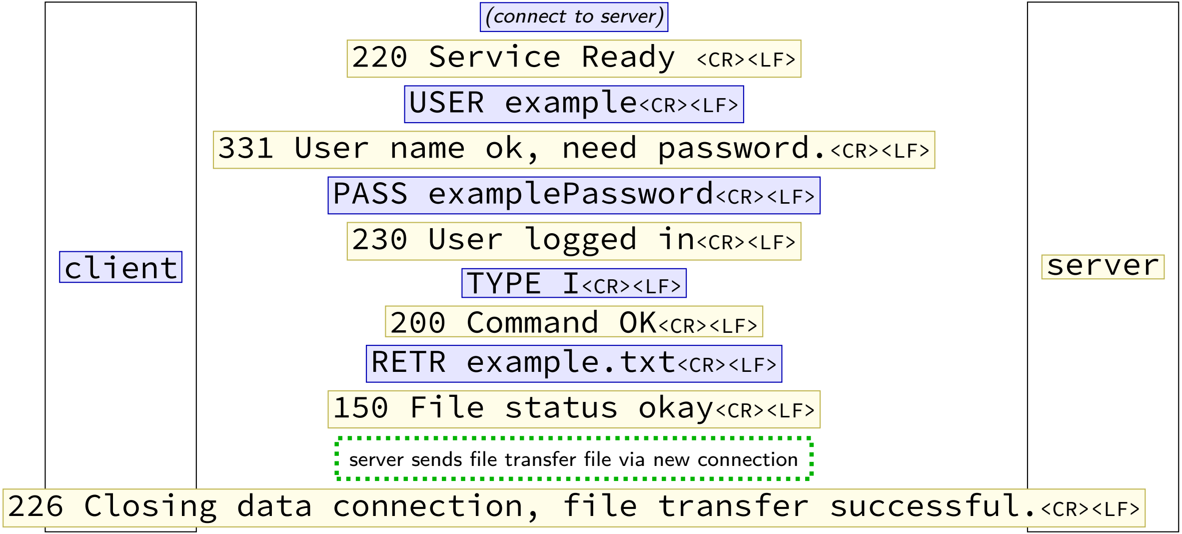
RPC / Network FSes

last time

names and addresses
  - IPv4, IPV6 addresses, router's tables
  - DNS: hierarchical database

POSIX socket API
  - socket
  - bind/listen/accept
  - getaddrinfo

FTP protocol (simplified)



client

server

(connect to server)

```
220 Service Ready <CR><LF>
USER example<CR><LF>
331 User name ok, need password.<CR><LF>
PASS examplePassword<CR><LF>
230 User logged in<CR><LF>
TYPE I<CR><LF>
200 Command OK<CR><LF>
RETR example.txt<CR><LF>
150 File status okay<CR><LF>
```

server sends file transfer file via new connection

```
226 Closing data connection, file transfer successful.<CR><LF>
```

notable things about FTP

FTP is stateful — previous commands change future ones

- logging in for whole connection
- change current directory
- set image file type (binary, not text)

FTP uses separate connections for transferring data

- PASV: client connects separately to server
- PORT: client specifies where server connects
- (+ very rarely used default: connect back to port 20)

