Week 4

Multiprocess Communication

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January 28, 2025

Schedule Highlights

- Teams registration!
  - Make sure you register even if you’re working alone.

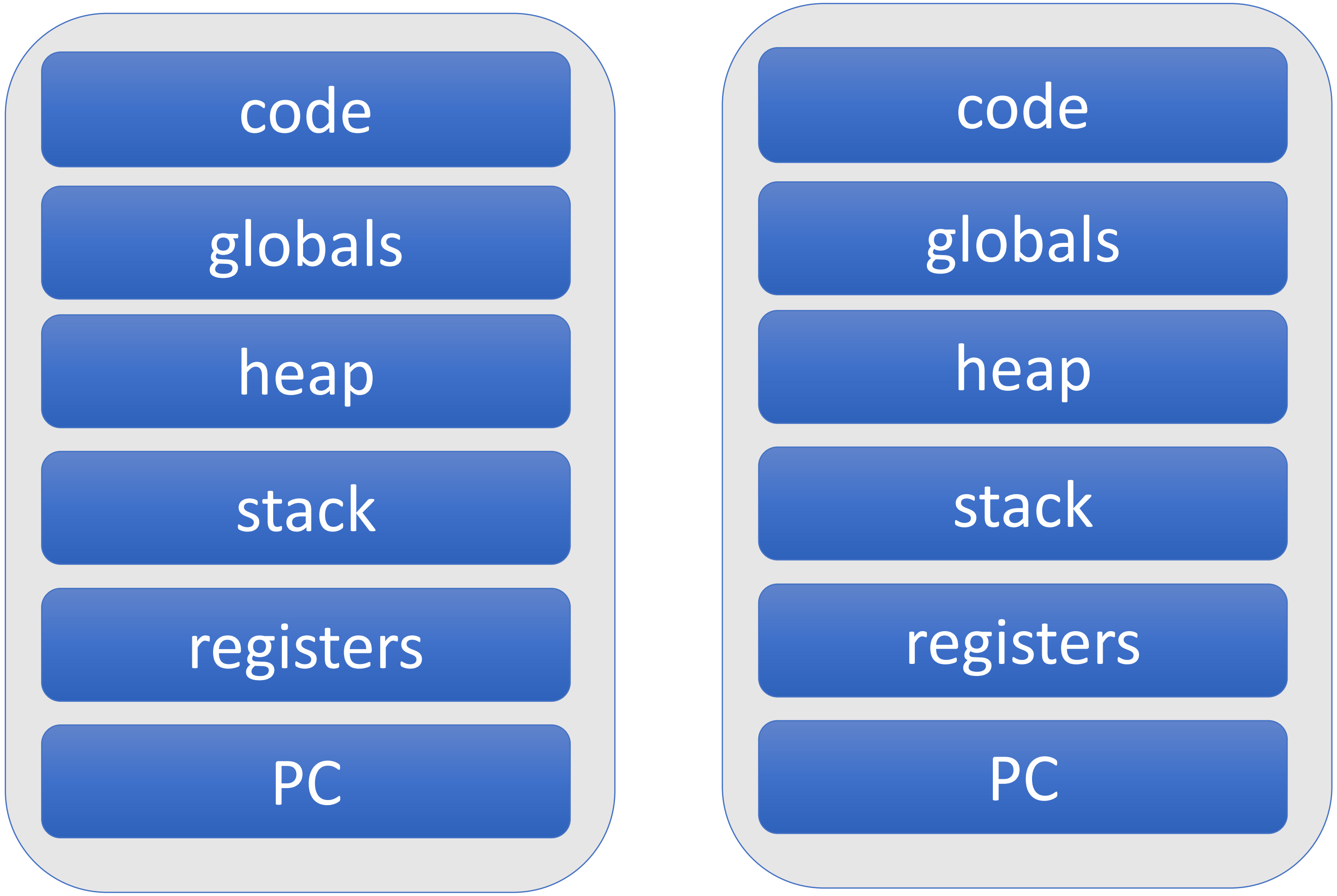
- Assignment gitlab setup:
  - Make sure your fork is set to “private”
  - Add your partner (if any) as a collaborator
  - Add myself and the TA in charge of grading as Reporters
  - **See last lecture for details**

Recap Week 3
Concurrency – Option 1

- Build apps from many communicating **processes**
- Communicate through message passing
  - No shared memory
- Pros
  - If one process crashes, other processes unaffected
- Cons
  - High communication overheads
  - Expensive context switching

This week's focus

Recap Week 3
Two Processes

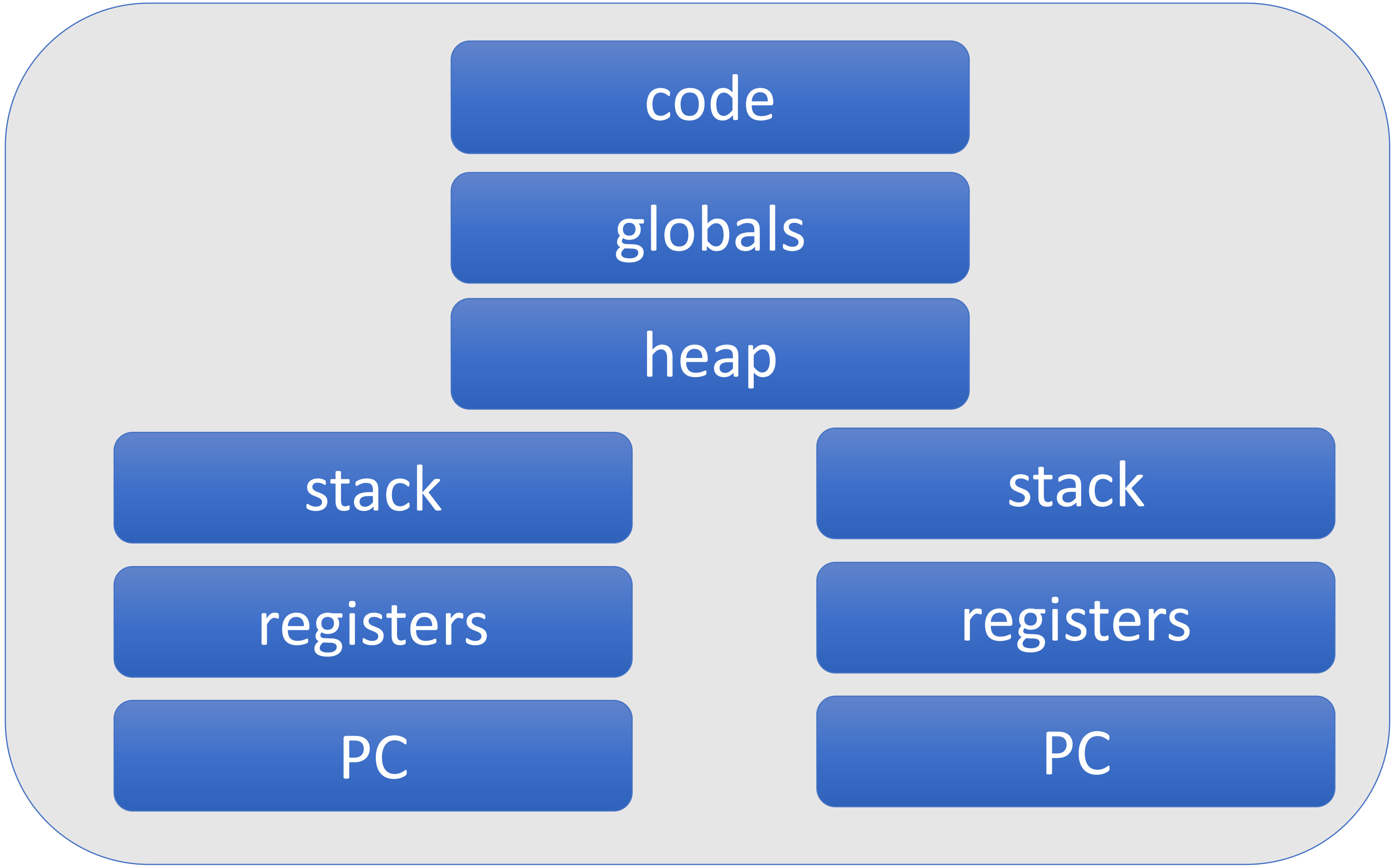


Recap Week 3
Concurrency – Option 2

- New abstraction: **thread**
- Multiple threads in a process
- Threads are like processes except
    - Multiple threads in the same process share an address space
        - Communicate through shared address space
    - If one thread crashes,
        - the entire process, including other threads, crashes

Will see more examples in Week 5

Recap Week 3
Two Threads in a Process



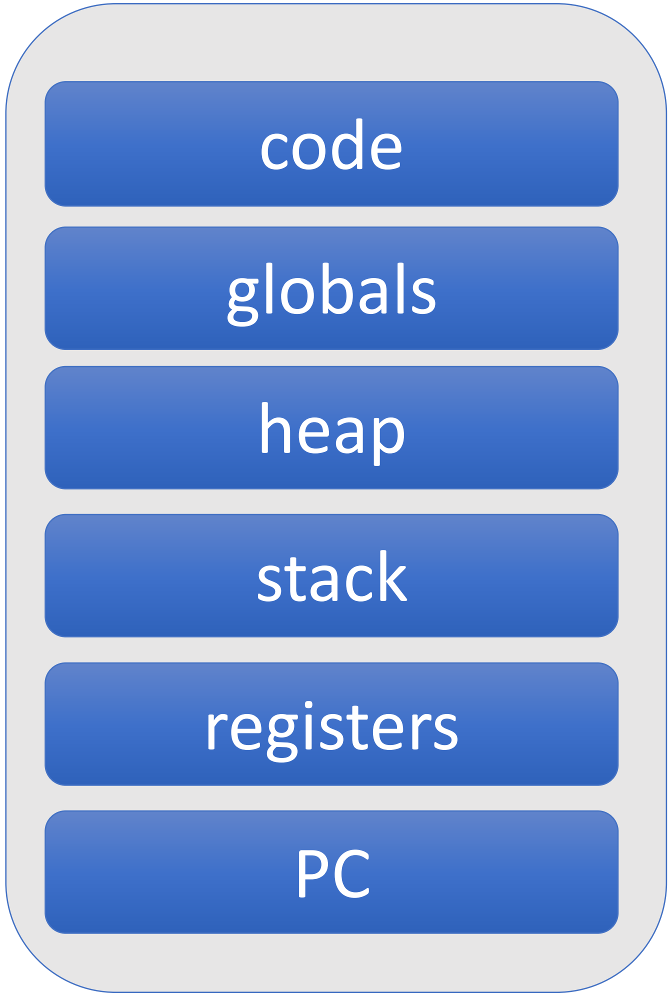
Key Concepts for Today

- Interprocess communication
- Message passing
- Remote procedure call (RPC)
  - Concept only – details not required
- + lock implementation from last week

So far

- One program

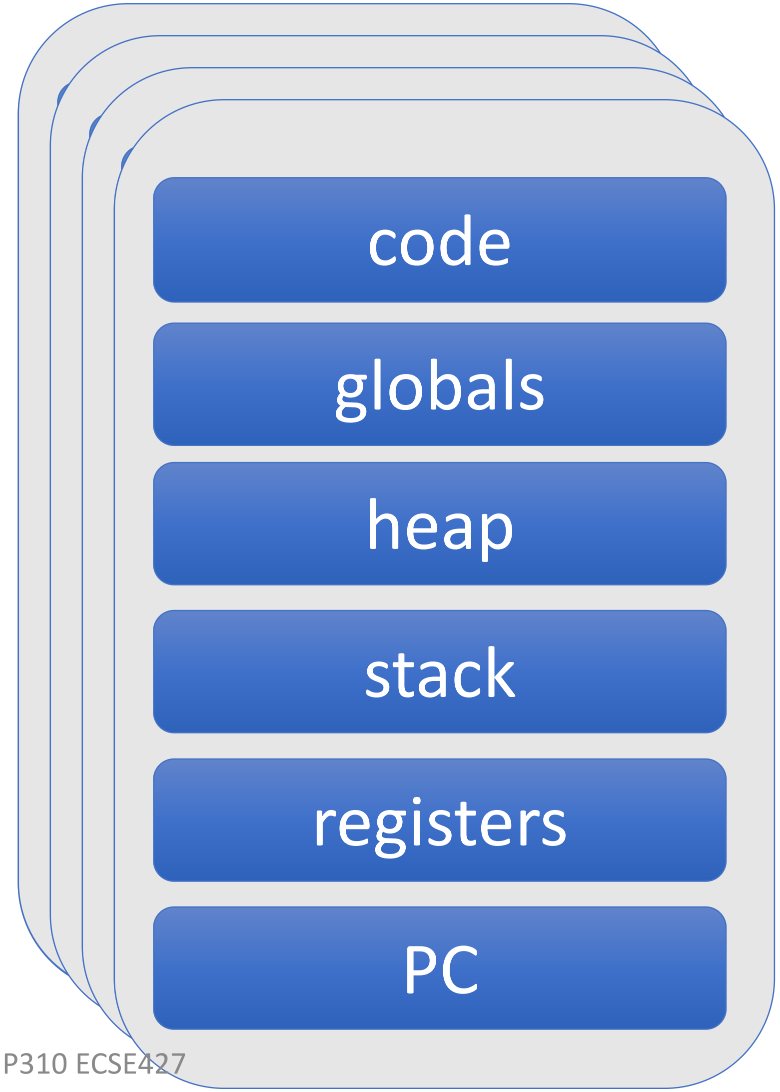
  = one process
- Examples:
  - Shell
  - Compiler
  - …



This is not always the case

- One program

  = multiple processes
- Example:
  - Web server



(Very Simple) Web Server

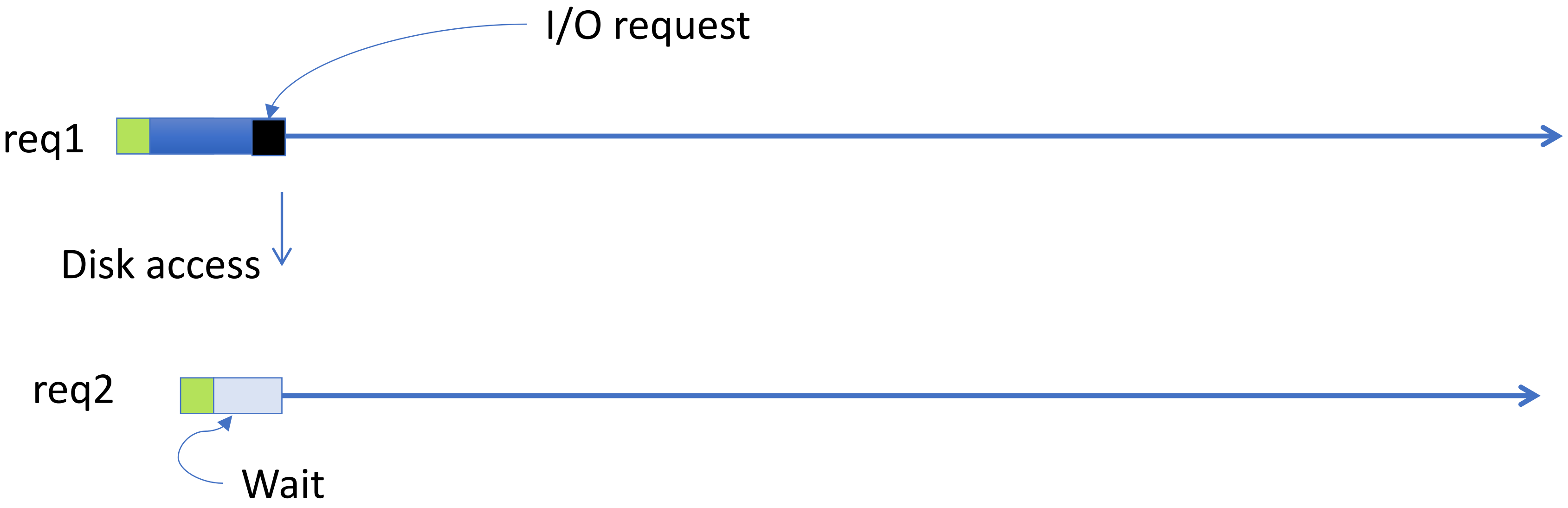
```
WebServerProcess {
        forever {
                wait for an incoming request
                read file from disk
                send file back in response
        }
}
```

