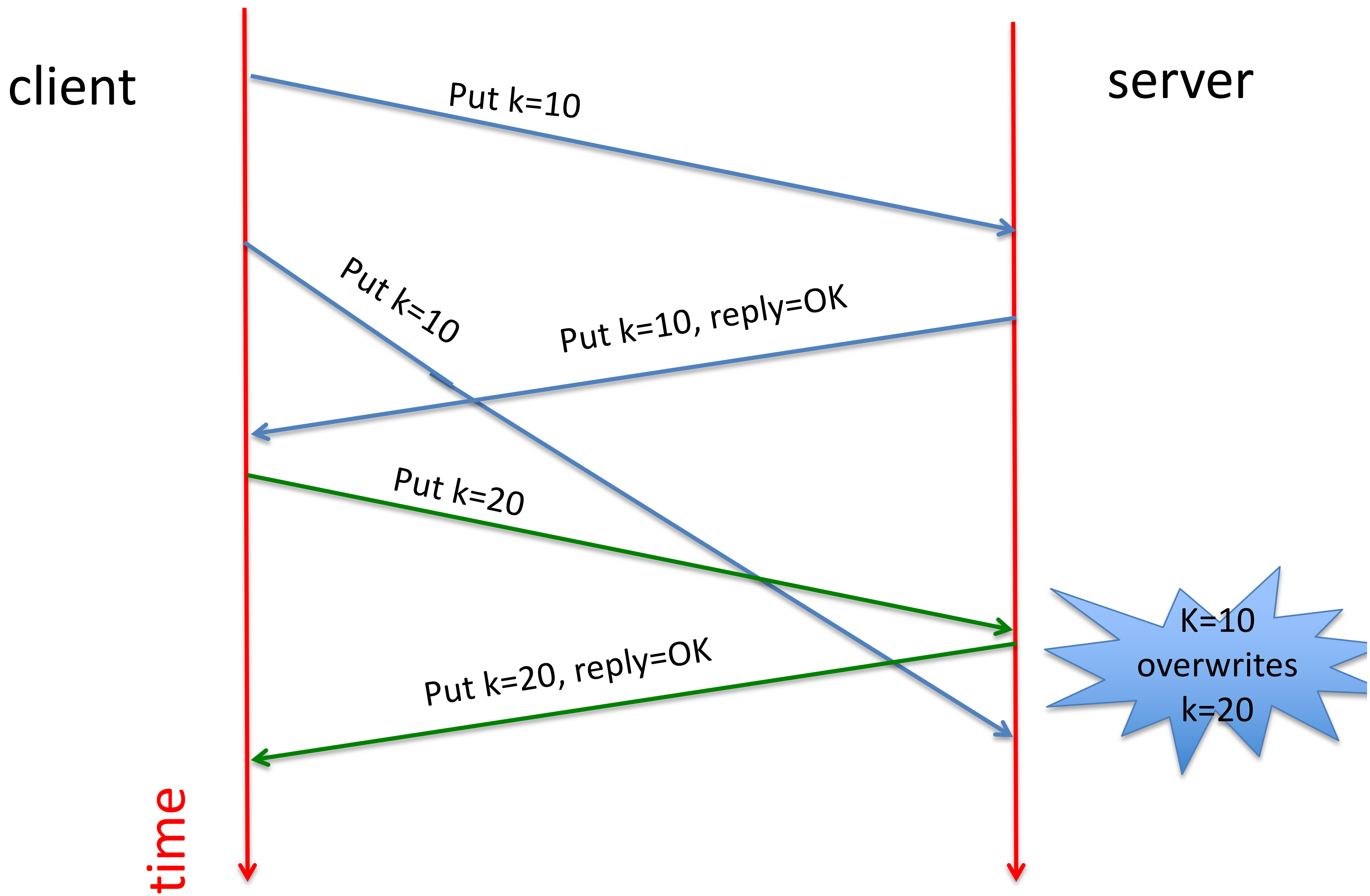
- A simple scheme to handle failure
  - RPC library waits for response for a while
  - If none arrives, re-send the request (re-establish network connection if necessary)
  - Repeat several times
  - If still no response, return an error to application client.

Perils of at-least-once semantics

```
err1 := clt.Call("KV.Put", &PutArgs{"k", 10}, ...)
err2 := clt.Call("KV.Put", &PutArgs{"k", 20}, ...)
```

- What's the expected value stored under "k" if err1==nil and err2== nil?
- Could it be otherwise?

Perils of at-least-once semantics



Perils of at-least-once

- Is at-least-once semantics ever okay?
  - If it's ok to repeat operations, e.g. read-only operations
  - If application has its own plan for coping with duplicates

At-most-once RPC semantics

- Idea:
  - RPC library detects duplicate requests, returns previous reply instead of re-running handler
- Client uses unique ID (xid) with each request, (use same xid to re-send)
- Server:

```
if oldreply, ok := seen[xid]; ok {
    reply = oldreply
} else {
    reply = handler()
    seen[xid] = reply
}
```

Complexities in realizing at-most-once

- How to ensure XID is unique?
  - random numbers (must be big)
  - unique client-id + sequence #
- How to eventually discard old RPC replies?
  - Possible solution-1:
    - xid = unique client-id + sequent #
    - clients include x in request, indicating “seen all replies <= x”
    - server discards replies <= x
  - Possible solution-2:
    - client agrees to retry for < 5 minutes
    - server discards after 5+ minutes

Complexities in realizing at-most-once

- How to handle duplicate request when original is in the middle of execution?
  - Server does not know the reply yet
  - Solution: “pending” flag per executing RPC; wait or ignore

- What if an at-most-once server crashes and restarts?
  - If server state is in-memory, server will forget.
  - How does server distinguish between crash-n-forget vs. never-before-seen?
  - Possible solution:
    - server uses a unique number (called “nonce” or “generation-number”) upon each startup,
    - client obtains server’s nonce upon connection, and includes it in every RPC request.
    - server rejects all requests with an old nonce

At-most-once semantics

err = clt.Call(...)

2 possible scenarios:

- if err == nil
- if err != nil

1. Handler is executed exactly once
2. Handler is executed >=1 times
3. Handler is not executed

Go RPC semantics

- Go RPC is “at-most-once”
  - Client opens TCP connection
  - writes request to TCP connection
  - TCP may retransmit, but server’s TCP filters out duplicates
  - No retry in Go RPC library (e.g. will NOT create another TCP connection if original one fails)
  - Go RPC returns error if it does not get a reply
    - after a TCP connection error

What about “exactly-once”?

- Can RPC implement “exactly-once”? Should it?
- If a RPC call returns error, how should the application client respond?
  - Re-transmit to the same server?
  - Re-transmit to a different server replica?
  - Applications need solutions to avoid duplicates
- Lab 3 will handle this in the context of a fault-tolerant key-value service
  - capable of handling unbounded client retransmits