status codes for every command

remote procedure calls

recall: transparency — hide network/distributedness

goal: I write a bunch of functions

can call them from another machine

some tool + library handles all the details

called *remote procedure calls*

stubs

typical RPC imlpementation: generates *stubs*

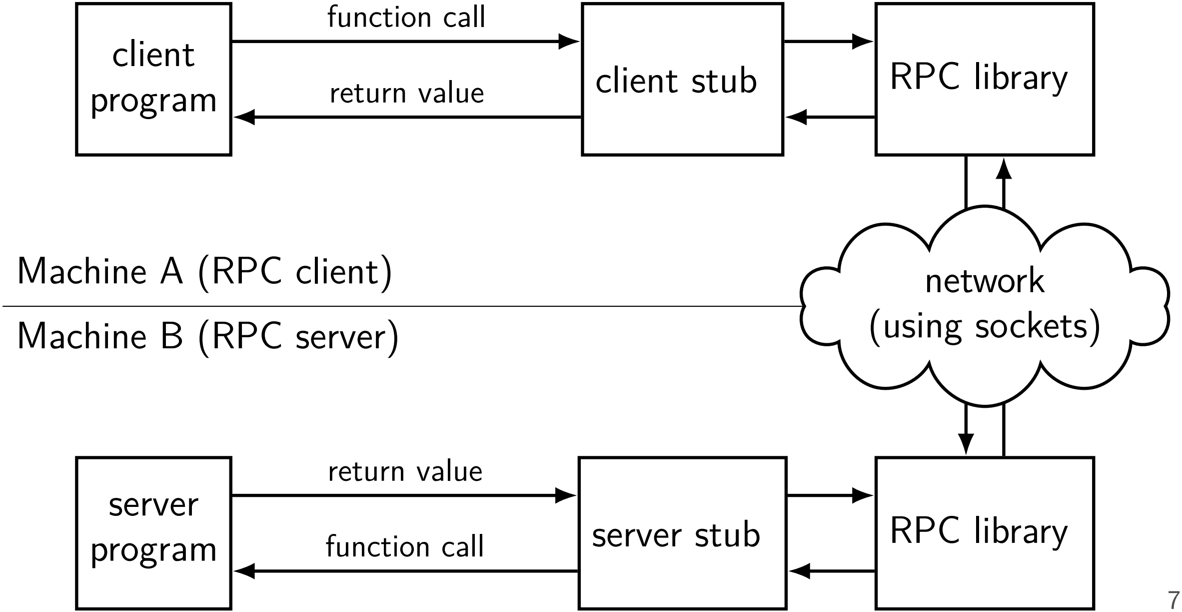
stubs = wrapper functions that stand in for other machine