Single-Process Web Server

Example: Web server receives two requests in quick succession

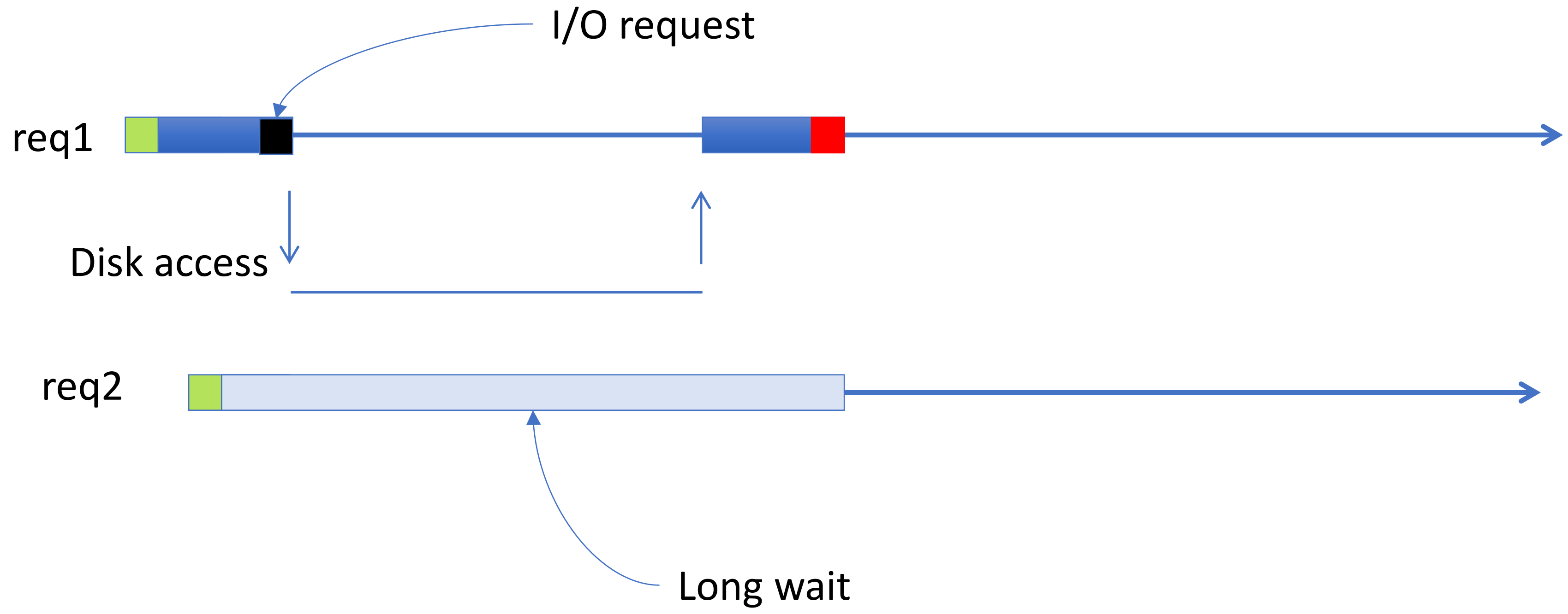
Single-Process Web Server

Example: Web server receives two requests in quick succession



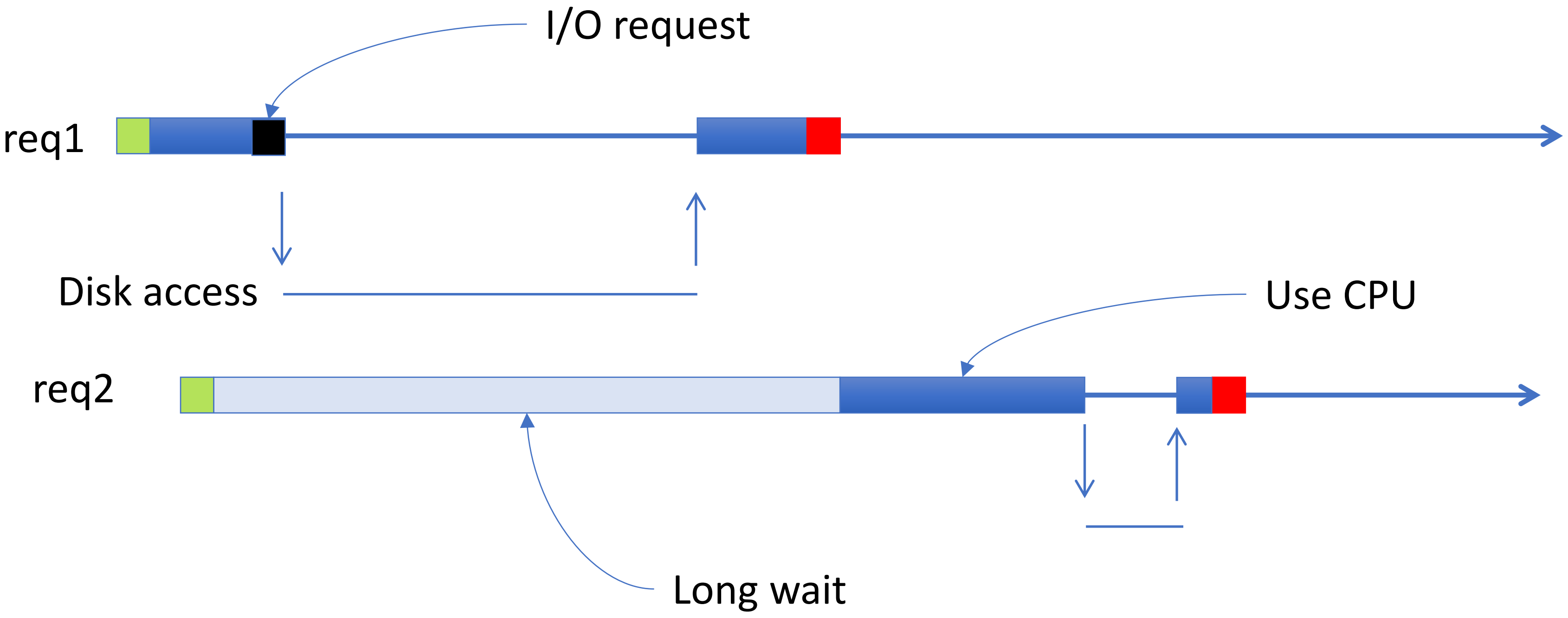
Single-Process Web Server

Example: Web server receives two requests in quick succession



Single-Process Web Server

Example: Web server receives two requests in quick succession



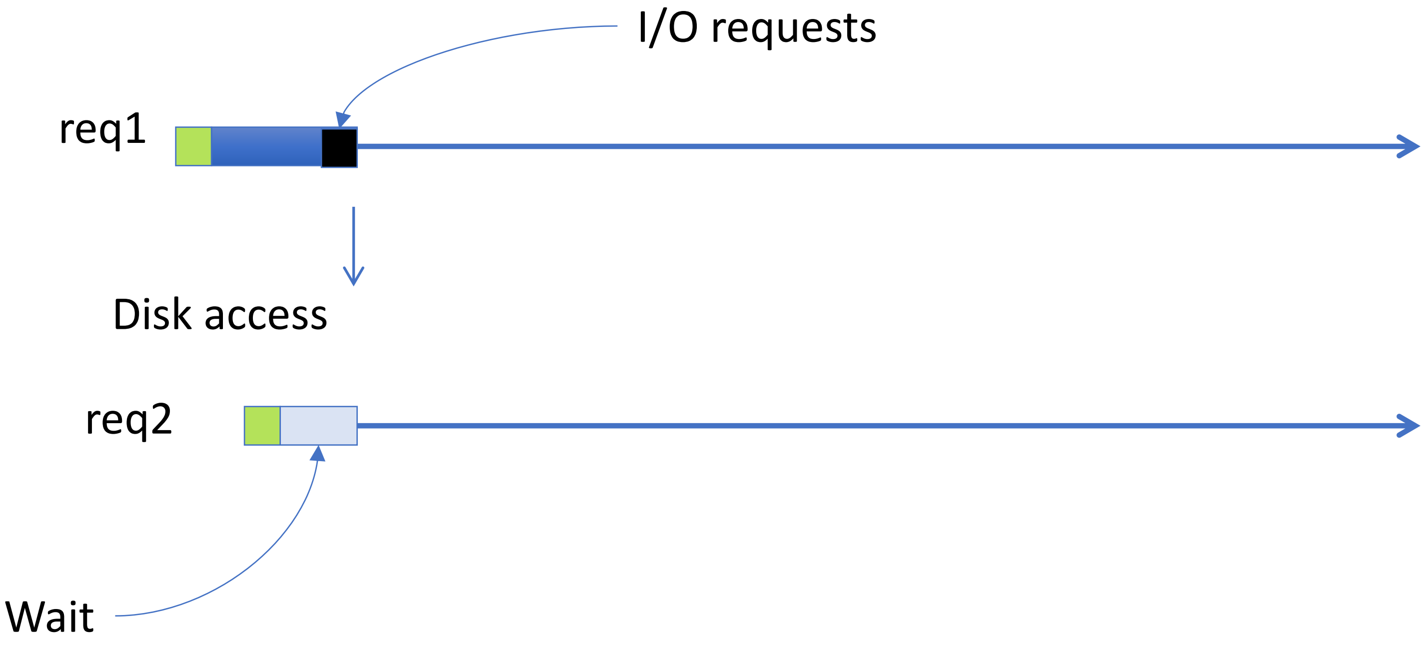
Multiprocess Web Server

```
ListenerProcess {
  forever {
    wait for incoming request
    CreateProcess( worker, request )
  }
}

WorkerProcess(request) {
  read file from disk
  send response
  exit
}
```

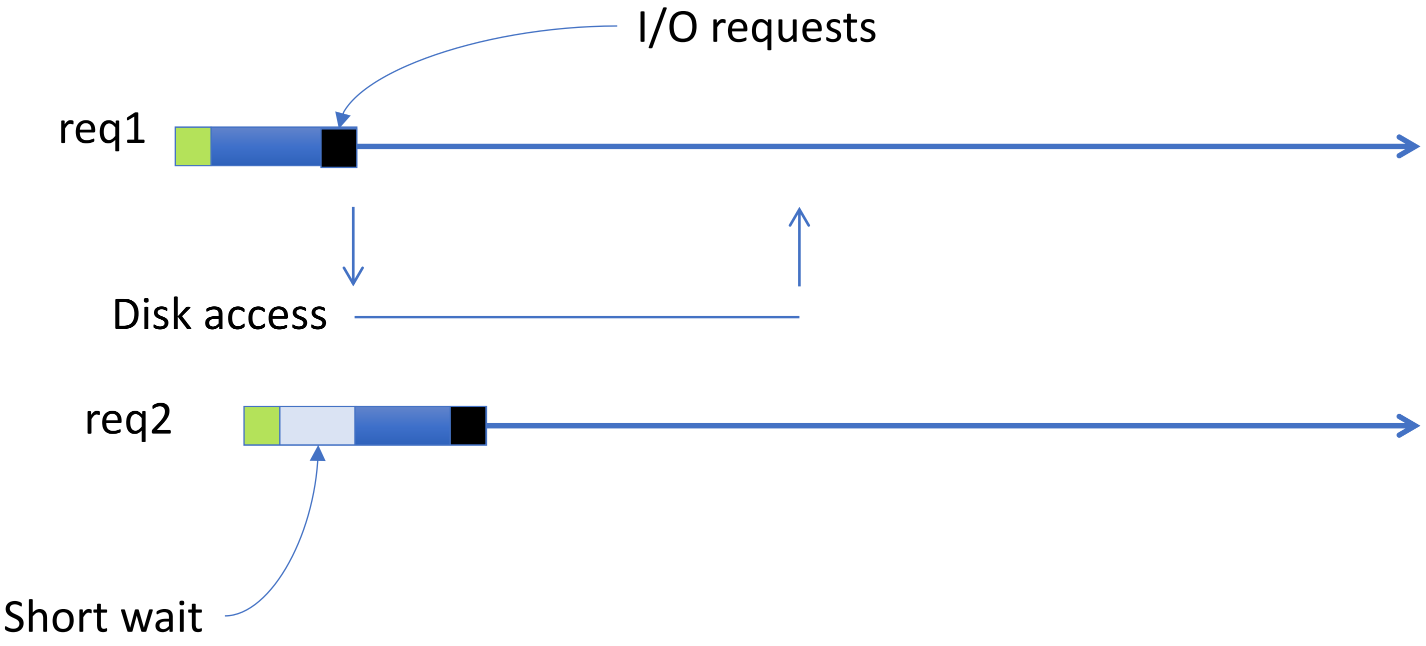
Multi vs. Single-process Web Server

Example: Web server receives two requests in quick succession



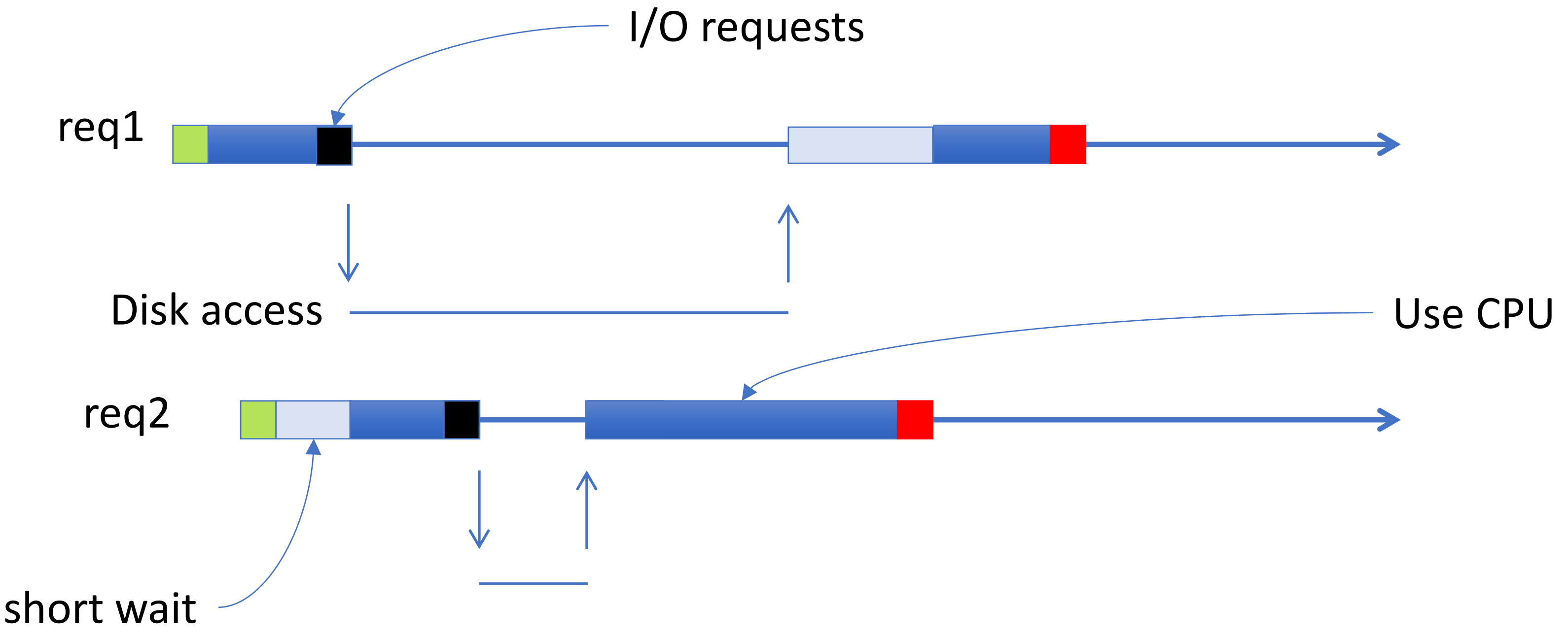
Multi vs. Single-process Web Server

Example: Web server receives two requests in quick succession

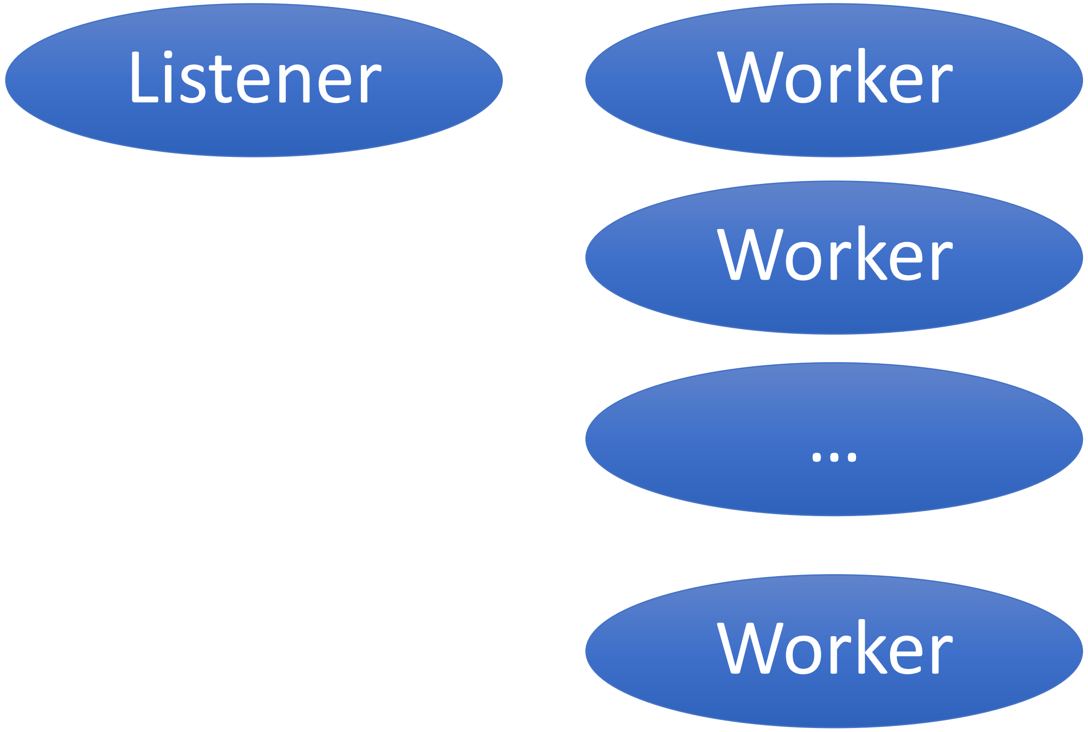


Multi vs. Single-process Web Server

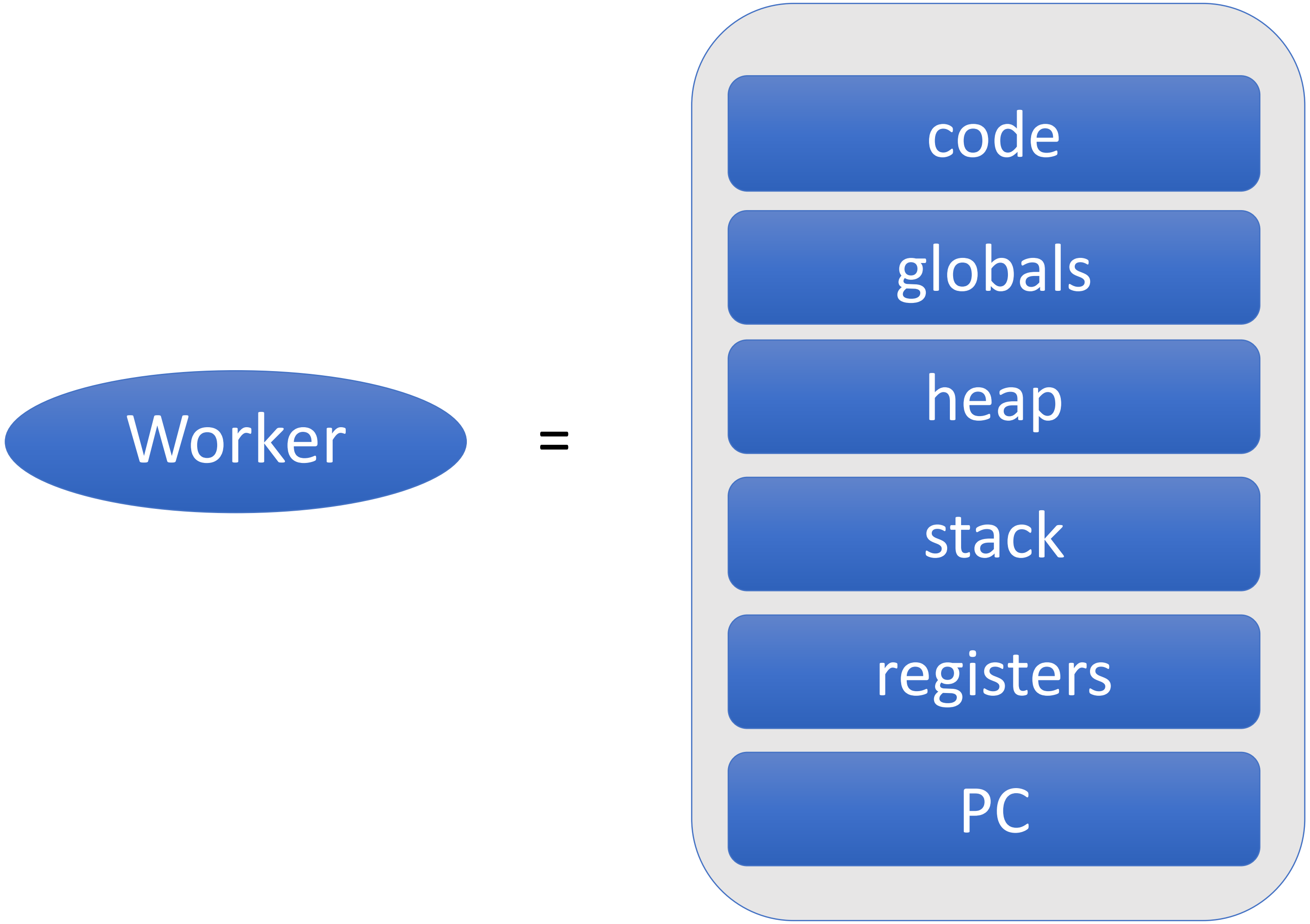
Example: Web server receives two requests in quick succession



Multiprocess Web Server



Each Worker is a Process



Amount of work on server per request

- Receive network packet
- Run listener process
- Create worker process
- Read file from disk
- Send network packet

Amount of work on server per request

- Receive network packet
- Run listener process
- *Create worker process is expensive*
- Read file from disk
- Send network packet

Multiprocess Web Server

```
ListenerProcess {
  forever {
    wait for incoming request
    CreateProcess( worker, request )
  }
}

WorkerProcess(request) {
  read file from disk
  send response
  exit
}
```

How can we avoid this?

Process Pool

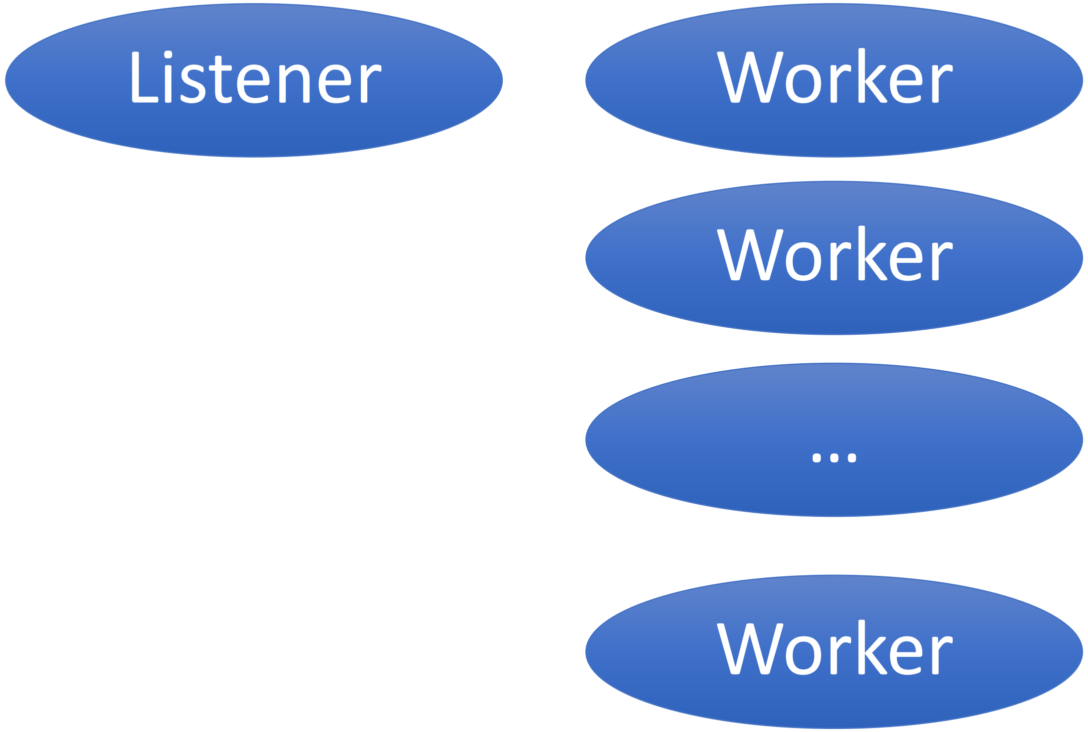
- Create worker processes during initialization
- Hand incoming request to them

Multiprocess Web Server with Process Pool

```
ListenerProcess {
  for(i=0; i<MAX_PROCESSES; i++) process[i] = CreateProcess(worker)
    forever {
            wait for incoming request
            send(request, process[?])
    }
}

WorkerProcess[?] {
  forever {
    wait for message(&request)
    read file from disk
    send response
  }
}
```

Pictures remain the same



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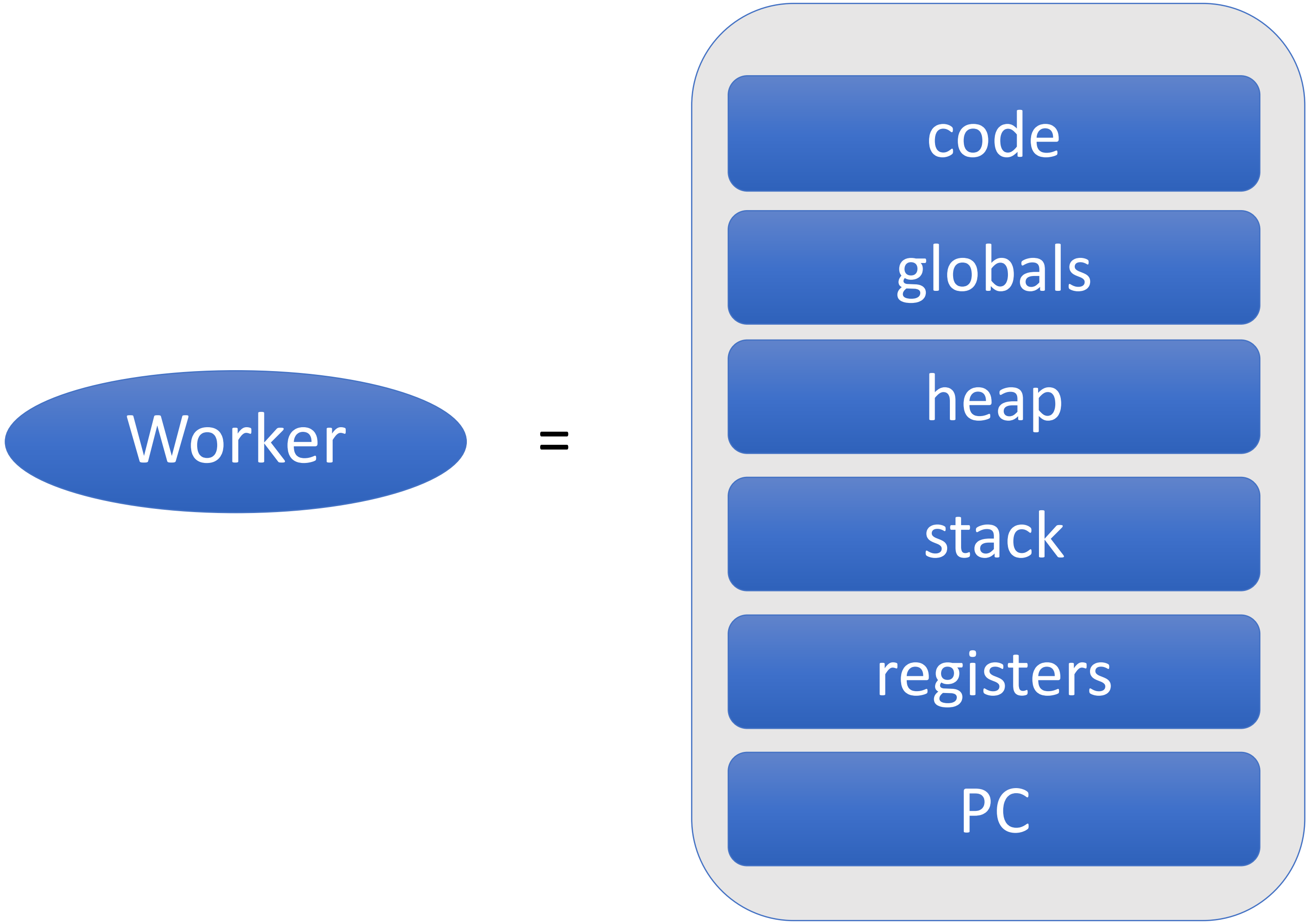

What changed:
Amount of work on server per request

- Receive network packet
- Run listener process
- *Send message to worker process (cheaper)*
- Read file from disk
- Send network packet

Interprocess Communication (IPC)

Interprocess Communication (IPC)

- OS support to allow the processes to manage shared data
  - Through message passing
  - Through remote procedure calls (RPC)
    - We won’t get into RPC details

Where do you need IPC?

Multiprocess Web Server with Process Pool

```
ListenerProcess {
  for( i=0; i<MAX_PROCESSES; i++ ) process[i] = CreateProcess(worker)
    forever {
          receive incoming request
          send( request, process[?] )
    }
}

WorkerProcess[?] {
  forever {
    wait for message( &request )
    read file from disk
    send response
  }
}
```

Need IPC here

For client-server communication

Multiprocess Web Server with Process Pool

```
ListenerProcess {
 for( i=0; i<MAX_PROCESSES; i++ ) process[i] = CreateProcess(worker)
  forever {
      receive incoming request
      send( request, process[?] )
  }
}

WorkerProcess[?] {
 forever {
  wait for message( &request )
  read file from disk
  send response
 }
}
```

Need IPC here

For communication between cooperating processes

(e.g., between listener and workers)

Where do you need IPC?

- Between client and server
- Between cooperating processes

How to do IPC?

- Message passing
  - Low-level communication primitive
- Remote procedure calls (RPC)
  - Abstraction over message passing
  - Natural, convenient, & common

Message Passing Primitives

- Send message
- Receive message

Message Passing Send / Receive

```
msg = alloc()
msg->field0 = 1
….
Send(msg, …)
```

```
msg = alloc()
Receive( msg )
a = msg->field0
…
```

Message Passing Send / Receive

msg

```
msg = alloc()
msg->field0 = 1
….
Send(msg, …)
```

```
msg = alloc()
Receive( msg )
a = msg->field0
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Message Passing Send / Receive

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msg = alloc()
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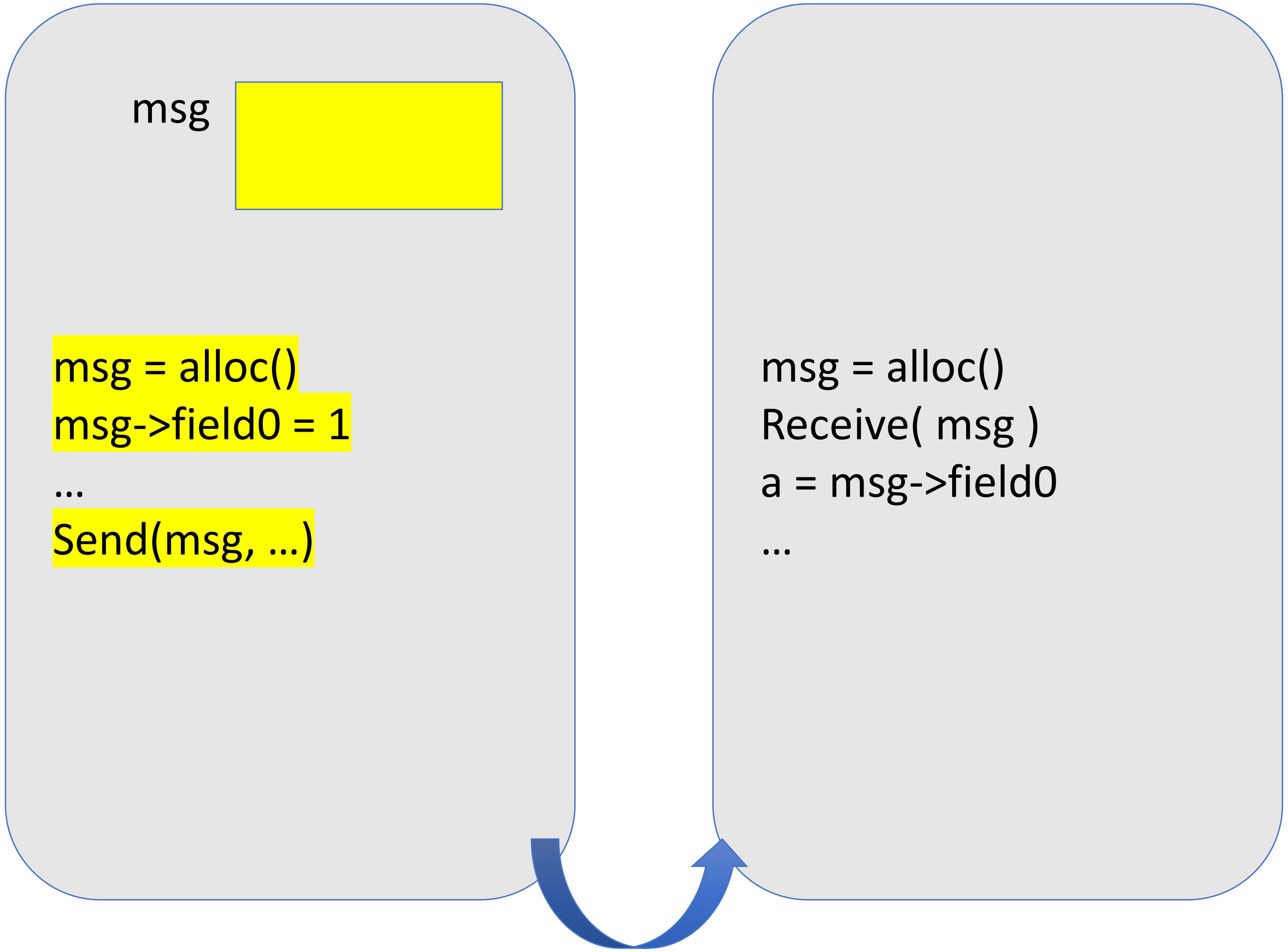
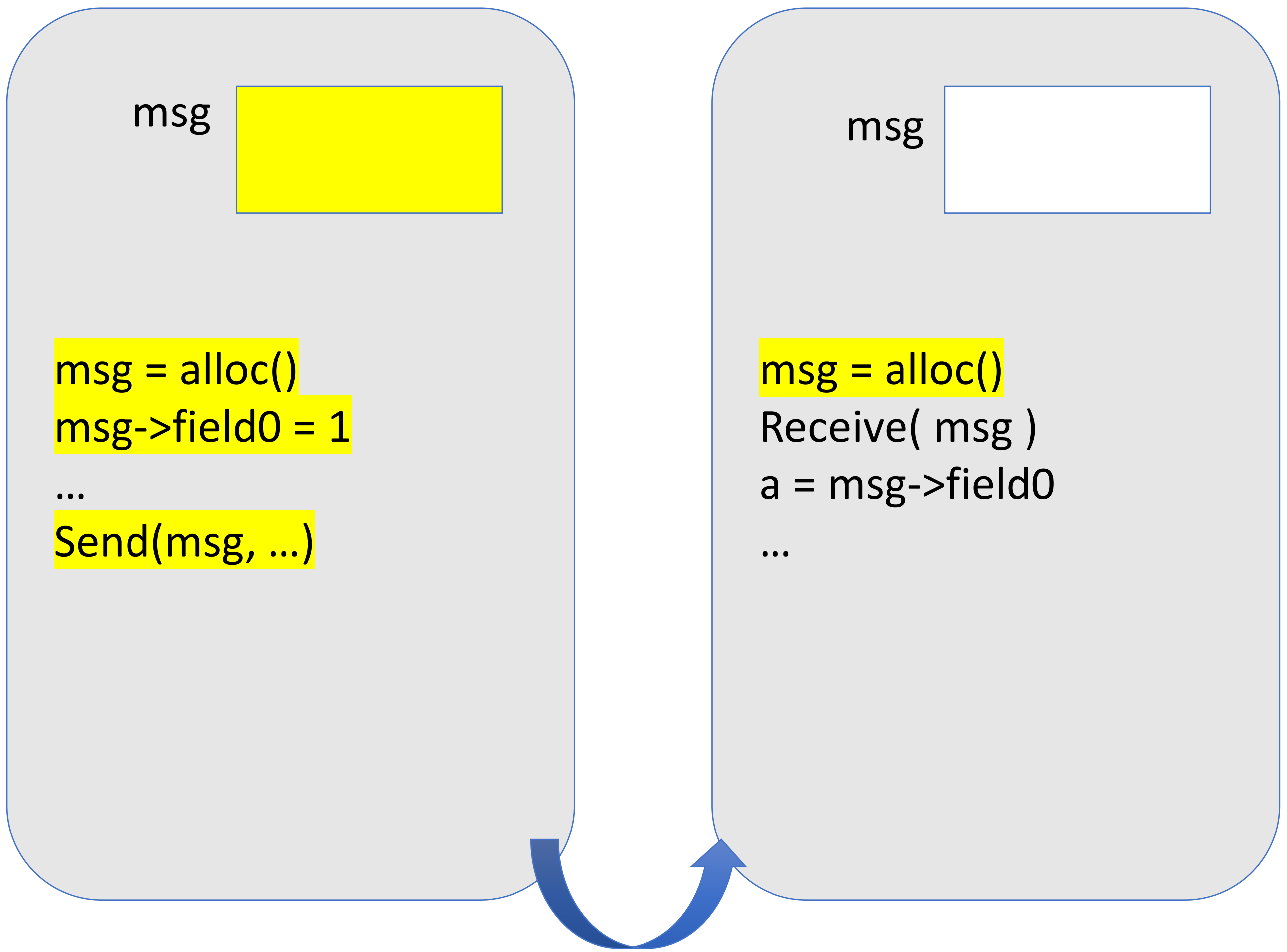
```