calling remote procedure? call the stub

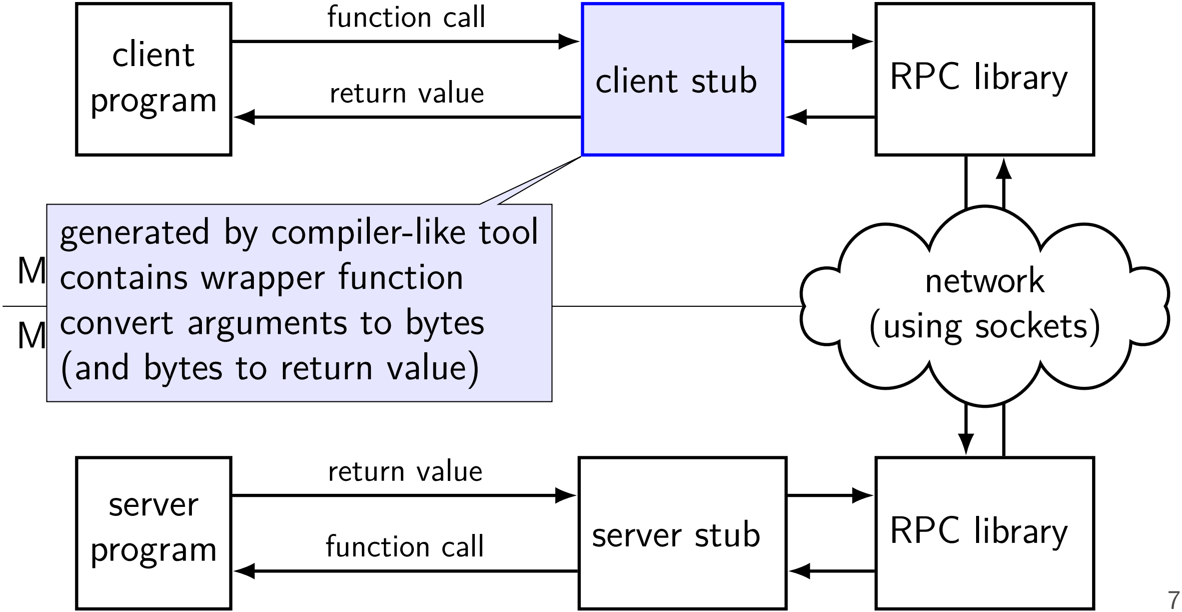
- same prototype are remote procedure

implementing remote procedure? a stub function calls you

typical RPC data flow

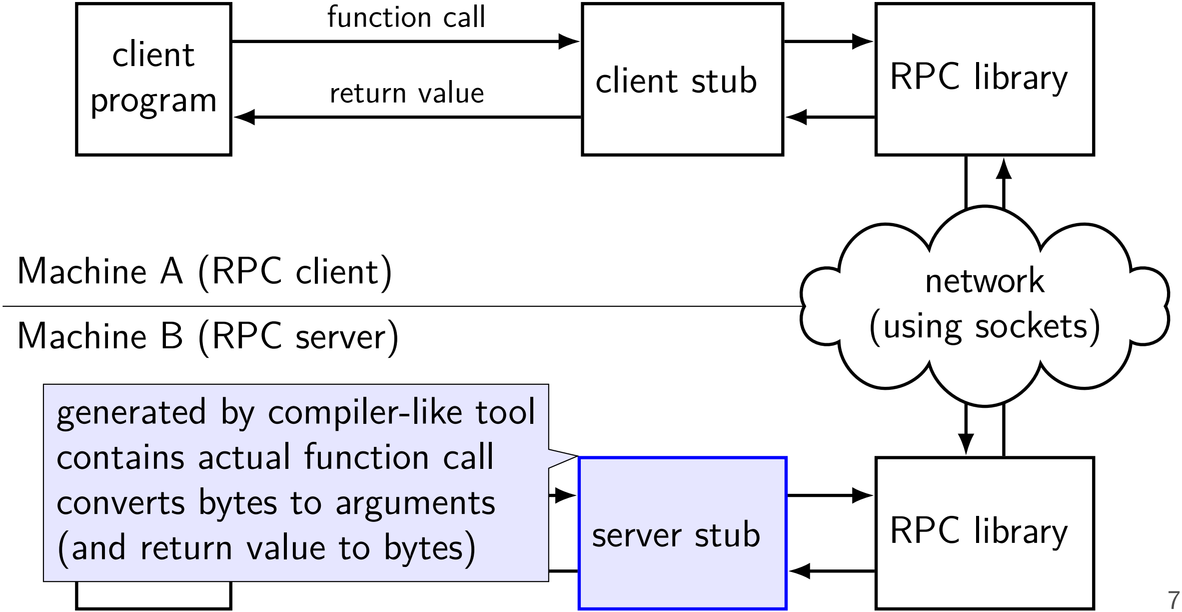


typical RPC data flow



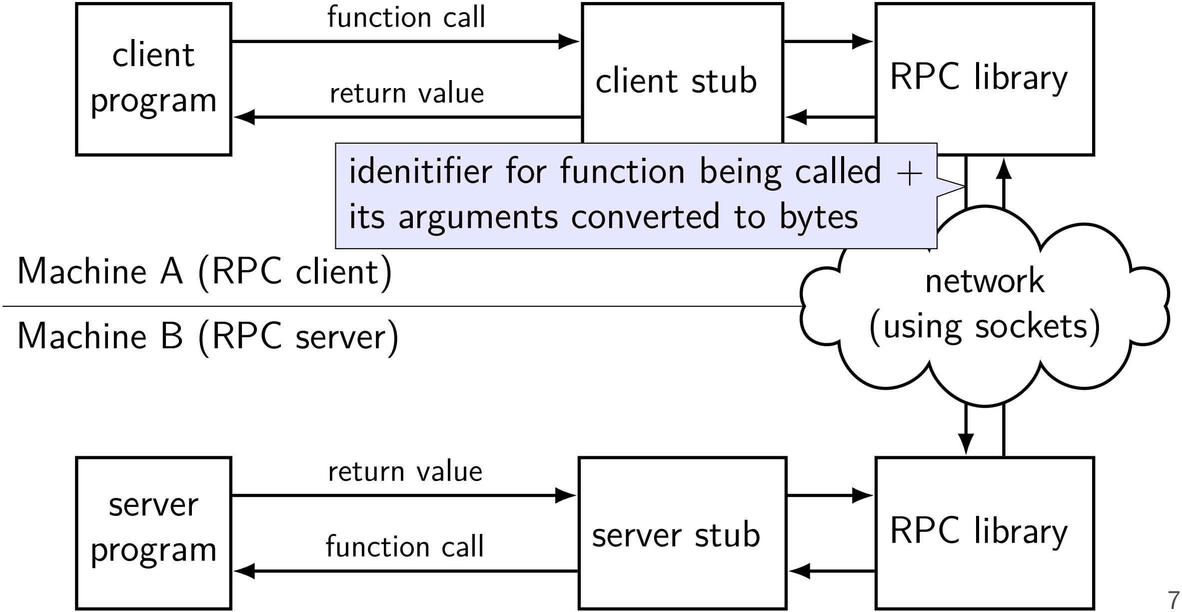
generated by compiler-like tool
contains wrapper function
convert arguments to bytes
(and bytes to return value)

typical RPC data flow



generated by compiler-like tool
contains actual function call
converts bytes to arguments
(and return value to bytes)

typical RPC data flow



client program

function call

return value

client stub

RPC library

idenitifier for function being called + its arguments converted to bytes

Machine A (RPC client)

Machine B (RPC server)

network (using sockets)

server program

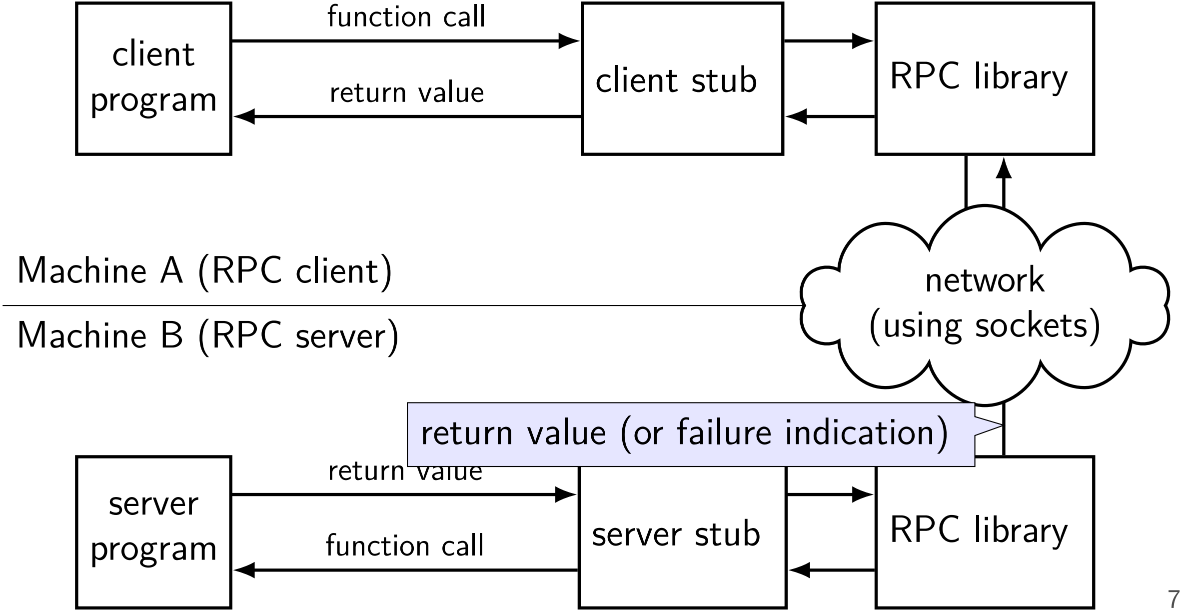
return value

function call

server stub

RPC library

typical RPC data flow



RPC use pseudocode (C-like)

client:

```
    RPCContext context = RPC_GetContext("server␣name");
    ...
    // dirprotocol_mkdir is the client stub
    result = dirprotocol_mkdir(context, "/directory/name");
```

---

server:

```
main() {
  dirprotocol_RunServer();
}

// called by server stub
int real_dirprotocol_mkdir(RPCLibraryContext context, char *name) {
  ...
}
```

RPC use pseudocode (OO-like)

client:

```
   DirProtocol* remote = DirProtocol::connect("server␣name");

   // mkdir() is the client stub
   result = remote−>mkdir("/directory/name");
```

---

server:

```
main() {
    DirProtocol::RunServer(new RealDirProtocol, PORT_NUMBER);
}

class RealDirProtocol : public DirProtocol { public:
  int mkdir(char *name) {
    ...
  }
};
```

marshalling

RPC system needs to send arguments over the network

- and also return values

called *marshalling* or *serialization*

can't just copy the bytes from arguments

- pointers (e.g. `char*`)
- different architectures (32 versus 64-bit; endianness)

interface description langauge

typically have file specifying protocol
  - procedures exposed
  - any data structures used as arguments/return values

compiled into client/server stubs/marhsalling/unmarshalling code

IDL pseudocode + marshalling example

```
protocol dirprotocol {
    1: int32 mkdir(string);
    2: int32 rmdir(string);
}
```