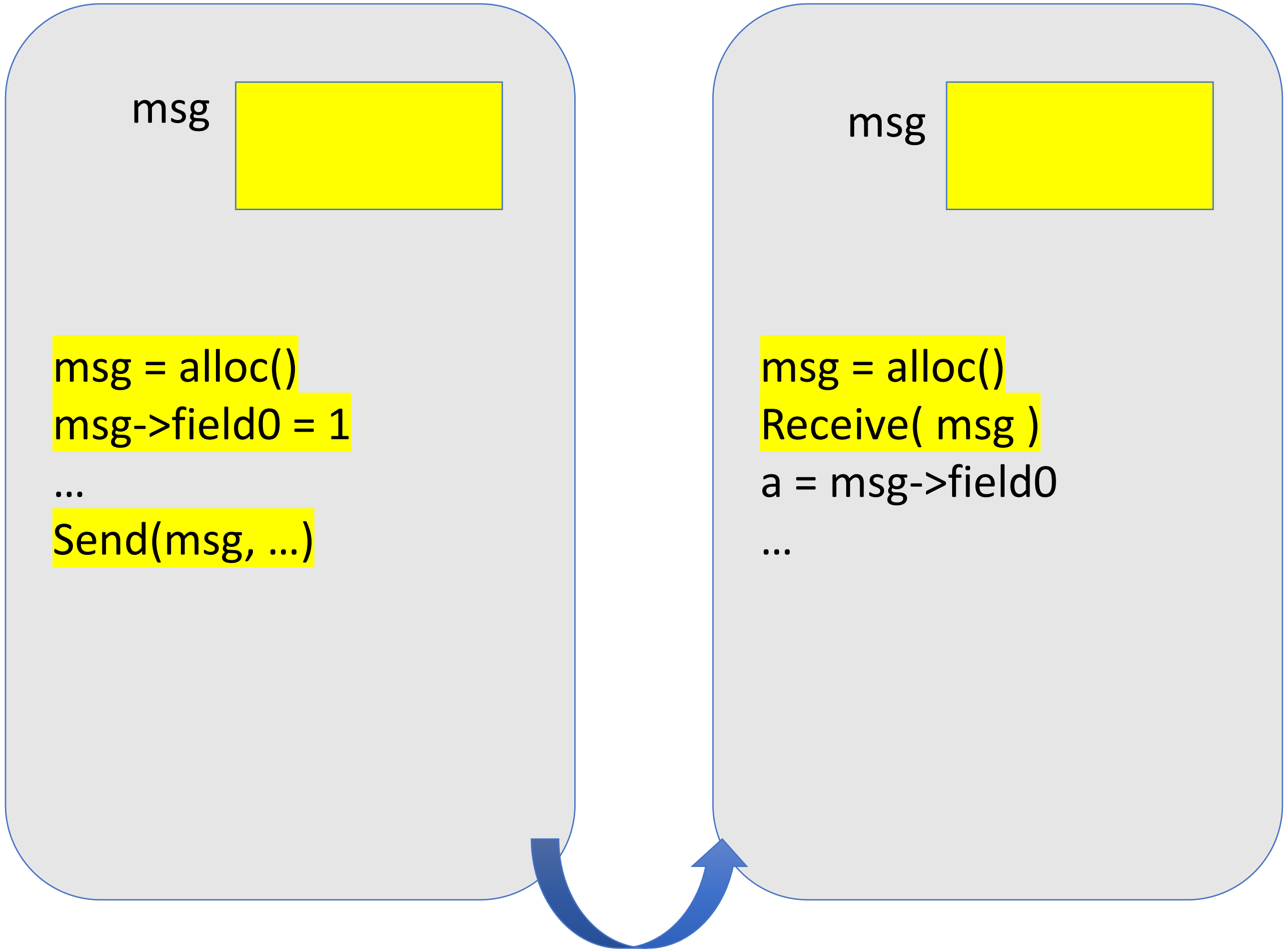
Message Passing Send / Receive



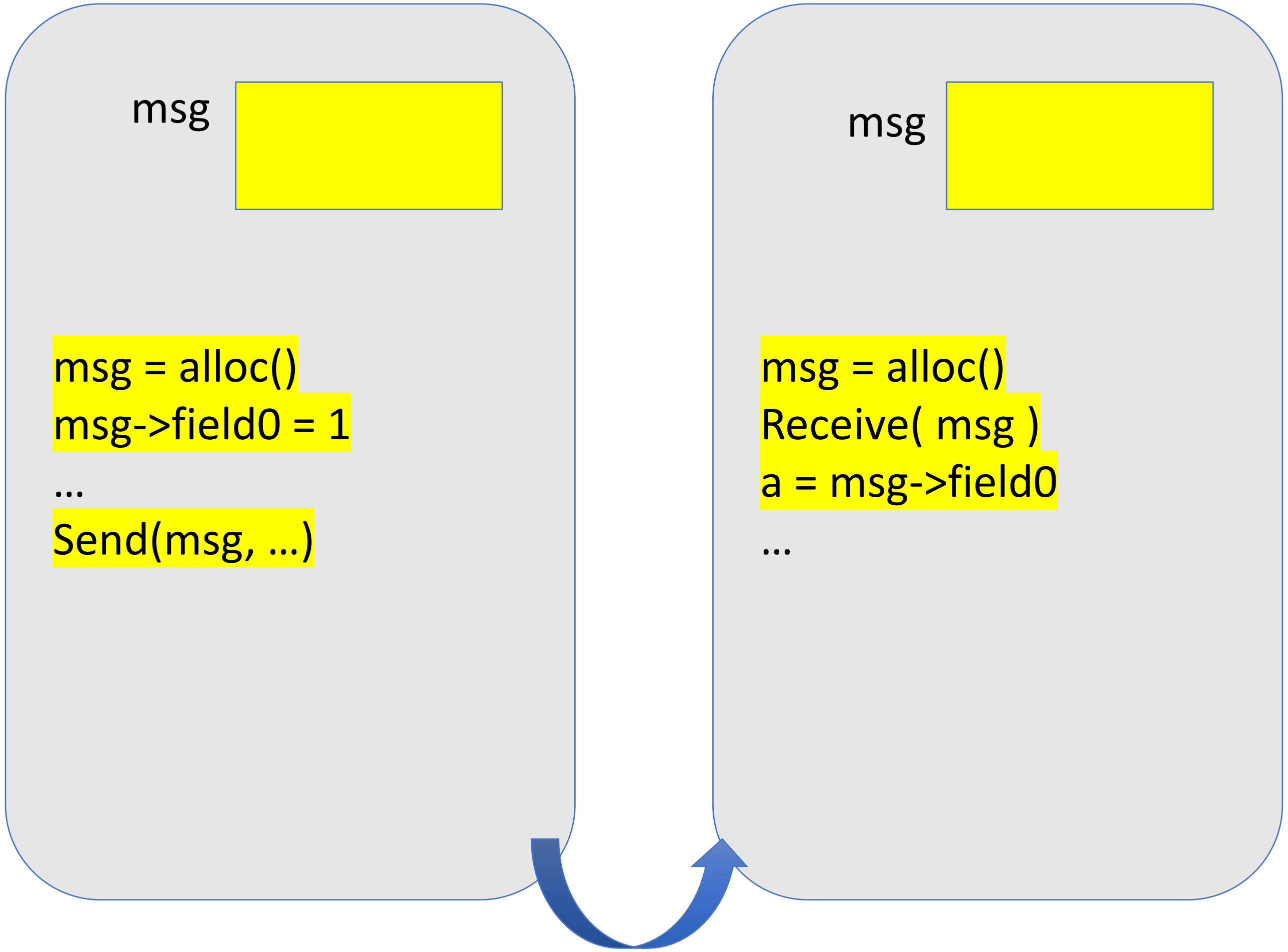
Message Passing Send / Receive



Message Passing Send / Receive



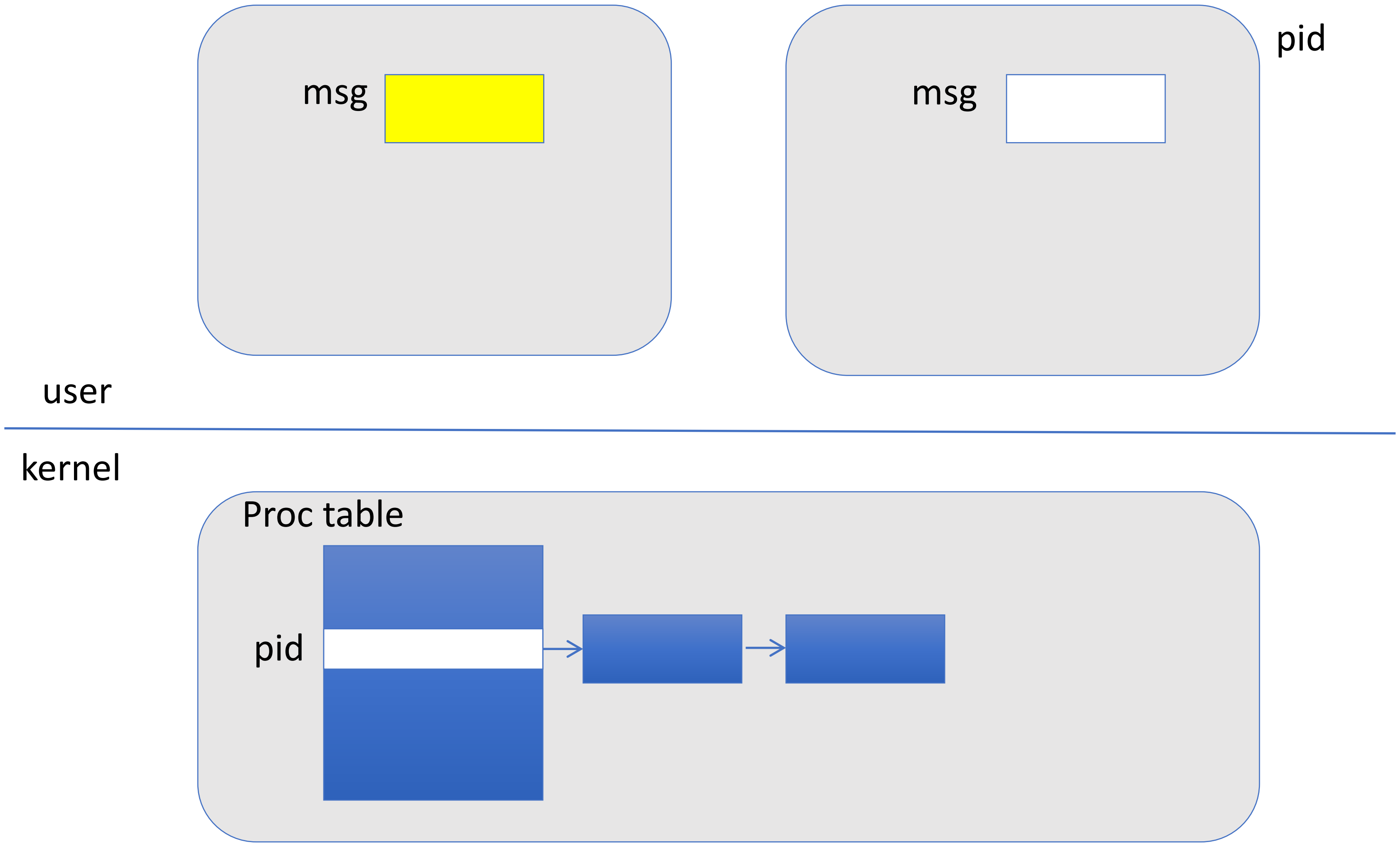
Message Passing Send / Receive



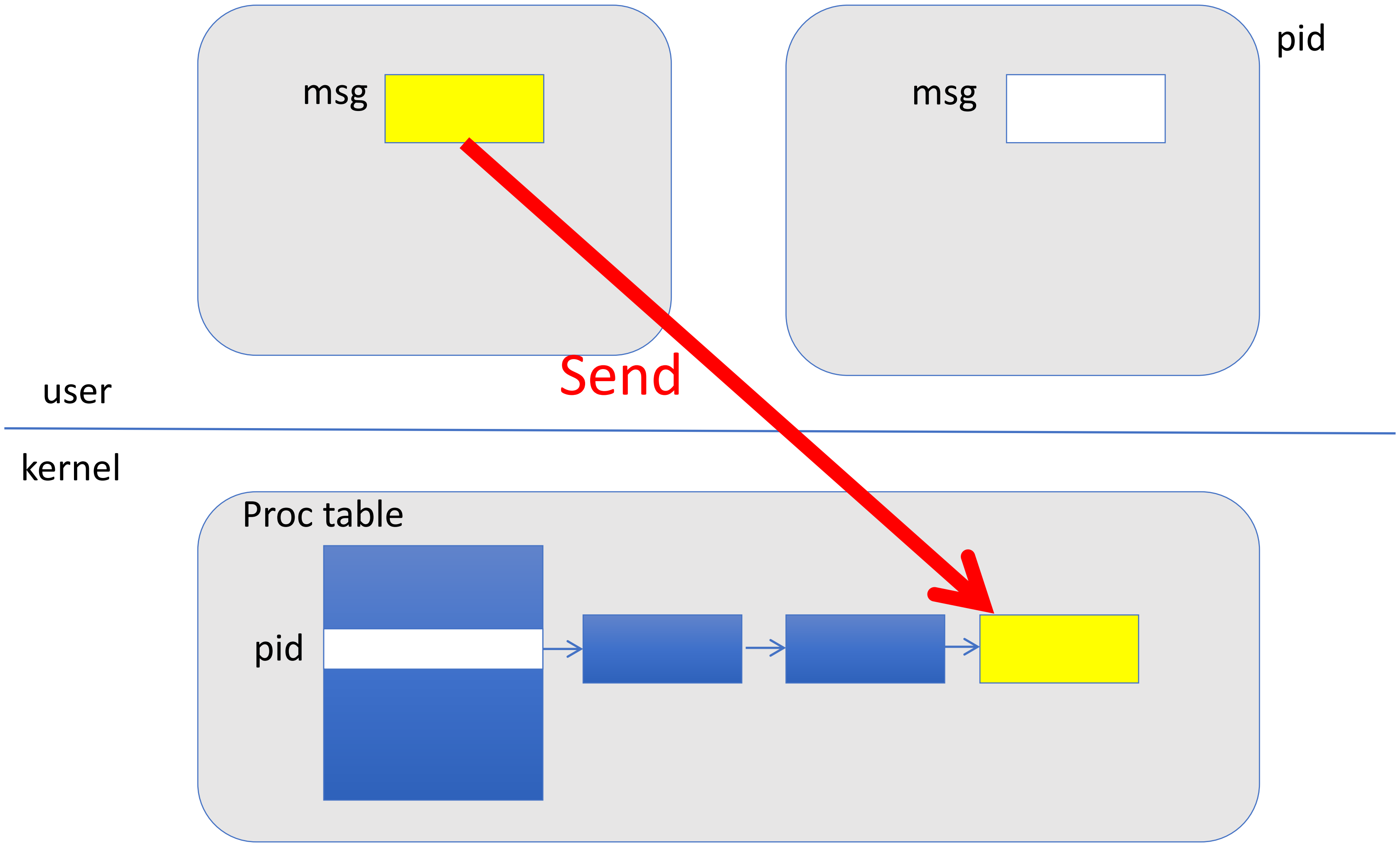
Message Passing

- By value communication
- **Never by reference**
- Receiver cannot affect message in sender
  - Different processes don't share memory!