`mkdir("/directory/name")` returning `0`

client sends: `\x01/directory/name\x00`

server sends: `\x00\x00\x00\x00`

GRPC examples

will show examples for gRPC

RPC system originally developed at Google

defines interface description language, message format

uses a protocol on top of HTTP/2

note: gRPC makes some choices other RPC systems don't

GRPC IDL example

```
message MakeDirArgs { required string path = 1; }
message ListDirArgs { required string path = 1; }

message DirectoryEntry {
    required string name = 1;
    optional bool is_directory = 2;
}

message DirectoryList {
    repeated DirectoryEntry entries = 1;
}

service Directories {
    rpc MakeDirectory(MakeDirArgs) returns (Empty) {}
    rpc ListDirectory(ListDirArgs) returns (DirectoryList) {}
}
```

GRPC IDL example

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message MakeDirArgs { required string path = 1; }
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service Directories {
    rpc
    rpc                                                     {}
}
```

messages: turn into C++ classes
with accessors + marshalling/demarshalling functions
part of *protocol buffers* (usable without RPC)

GRPC IDL example

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message DirectoryList {
    repeated DirectoryEntry entries = 1;
}

service D
    rpc M
    rpc L                                              ) {}
}
```

fields are numbered (can have more than 1 field)
numbers are used in byte-format of messages
allows changing field names, adding new fields, etc.

GRPC IDL example

will become method of C++ class

```
message MakeDirArgs { required string path = 1; }
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```

GRPC IDL example

rule: arguments/return value always a *message*

```
message Mak
message ListDirArgs { required string path = 1; }

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}
```

RPC server implementation (method 1)

```
class DirectoriesImpl : public Directories::Service {
public:
    Status MakeDirectory(ServerContext *context,
                         const MakeDirArgs* args,
                         Empty *result) {
        std::cout << "MakeDirectory(" << args->name() << ")\n";
        if (-1 == mkdir(args->path().c_str()) {
            return Status(StatusCode::UNKNOWN, strerror(errno));
        }
        return Status::OK;
    }
    ...
};
```

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RPC server implementation (method 2)

```
class DirectoriesImpl : public Directories::Service {
public:
    Status ListDirectory(ServerContext *context,
                         const ListDirArgs* args,
                         DirectoryList *result) {
        ...
        for (...) {
            result->add_entry(...);
        }
        return Status::OK;
    }
    ...
};
```

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};
```

RPC server implementation (starting)

```
DirectoriesImpl service;
ServerBuilder builder;
builder.AddListeningPort("127.0.0.1:43534",
            grpc::InsecureServerCredentials());
builder.RegisterService(&service);
unique_ptr<Server> server = builder.BuildAndStart();
server->Wait();
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RPC client implementation (method 1)

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unique_ptr<Directories::Stub> stub(Directories::NewStub(channel));
ClientContext context; MakeDirectoryArgs args; Empty empty;
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Status status = stub->MakeDirectory(&context, args, &empty);
if (!status.ok()) { /* handle error */ }
```

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for (int i = 0; i < list.entries_size(); ++i) {
    cout << list.entries(i).name() << endl;
}
```

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RPC non-transparency

setup is not transparent — what server/port/etc.
- ideal: system just knows where to contact?

errors might happen
- what if connection fails?

server and client versions out-of-sync
- can't upgrade at the same time — different machines

performance is very different from local

some gRPC errors

method not implemented

- e.g. server/client versions disagree
- local procedure calls — linker error

deadline exceeded

- no response from server after a while — is it just slow?

connection broken due to network problem

leaking resources?

```
RemoteFile rfh;
stub.RemoteOpen(&context, filename, &rfh);

RemoteWriteRequest remote_write;
remote_write.set_file(rfh);
remote_write.set_data("Some␣text.\n");
stub.RemotePrint(&context, remote_write, ...);
stub.RemoteClose(rfh);
```

---

what happens if client crashes?

does server still have a file open?

- related to issue of statefullness

on versioning

normal software: multiple versions of library?

- extra argument for function
- change what function does
- …

want this for RPC, but how?

gRPC’s versioning

gRPC: messages have field numbers

rules allow adding new *optional* fields

- get message with extra field — ignore it
- (extra field includes field numbers not in *our* source code)
- get message missing optional field — ignore it

otherwise, need to make new methods for each change

- …and keep the old ones working for a while

versioned protocols

ONC RPC solution: whole service has versions

have implementations of multiple versions in server

verison number is part of every procedures name

RPC performance

local procedure call: ~ 1 ns

system call: ~ 100 ns

network part of remote procedure call

- (typical network) $> 400\,000$ ns
- (super-fast network) $2\,600$ ns

RPC locally

not uncommon to use RPC one machine

more convenient than pipes?

allows shared memory implementation

- mmap one common file
- use mutexes+condition variables+etc. inside that memory

network filesystems

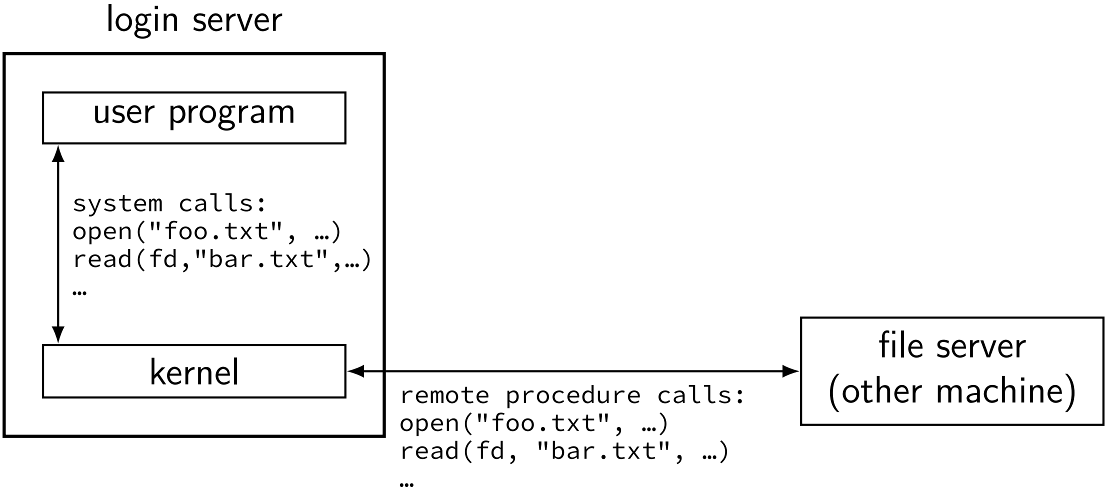
department machines — your files always there

- even though several machines to log into

how? there's a *network file server*

filesystem is backed by a remote machine

simple network filesystem



login server

user program

system calls:
`open("foo.txt", …)`
`read(fd,"bar.txt",…)`
…

kernel

remote procedure calls:
`open("foo.txt", …)`
`read(fd, "bar.txt", …)`
…

file server
(other machine)

system calls to RPC calls?

just turn system calls into RPC calls?

(or calls to the kernel's internal fileystem abstraction, e.g. Linux's Virtual File System layer)

has some problems:

what state does the server need to store?

what if a client machine crashes?

what if the server crashes?

how fast is this?

state for server to store?

open file descriptors?

- what file
- offset in file