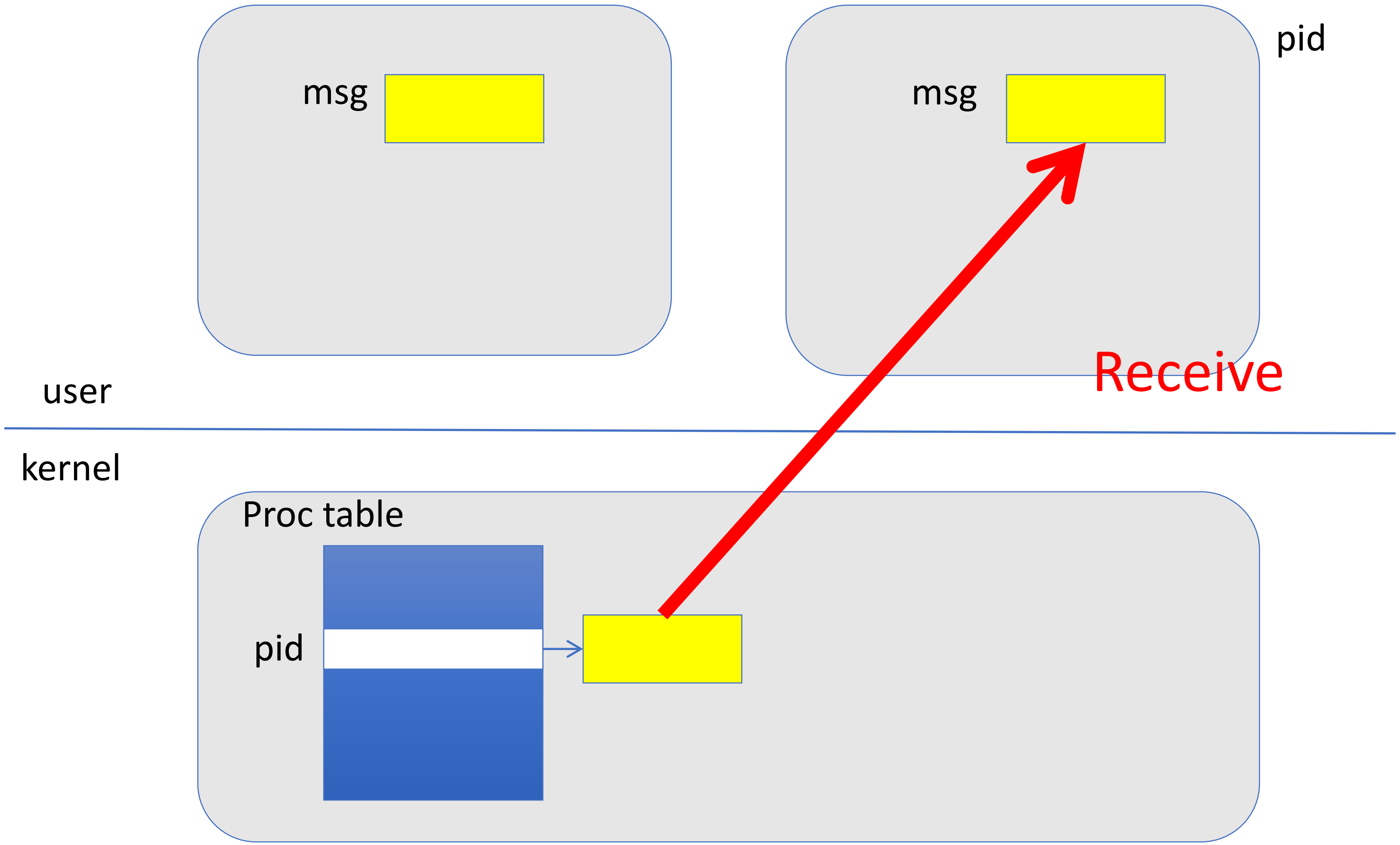
Message Passing Implementation



Message Passing Implementation



Message Passing Implementation



Message Passing Alternatives

- Symmetric / asymmetric addressing
- Blocking / nonblocking

Symmetric Addressing

- **Send**(msg, to_pid)
- **Receive**(msg, from_pid)

- Message is (typically) a struct
- to_pid, from_pid are process identifiers

- Symmetric addressing seldom used

Asymmetric Addressing

- **Send**(msg, pid)
  - Send msg to process pid

- pid = **Receive**(msg)
  - Receive msg from *any* process
  - Return the pid of sending process

- More common and useful form of addressing

Blocking or Nonblocking Send

- Nonblocking:
  - Send returns immediately after message is sent
- Blocking
  - Sender blocks until message is delivered
- Nonblocking is the more common form

Blocking or Nonblocking Receive

- Nonblocking
  - Receive returns immediately
  - Regardless of message present or not
- Blocking
  - Receive blocks until message is present
- Blocking is the more common form

(Slightly Rewritten) Example: Multiprocess Web Server with Process Pool

```
ListenerProcess {
  for(i=0; i<MAX_PROCESSES; i++) process[i] = CreateProcess(worker)
    forever {
            client_pid = receive(msg)
            msg' = slightly modify msg to include client_pid
            send(msg', worker_process[i])
    }
}

WorkerProcess[i] {
  forever {
    receive(msg)
    read file from disk
    send(resp, client_pid)
  }
}
```

Asymmetric Addressing: Send

```
ListenerProcess {
  for(i=0; i<MAX_PROCESSES; i++) process[i] = CreateProcess(worker)
    forever {
              client_pid = receive(msg)
              msg' = slightly modify msg to include client_pid
              send(msg', worker_process[i])
    }
}

WorkerProcess[i] {
  forever {
    receive(msg)
    read file from disk
    send(resp, client_pid)
  }
}
```

Asymmetric Addressing: Receive

```
ListenerProcess {
  for(i=0; i<MAX_PROCESSES; i++) process[i] = CreateProcess(worker)
    forever {
            client_pid = receive(msg) /* receive msg from any client */
            msg’ = slightly modify msg to include client_pid
            send(msg’, worker_process[i])
    }
}

WorkerProcess[i] {
  forever {
    receive(msg) /* receive msg’ from listener; could be symmetric */
    read file from disk
    send(resp, client_pid)
  }
}
```

Blocking Receive

```
ListenerProcess {
  for(i=0; i<MAX_PROCESSES; i++) process[i] = CreateProcess(worker)
    forever {
              client_pid = receive(msg) /* nothing else to do*/
              msg' = slightly modify msg to include client_pid
              send(msg', worker_process[i])
    }
}

WorkerProcess[i] {
  forever {
    receive(msg) /* nothing else to do*/
    read file from disk
    send(resp, client_pid)
  }
}
```

Nonblocking Send

```
ListenerProcess {
  for(i=0; i<MAX_PROCESSES; i++) process[i] = CreateProcess(worker)
    forever {
        client_pid = receive(msg)
        msg' = slightly modify msg to include client_pid
        send(msg', worker_process[i]) /* must not block */
    }
}

WorkerProcess[i] {
  forever {
    receive(msg)
    read file from disk
    send(resp, client_pid) /* must not block */
  }
}
```

Client-Server Communication

(Server Side) Client-Server Communication

```
ListenerProcess {
  for(i=0; i<MAX_PROCESSES; i++) process[i] = CreateProcess(worker)
    forever {
        receive incoming request
        send( request, process[?] )
    }
}

WorkerProcess[?] {
  forever {
    wait for message( &request )
    read file from disk
    send response
  }
}
```

(Client-Side) Client-Server Communication

send(msg to server)

receive(reply msg from server)

A Very Common Pattern

- Client:
  - Send /* send request to server */
  - Blocking receive /* wait for reply */
- Server
  - Blocking receive /* wait for request */
  - Send /* send reply */

This looks like …

- Client:
  - Send
  - Blocking receive
- Server
  - Blocking receive
  - Send

calling site

call procedure

return

callee site

invoke procedure

return

Remote Procedure Call (RPC)

- Client:
  - Send
  - Blocking receive
- Server
  - Blocking receive
  - Send

calling site

call procedure

return

callee site

invoke procedure

return

RPC: when client wants to call a function that belongs to server code

RPC Interface

- Interface
  - List of remotely callable procedures
  - With their arguments and return values

- Example: file system interface
  - Open(string filename)
  - returns int fd
    - fd = file descriptor; will see later in course
  - …

RPC Client Code

- Import file system interface

- fd = open("/a/b/c")
- nbytes = read(fd, buffer, size)

RPC Server Code

- Export file system interface

- int open(stringname) { … }
- int read(fd, buffer, nbytes) { … }
- …

Problem

- Want a procedure call interface
- Have only message passing between processes
  - Message passing code doesn't look like procedure call
- How to bridge the gap?

Solution: Stub Library

- Client stub and server stub
- Client stub linked with client process
- Server stub linked with server process

Two Message Types

- Call message
  - From client to server
  - Contains arguments
- Return message
  - From server to client
  - Contains return values

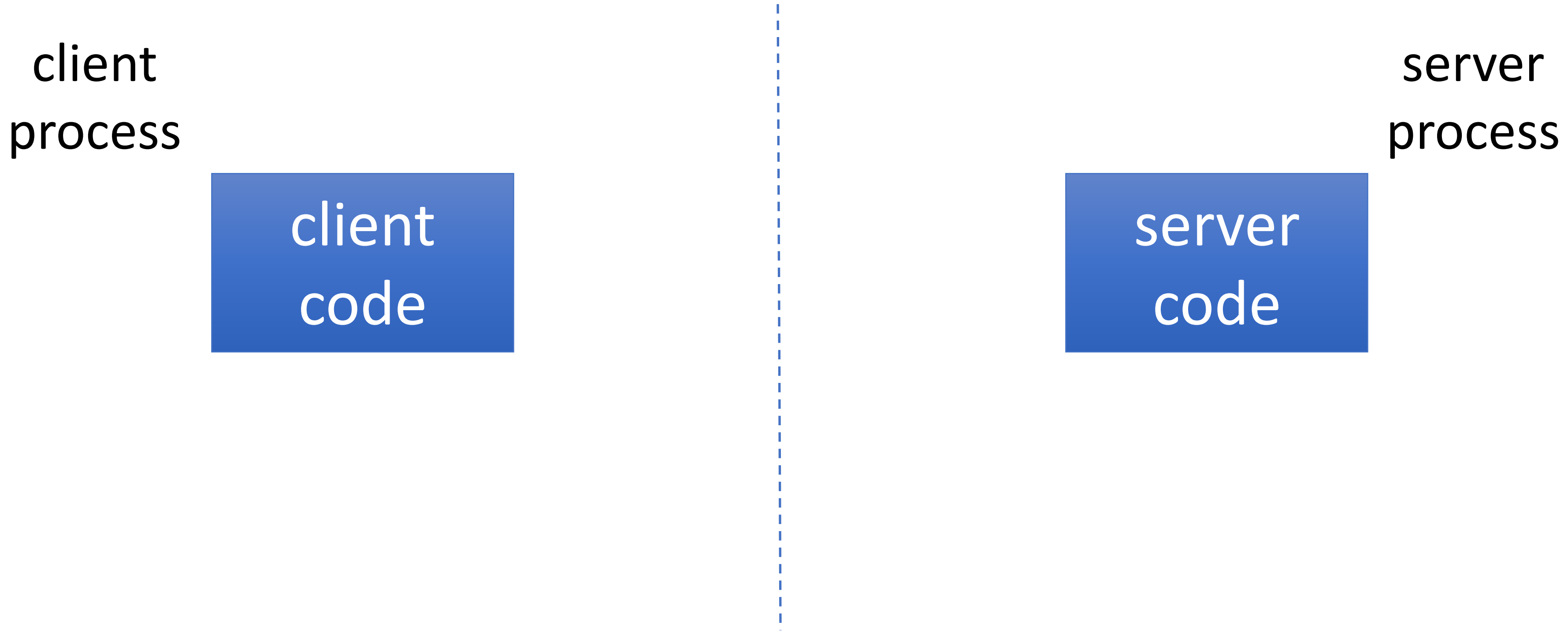
Client Stub

- Sends arguments in call message
- Receives return values in return message

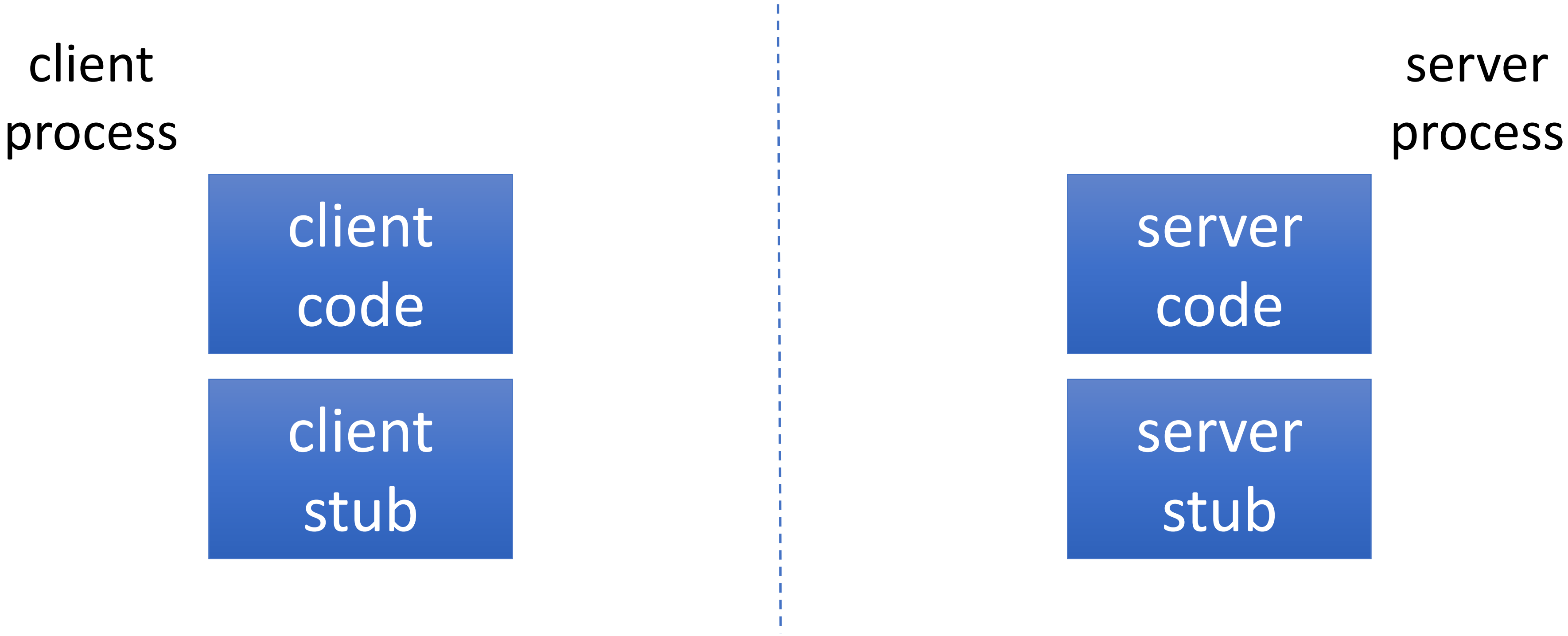
Server Stub

- Receives arguments in call message
- Invokes procedure
- Sends return values in return message