current working directory?

gets pretty expensive across N files

if a client crashes?

well, it hasn't responded in N minutes, so

can the server delete its open file information yet?

what if its cable is plugged back in and it works again?

if the server crashes?

well, first we restart the server/start a new one...

then, what do clients do?

probably need to restart to?

can we do better?

performance

usually reading/writing files/directories goes to local memory

- lots of work to have big caches, read-ahead

so open/read/write/close/rename/readdir/etc. take microseconds

- open that file? yes, I have the direntry cached

now they take milliseconds+

- open that file? let's ask the server if that's okay

can we do better?

NFSv2

NFS (Network File System) version 2

standardized in RFC 1094 (1989)

based on RPC calls

NFSv2 RPC calls (subset)

LOOKUP(dir file ID, filename) → file ID

GETATTR(file ID) → (file size, owner, ...)

READ(file ID, offset, length) → data

WRITE(file ID, data, offset) → success/failure

CREATE(dir file ID, filename, metadata) → file ID

REMOVE(dir file ID, filename) → success/failure

SETATTR(file ID, size, owner, ...) → success/failure

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S

file ID: opaque data (support multiple implementations)
example implementation: device+inode number+“generation number”

NFSv2 client versus server

clients: file descriptor →server name, file ID, offset

client machine crashes? mapping automatically deleted

- “fate sharing”

server: convert file IDs to files on disk

- typically find unique number for each file
- usually by inode number

server doesn’t get notified unless client is using the file

file IDs

device + inode + “generation number”?

generation number: incremented every time inode reused

problem: client removed while client has it open

later client tries to access the file

- maybe inode number is valid *but for different file*
- inode was deallocated, then reused for new file

Linux filesystems store a “generation number” in the inode

- basically just to help implement things like NFS

NFSv2 RPC calls (subset)

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SETATTR(file