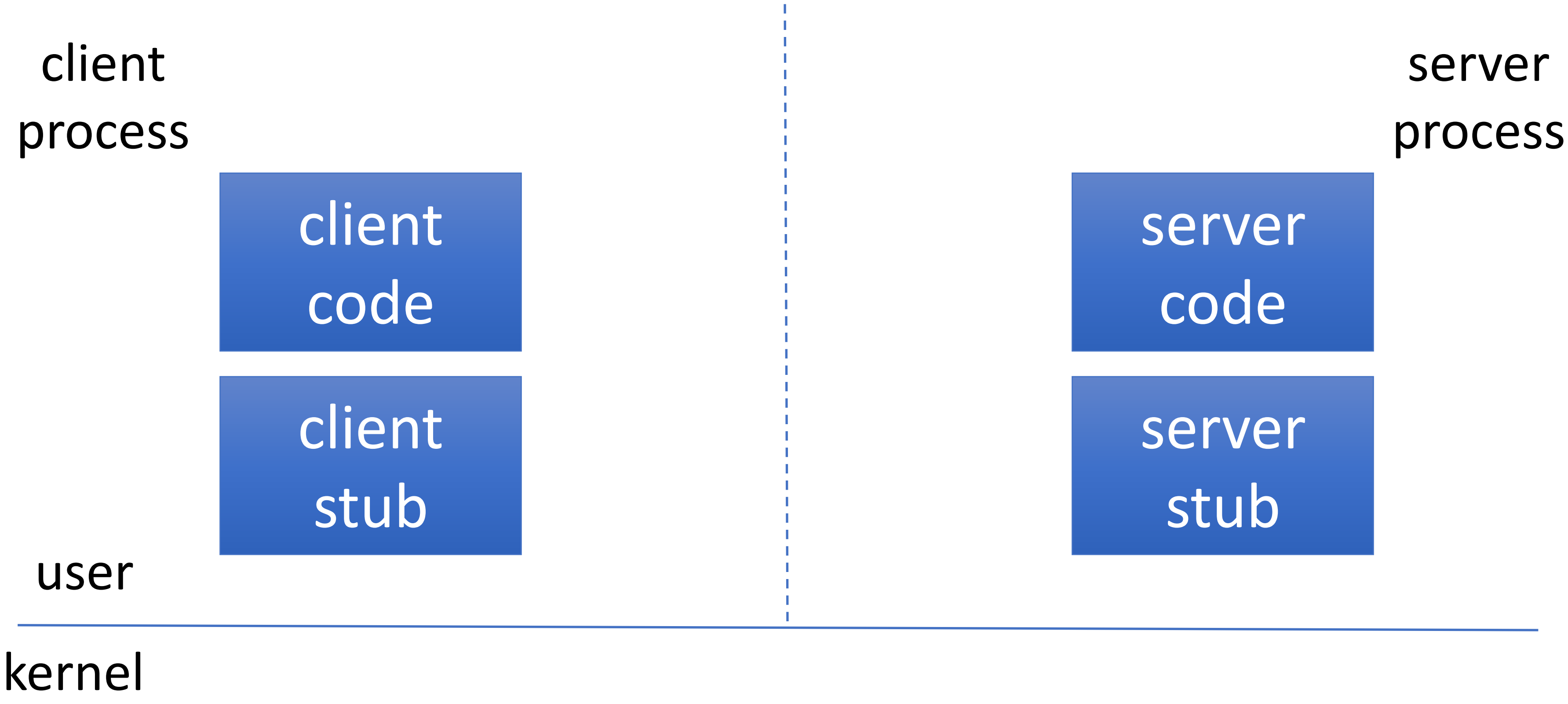
RPC Implementation



Client and Server Stubs



RPC Implementation: Call



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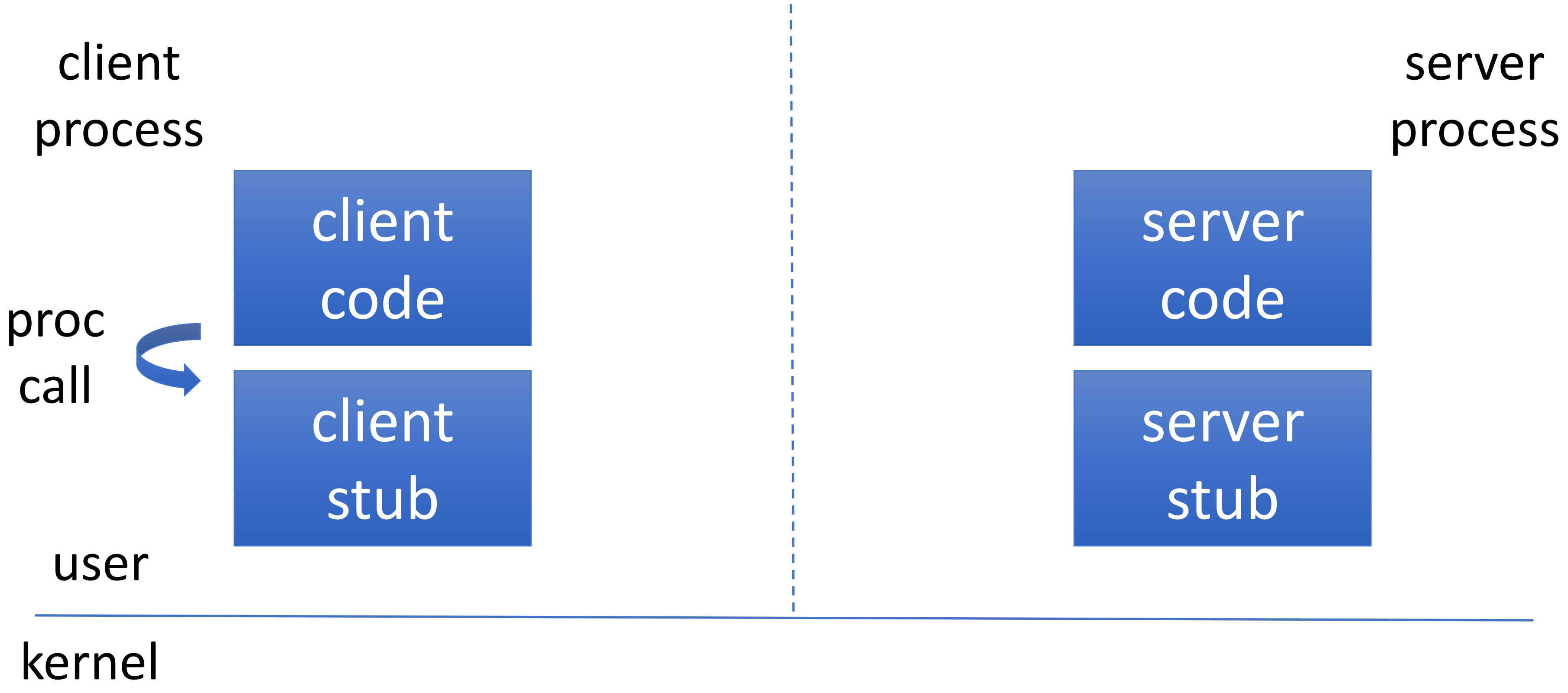

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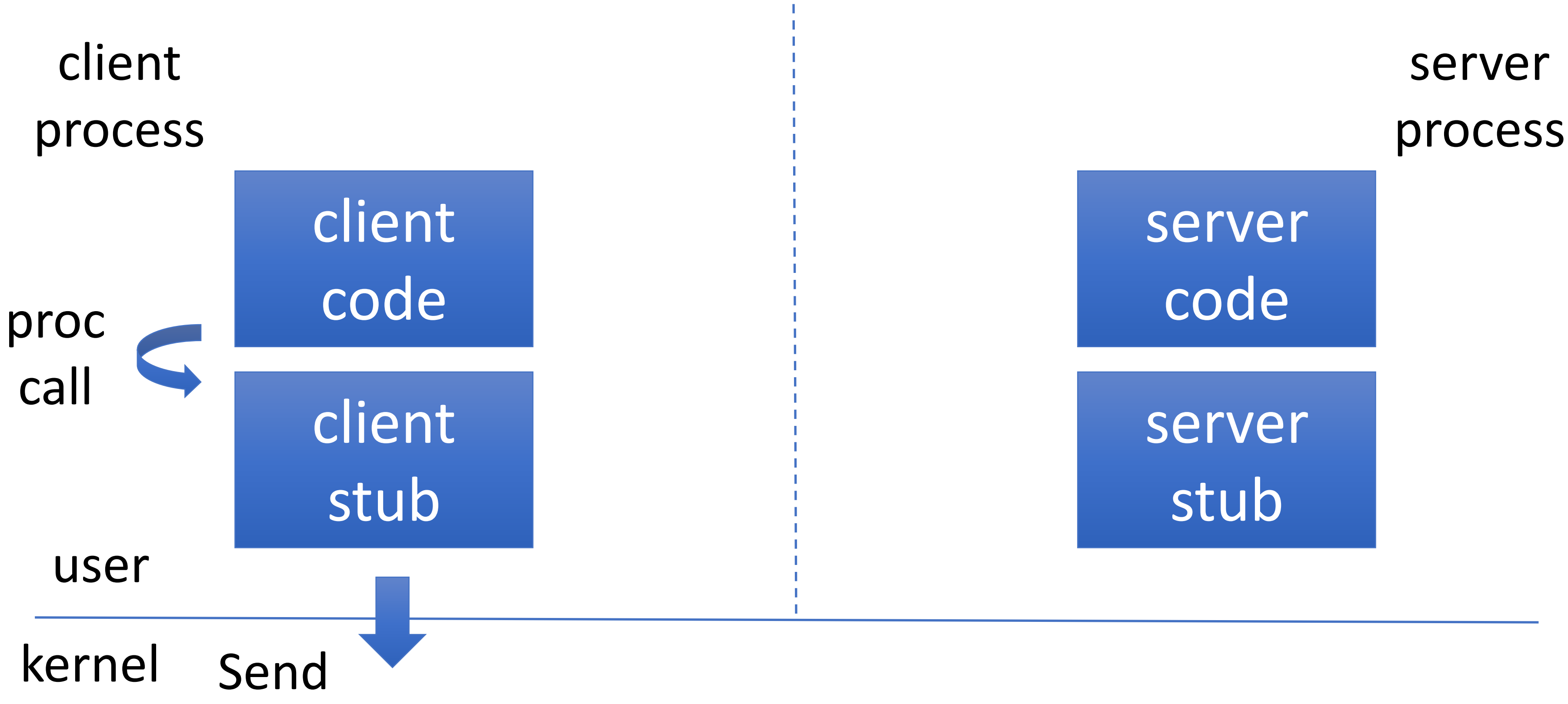

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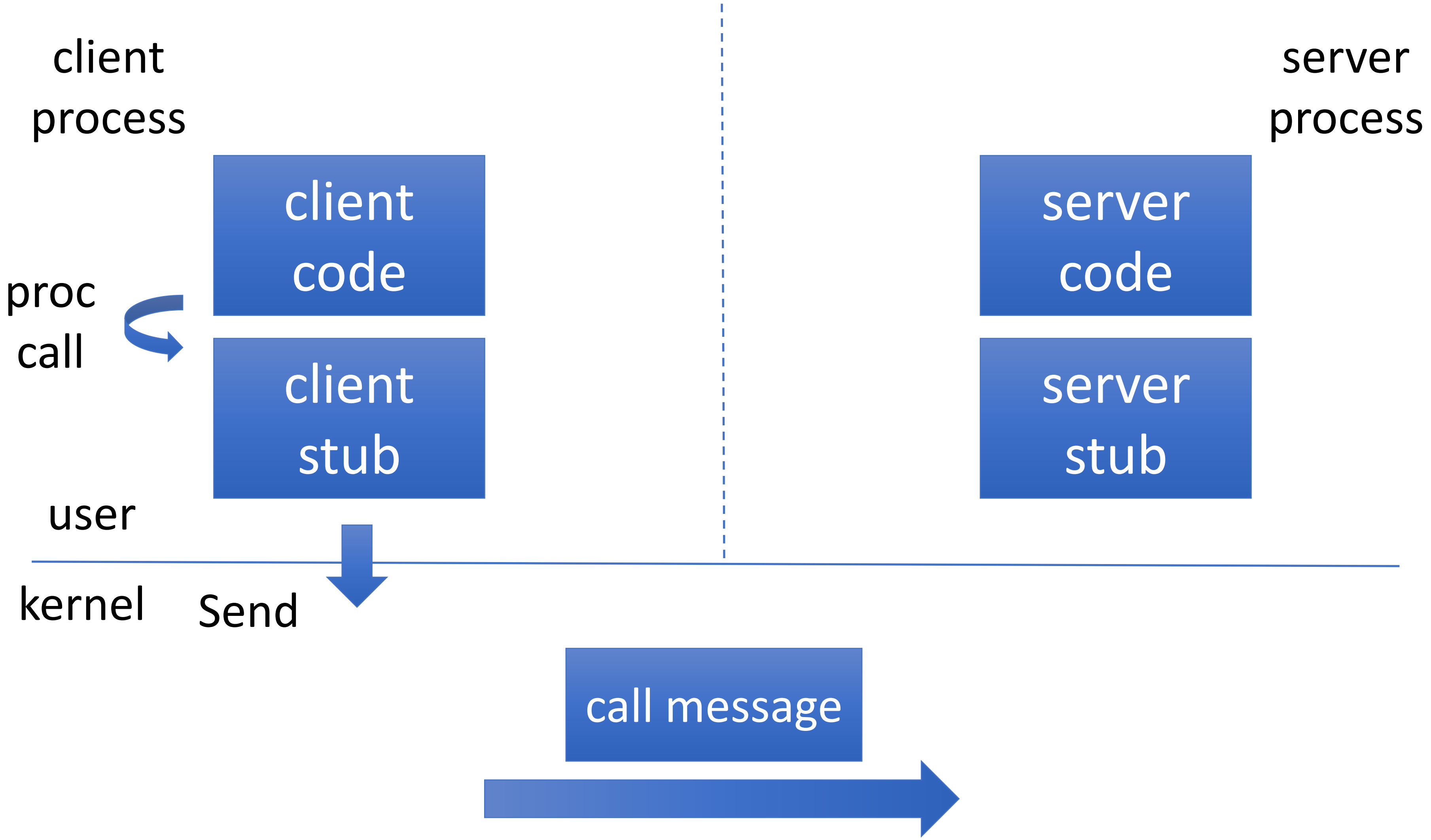

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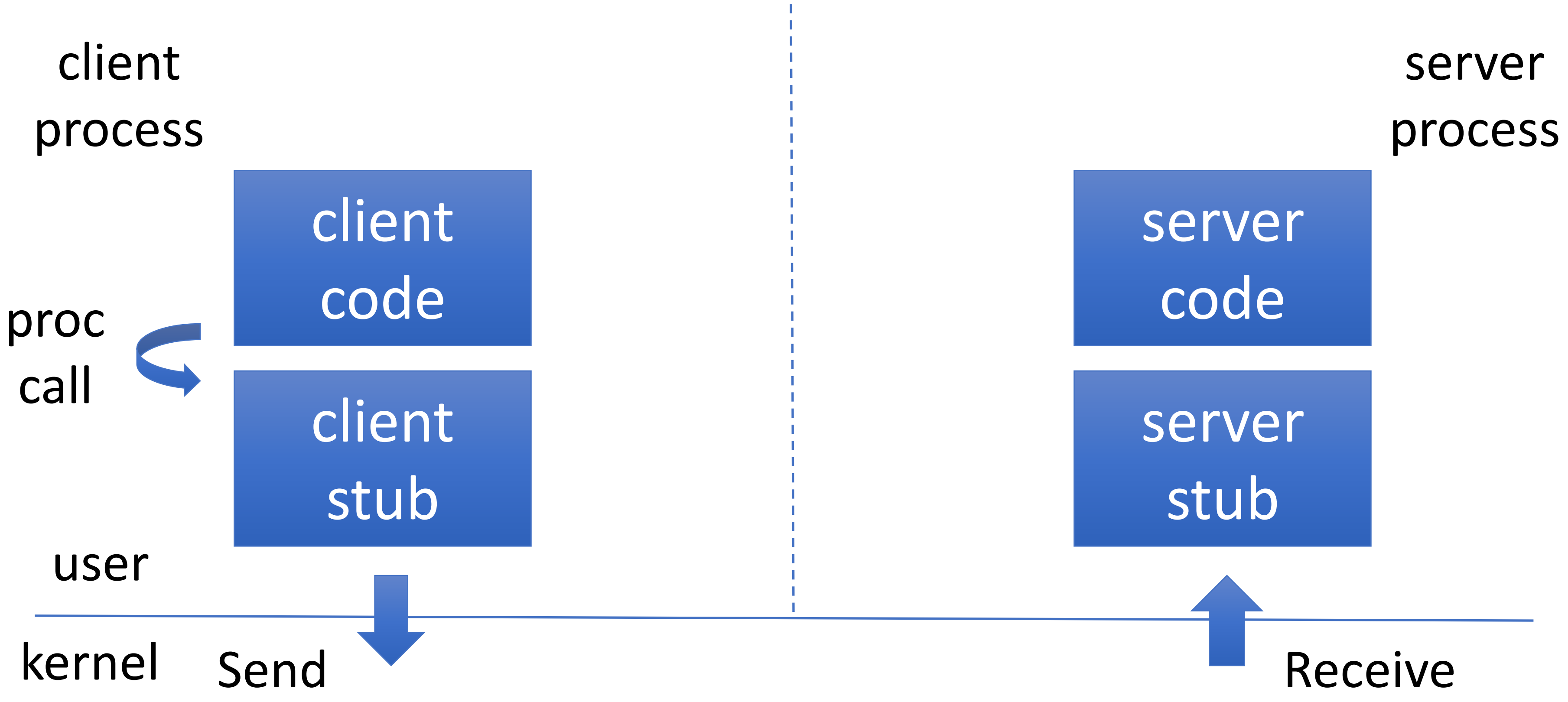

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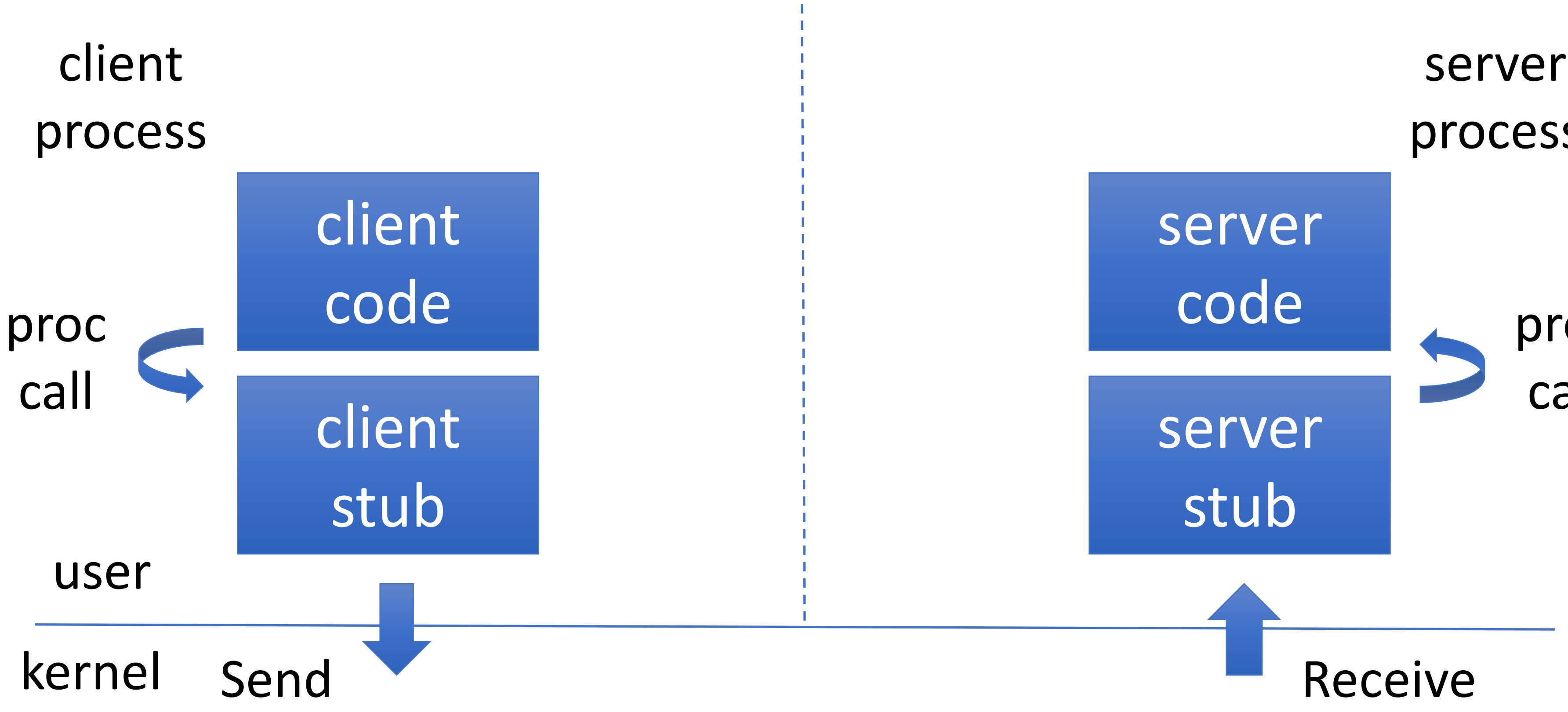

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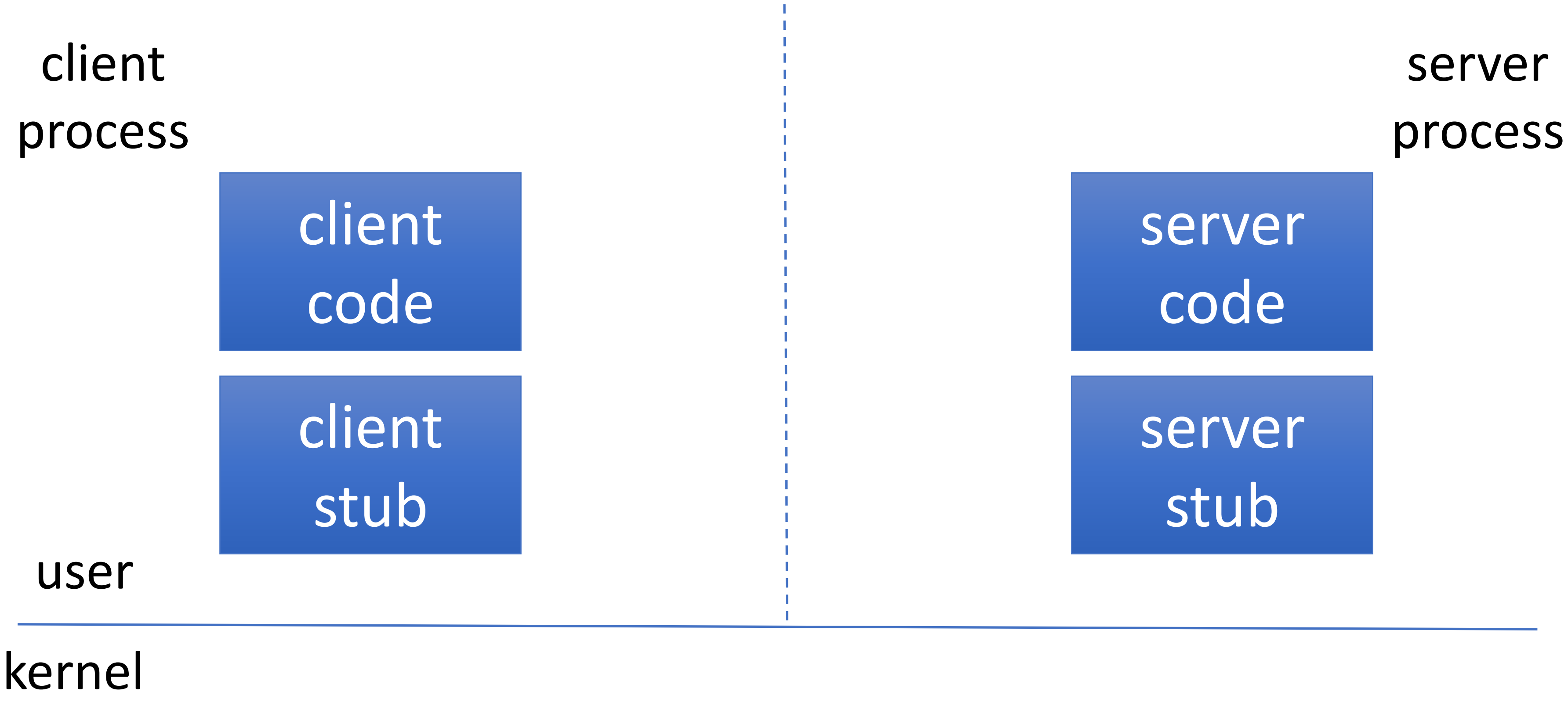

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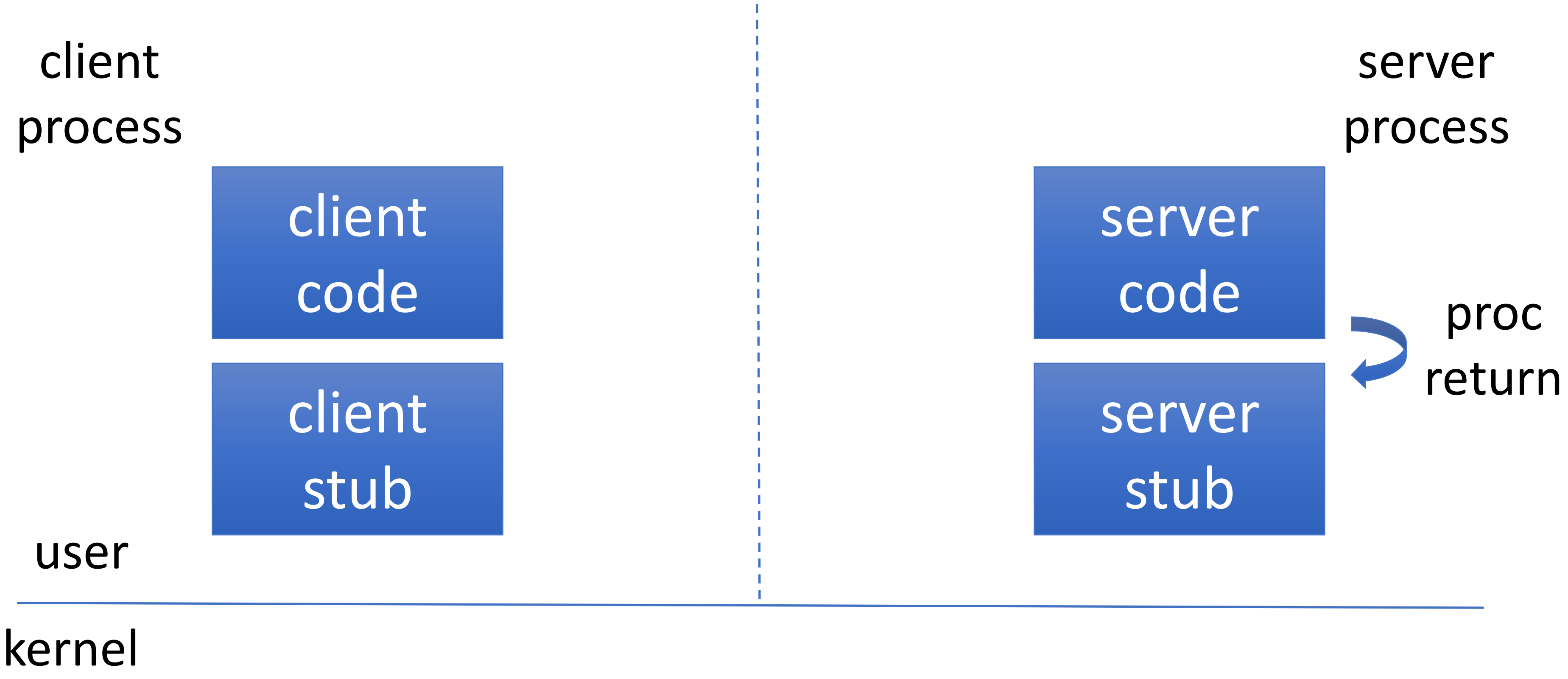

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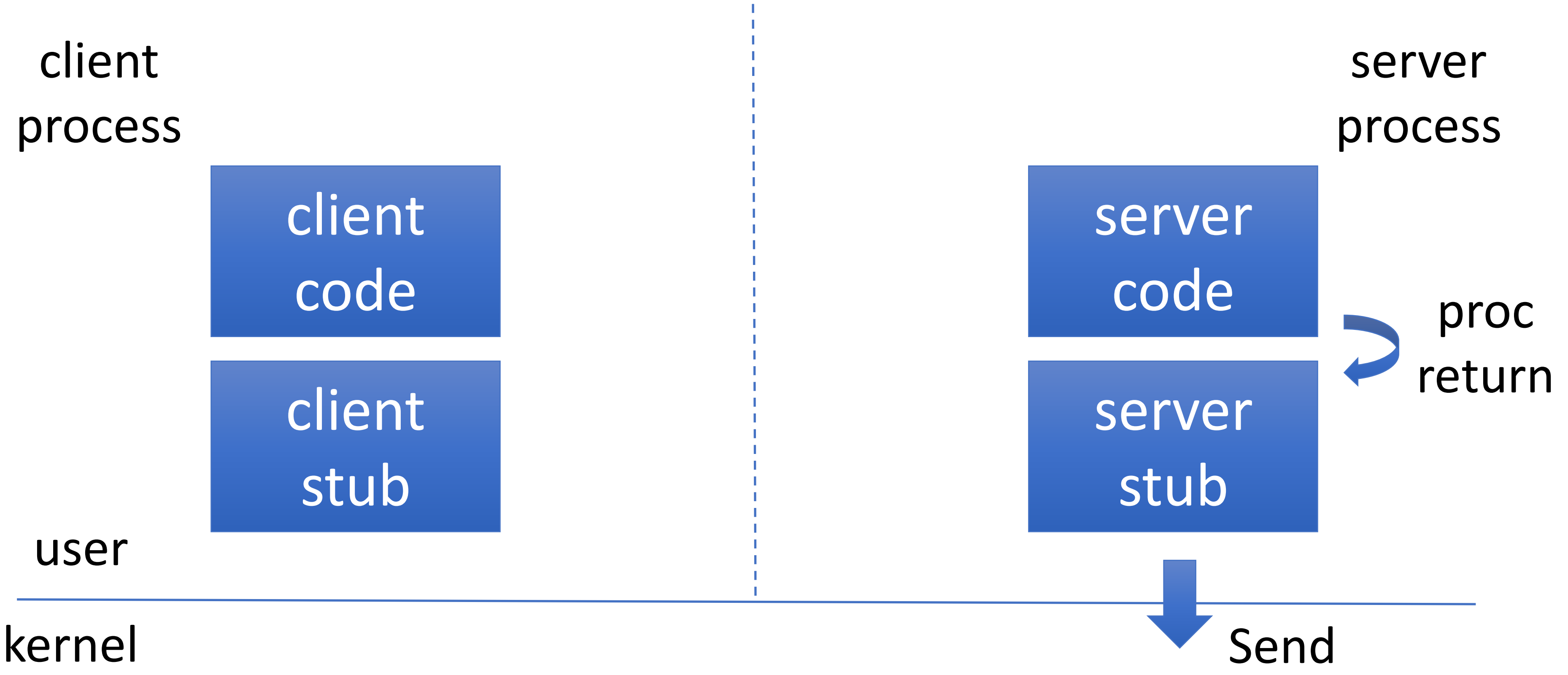

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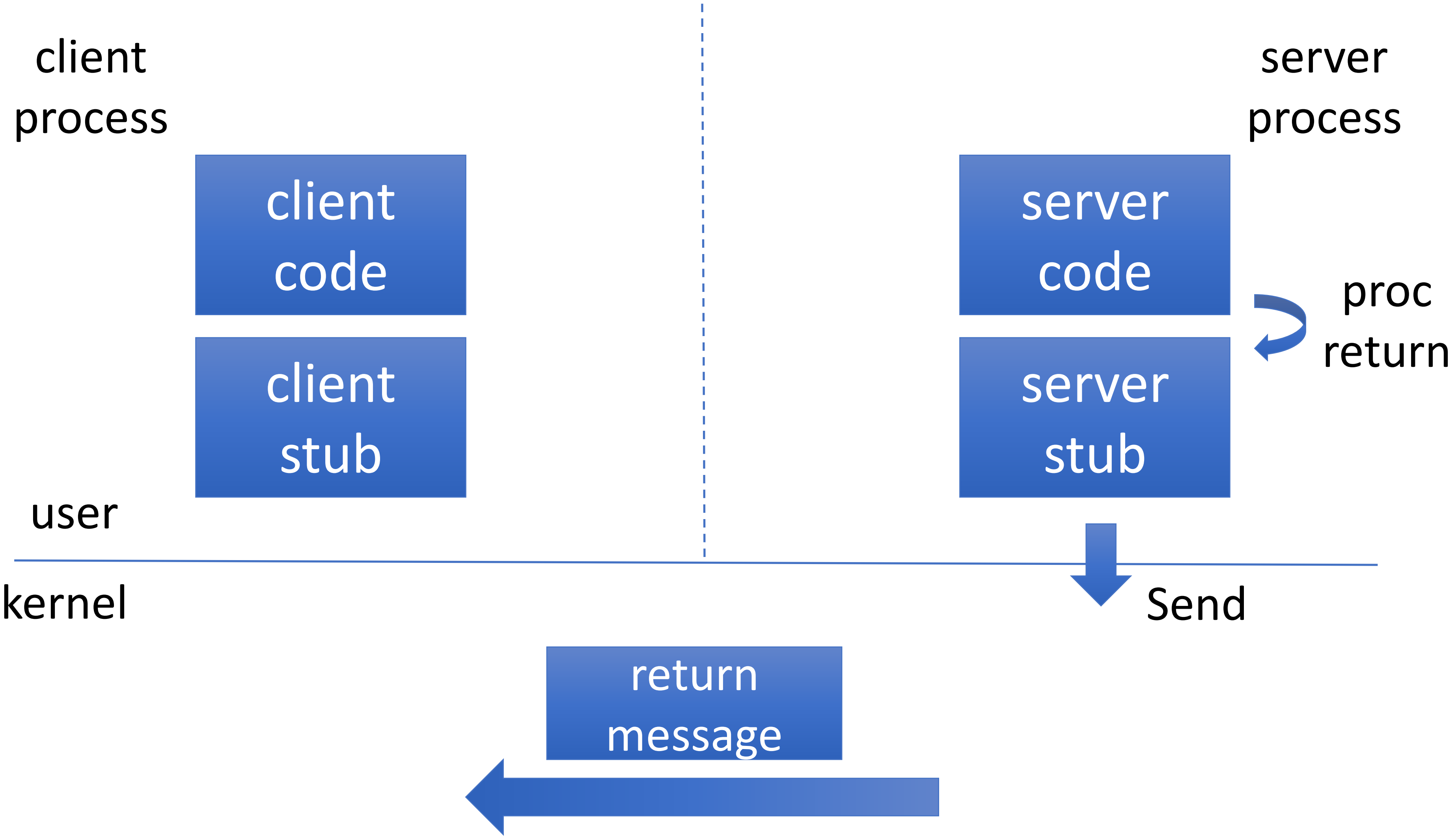

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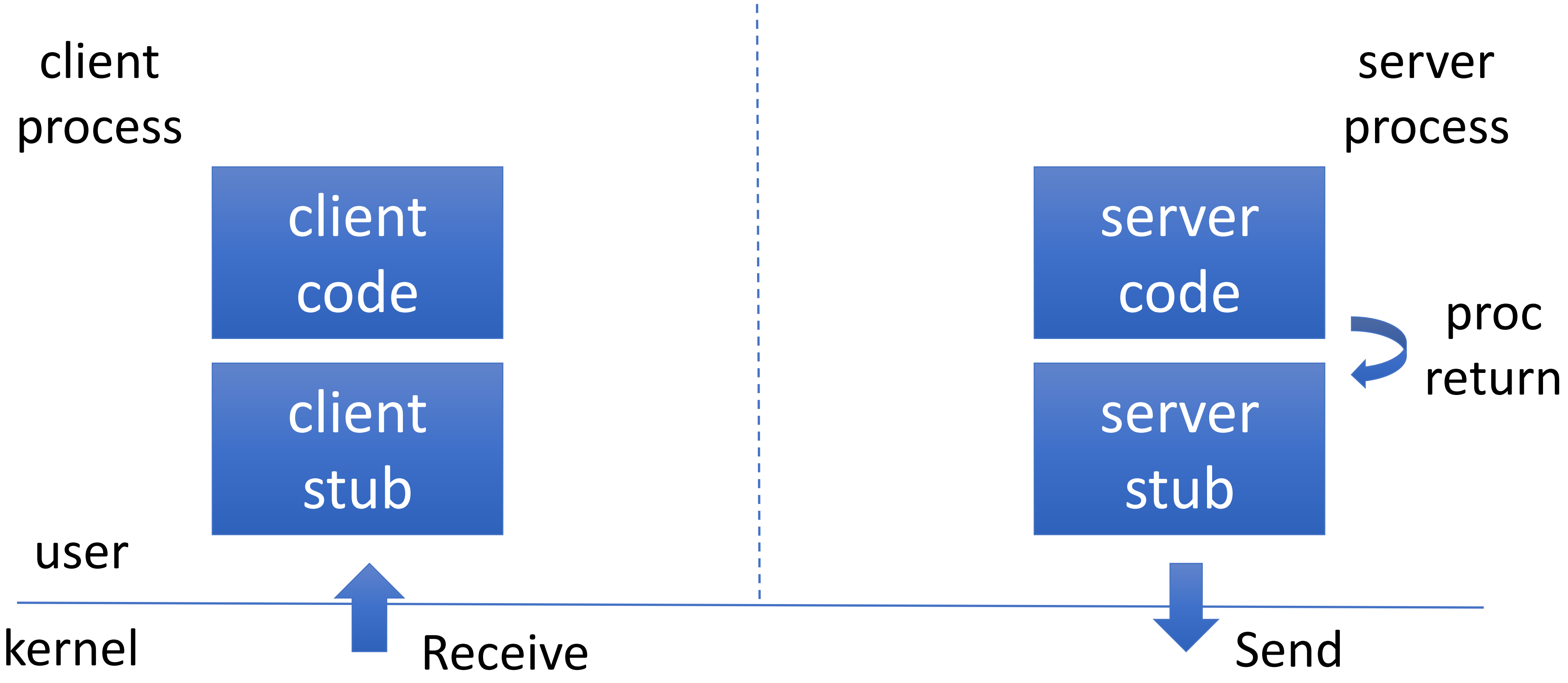

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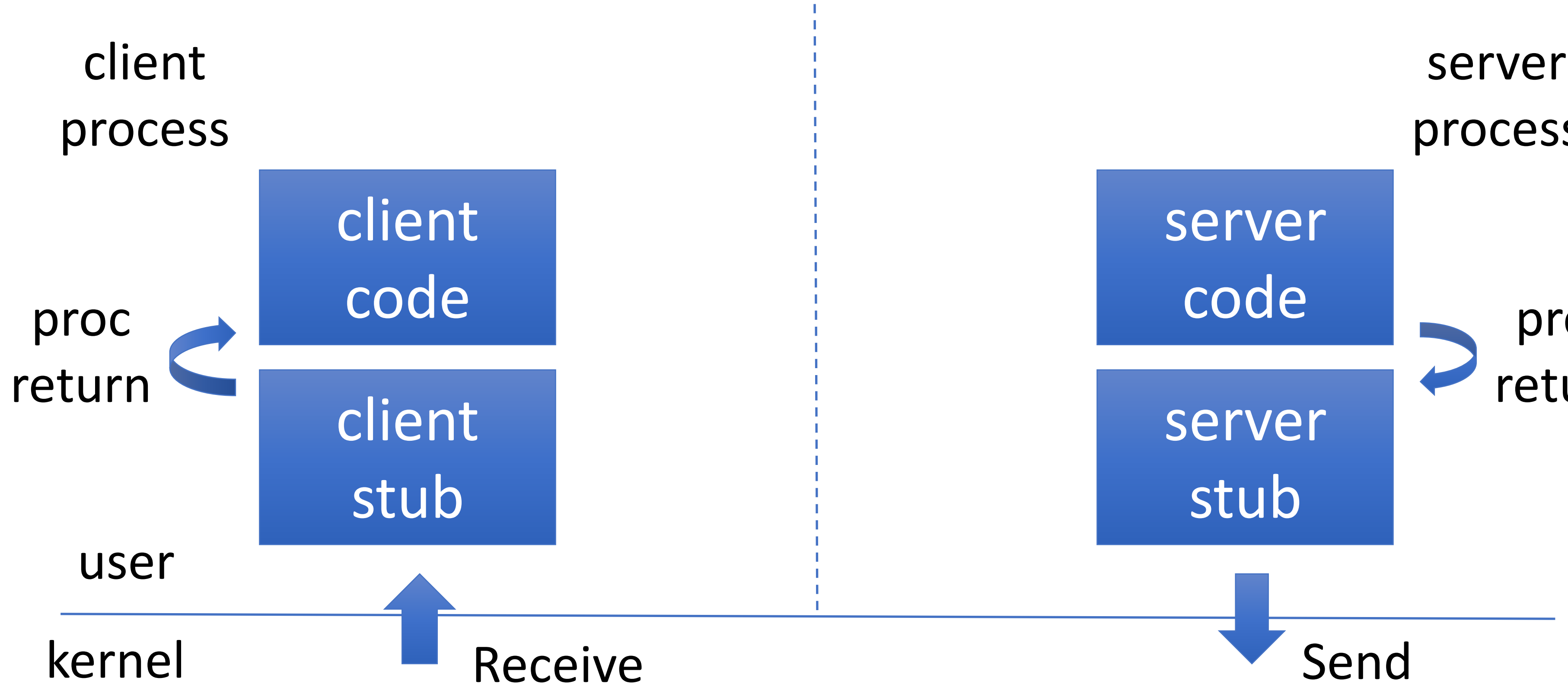

Example 1: Timeserver

- Supports GetTime() and SetTime()

Interface

```
long GetTime()
boolean SetTime(long time)
```

Server Code

```
GetTime()
 {
   return(ReadHardwareClock())
 }
SetTime(time)
 {
   WriteHardwareClock(time)
   return(1)
 }
```

Client Code

```
main()
{
   time = GetTime()
   SetTime(time + 100)
}
```

Message Format

- We already saw:
  - Call message contains arguments
- Must also include which procedure is called

Message Format

Call Message

procno
arg0

Return Message

retval0

Client Stub

```
GetTime()
{
   msg->procno = 1
   Send(msg)
   Receive(msg)
   return(msg->retval0)
}
SetTime(long time)
{
   msg->procno = 2
   msg->arg0 = time
   Send(msg)
   Receive(msg)
   return(msg->retval0)
}
```

Server Stub

```
while(true) do
 {
   Receive(msg)
   switch msg->procno {
     case 1: { time = GetTime()
               msg->retval0 = time
               Send(msg) }

     case 2: { ret = SetTime(msg->arg0)
                         msg->retval0 = ret
                         Send(msg) }
 }
```

client code

```
main()
{
 time = GetTime()
 SetTime(time + 100)
}
```

client stub

```
GetTime()
{
 msg->procno = 1
 Send(msg)
 Receive(msg)
 return(msg->retval0)
}

SetTime(long time)
{
 msg->procno = 2
 msg->arg0 = time
 Send(msg)
 Receive(msg)
 return(msg->retval0)
}
```

server code

```
GetTime()
{
 return(ReadHardwareClock())
}
SetTime(time)
{
 WriteHardwareClock(time)
 return(1)
}
```

server stub

```
while(true) do
{
 Receive( msg )
 switch msg->procno {
  case 1: { time = GetTime()
          msg->retval0 = time
          Send(msg) }
  case 2: { ret = SetTime(msg->arg0)
                 msg->retval0 = ret
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 }
```

client code

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main()
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  time = GetTime()
  SetTime(time + 100)
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client stub

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GetTime()
{
  msg->procno = 1
  Send(msg)
  Receive(msg)
  return(msg->retval0)
}

SetTime(long time)
{
  msg->procno = 2
  msg->arg0 = time
  Send(msg)
  Receive(msg)
  return(msg->retval0)
}
```

server code

```
GetTime()
{
  return(ReadHardwareClock())
}
SetTime(time)
{
  WriteHardwareClock(time)
  return(1)
}
```

server stub

```
while(true) do
{
  Receive( msg )
  switch msg->procno {
    case 1: { time = GetTime()
              msg->retval0 = time
              Send(msg) }
    case 2: { ret = SetTime(msg->arg0)
                    msg->retval0 = ret
                    Send(msg) }
  }
```

client code

```
main()
{
  time = GetTime()
  SetTime(time + 100)
}
```

client stub

```
GetTime()
{
  msg->procno = 1
  Send(msg)
  Receive(msg)
  return(msg->retval0)
}

SetTime(long time)
{
  msg->procno = 2
  msg->arg0 = time
  Send(msg)
  Receive(msg)
  return(msg->retval0)
}
```

server code

```
GetTime()
{
  return(ReadHardwareClock())
}
SetTime(time)
{
  WriteHardwareClock(time)
  return(1)
}
```

server stub

```
while(true) do
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  switch msg->procno {
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  time = GetTime()
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client stub

```
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{
  msg->procno = 1
  Send(msg)
  Receive(msg)
  return(msg->retval0)
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{
  msg->procno = 2
  msg->arg0 = time
  Send(msg)
  Receive(msg)
  return(msg->retval0)
}
```

server code

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{
  return(ReadHardwareClock())
}
SetTime(time)
{
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server stub

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  Receive( msg )
  switch msg->procno {
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  Receive(msg)
  return(msg->retval0)
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client code

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client stub

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GetTime()
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  Receive(msg)
  return(msg->retval0)
}

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{
  msg->procno = 2
  msg->arg0 = time
  Send(msg)
  Receive(msg)
  return(msg->retval0)
}
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server code

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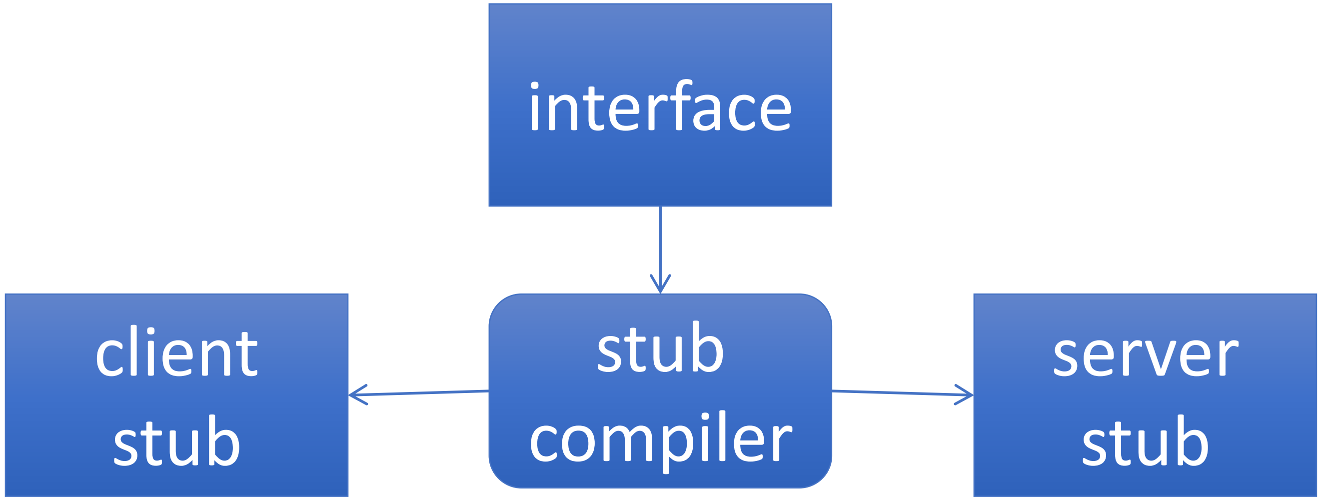
          msg->retval0 = time
          Send(msg) }
  case 2: { ret = SetTime(msg->arg0)
                msg->retval0 = ret
                Send(msg) }
 }
```

Note: Stubs Generated Automatically



Note: Network Packets

- “Messages” very similar to network packets
- In fact, can use RPC over networks
- RPC interface *most often* used for processes on *different machines*

- In this class we are only concerned with MPC on one machine
  - Comp 512, 535 are courses on computer networking

On Your Own

- If you’re interested in computer networks or distributed systems…

- Remainder of the slide deck has an actual example that you can try
- Details of RPC and implementing RPC interfaces **not** required
  - You may be tested on the concept of RPC
  - + how it relates to message passing
  - - but not on the details of client/server stubs or writing RPC code

Let’s see how this works in Linux

RPC library

- Make procedure calls on other machines across the network
  - Can also be used for inter-process communication on localhost
  - https://man7.org/linux/man-pages/man3/rpc.3.html

- Beyond the scope of the class to be fluent in RPC. We will just see a simple example.
  - Can continue exploring this in Networking classes (e.g., Distributed systems COMP512, Computer Networks COMP535).

Automatic stub generation

- **rpcbind** — universal addresses to RPC program number mapper
  - A server that converts RPC program numbers into universal addresses.
  - It must be running on the host to be able to make RPC calls on a server on that machine.
  - **sudo apt-get install rpcbind**

Automatic stub generation cont'd

rpcgen – tool that generates remote program interface modules.

- compiles source code written in the RPC language.
- RPC language is similar in syntax and structure to C.
- produces one or more C language source modules, which are then compiled by a C compiler.
- ☺ rpcgen reduces the development time that would otherwise be spent developing low-level routines.
    - Have a look at a tutorial

Another example: Sum Server

- Client
  - sends 2 integers: a and b
- Server
  - replies with a+b

Step 1: Defining the data structures with XDR routines, in add.x file

```
//add.x

struct numbers {
  int a;
  int b;
};


program ADD_PROG {                                  /* program number */
  version ADD_VERS {                                /* version number */
    int add(numbers) = 1;                   /* procedure */
  } = 1;
} = 0x12345;
```

Step 2: Compile **XDR routines** into **C code**

```
//add.x

struct numbers {
  int a;
  int b;
};


program ADD_PROG {                                  /* program number */
  version ADD_VERS {                                /* version number */
    int add(numbers) = 1;                  /* procedure */
  } = 1;
} = 0x12345;
```

```
~/comp310-w25/RPC$ rpcgen -a -C add.x
```

Step 3: Modify the server/client code.

```
~/comp310-w25/RPC/RPC-class$ ls
add_client.c  add.h           add_svc.c  add_xdr.c
add_clnt.c    add_server.c  add.x        Makefile.add
```

- add_client.c : client code that we need to implement
- add_clnt.c : automatically generated stub code – No need to change
- add_server.c : server code that we need to implement
- add_svc.c : automatically generated stub code – No need to change

Step 3.1: Modify the server code add_server.c

```
#include "add.h"


int * add_1_svc(numbers *argp, struct svc_req *rqstp)
{
	static int  result;
	/*
	 * insert server code here
	 */
	 return &result;
}
```

Step 3.1: Modify the server code add_server.c

```
#include "add.h"


int * add_1_svc(numbers *argp, struct svc_req *rqstp)
{
	static int  result;
	/*
	 * insert server code here
	 */
	printf("add(%d,%d) is called\n", argp->a, argp->b);
	result = argp->a + argp->b;
	return &result;
}
```

Step 3.2: Modify the client code add_client.c

```
int main (int argc, char *argv[]) {
  char *host;
  if (argc < 2) {
    printf("usage: %s server_host\n", argv[0]);
    exit(1);
  }
  host = argv[1];
  add_prog_1(host);
  exit(0);
}
```

```
void add_prog_1(char *host) {
  CLIENT *clnt;
  int  *result_1;
  numbers  add_1_arg;

#ifndef DEBUG
  clnt = clnt_create (host, ADD_PROG, ADD_VERS, "udp");
  if (clnt == NULL) {
    clnt_pcreateerror (host);
    exit (1);
  }
#endif  /* DEBUG */

  result_1 = add_1(&add_1_arg, clnt);
  if (result_1 == (int *) NULL) {
    clnt_perror (clnt, "call failed");
  }
#ifndef DEBUG
  clnt_destroy (clnt);
#endif   /* DEBUG */
}
```

Step 3.2: Modify the client code add_client.c

```
int main (int argc, char *argv[]) {
  char *host;
  if (argc < 4) {
    printf("usage: %s server_host\n", argv[0]);
    exit(1);
  }
  host = argv[1];
  add_prog_1(host);
  add_prog_1(host, atoi(argv[2]), atoi(argv[3]));

  exit(0);
}
```

```
void add_prog_1(char *host, int x, int y) {
  CLIENT *clnt;
  int  *result_1;
  numbers  add_1_arg;

  //...

  add_1_arg.a = x;
  add_1_arg.b = y;

  result_1 = add_1(&add_1_arg, clnt);
  if (result_1 == (int *) NULL) {
    clnt_perror (clnt, "call failed");
  }  else {
    printf("Result:%d\n", *result_1);
  }
  //...
}
```

Step 4: Compile **C code**

```
~/comp310-w25/RPC/RPC-class$ ls
add_client.c  add.h           add_svc.c  add_xdr.c
add_clnt.c    add_server.c  add.x        Makefile.add
```

```
~/comp310-w25/RPC$ make -f Makefile.add
```

Step 5: Launch the server

```
~/comp310-w25/RPC$ ./add_server
```

Step 6: Use the client

Numbers we want to add

Open new terminal window

```
~/comp310-w25/RPC$ ./add_client localhost 1 2
Result:3
```

Server process is on the same machine, so we use localhost

Meanwhile, in the server window:

```
~/comp310-w25/RPC$ ./add_server
add(1,2) is called
```

Optional Homework

- Use the same process to create the Timeserver in example 1
- *Hint: The linked rpcgen tutorial will help*

Key Concepts for Today

- Interprocess communication
- Message passing
- Remote procedure call

Further Optional Reading

Operating Systems: Three Easy Pieces by R. & A. Arpaci-Dusseau

Chapters 25 – 32 (inclusive) https://pages.cs.wisc.edu/~remzi/OSTEP/

Credits:

Some slides adapted from the OS courses of Profs. Remzi and Andrea Arpaci-Dusseau (University of Wisconsin-Madison), Prof. Willy Zwaenepoel (University of Sydney), and Prof. Maurice Herlihy (Brown University)