"stateless protocol" — no open/close/etc.
each operation stands alone

NFSv2 RPC (more operations)

READDIR(dir file ID, count, optional offset “cookie”) →
(names and file IDs, next offset “cookie”)

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READDIR(dir file ID, count, optional offset “cookie”) →
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pattern: client storing opaque tokens
- for client: remember this, don’t worry about it

tokens represent something the server can easily lookup
- file IDs: inode, etc.
- directory offset cookies: byte offset in directory, etc.

strategy for making stateful service stateless

things NFSv2 didn't do well

performance — each read goes to server?

- would like to cache things in the clients

performance — each write goes to server?

- observation: usually only one user of file at a time
- would like to usually cache writes at clients
- writeback later

offline operation?

- would be nice to work on laptops where wifi sometimes goes out

statefulness

stateful protocol (example: FTP)

- previous things in connection matter
- e.g. logged in user
- e.g. current working directory
- e.g. where to send data connection

stateless protocol (example: HTTP, NFSv2)

- each request stands alone
- servers remember nothing about clients between messages
- e.g. file IDs for each operation instead of file descriptor

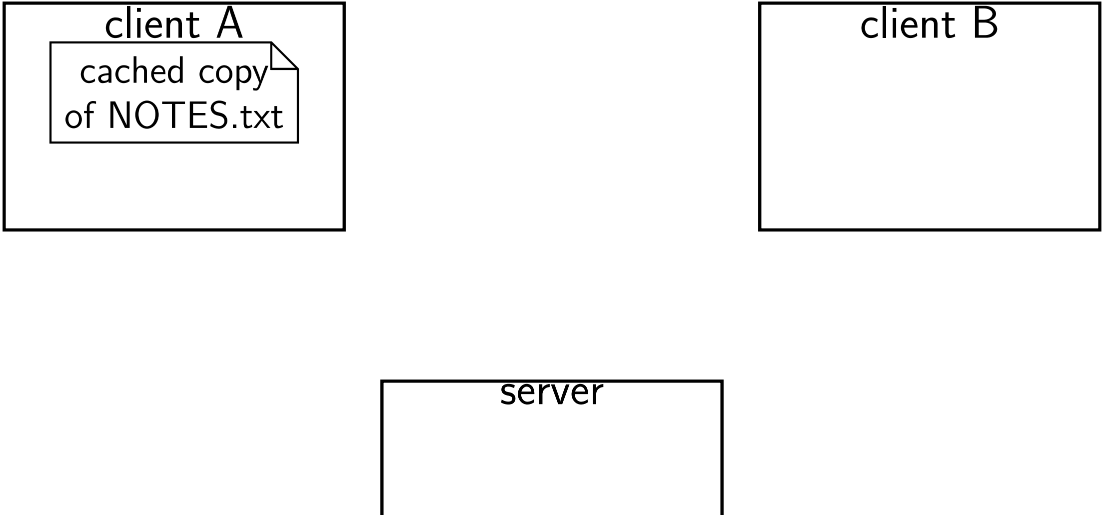
stateful versus stateless

in client/server protocols:

stateless: more work for client, less for server
- client needs to remember/forward any information
- can run multiple copies of server without syncing them
- can reboot server without restoring any client state

stateful: more work for server, less for client
- client sets things at server, doesn't change anymore
- hard to scale server to many clients (store info for each client
- rebooting server likely to break active connections

updating cached copies?



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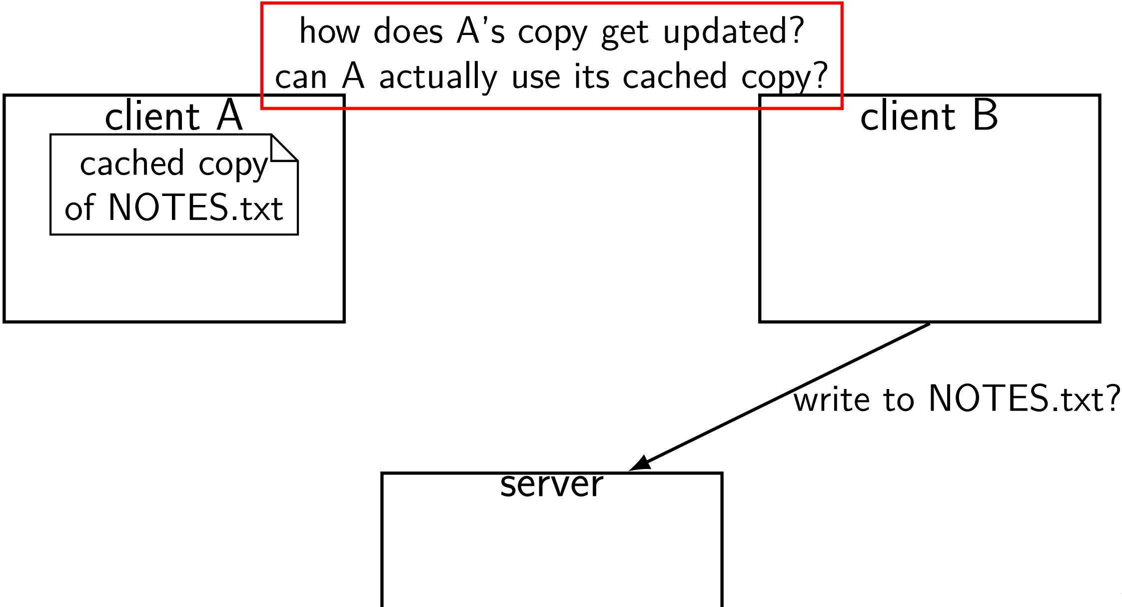
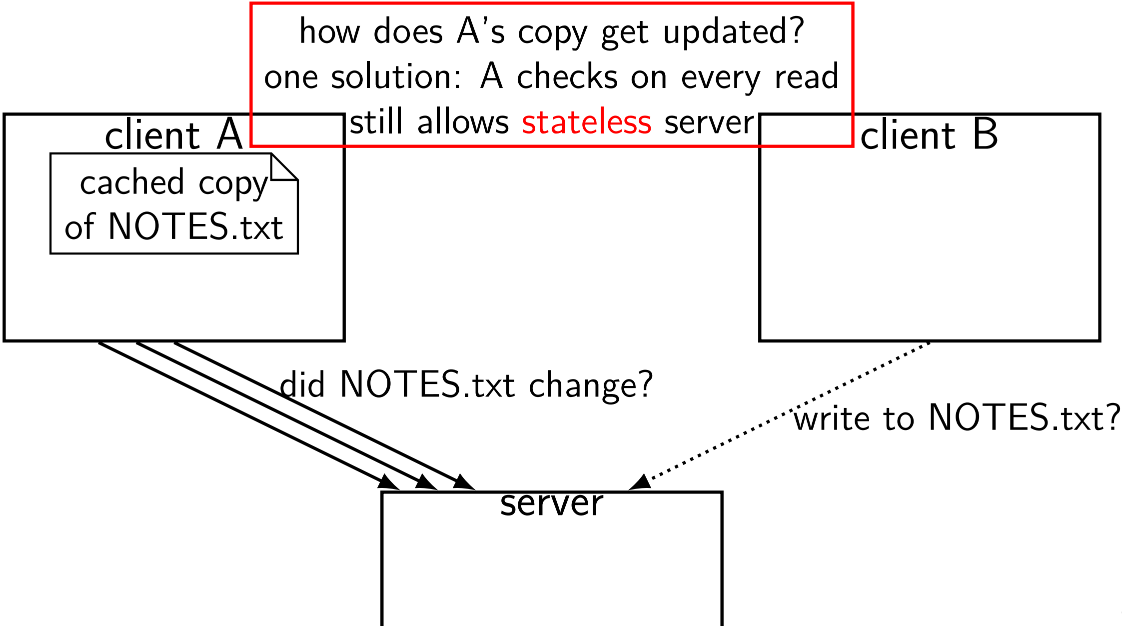


how does A's copy get updated?
can A actually use its cached copy?

updating cached copies?

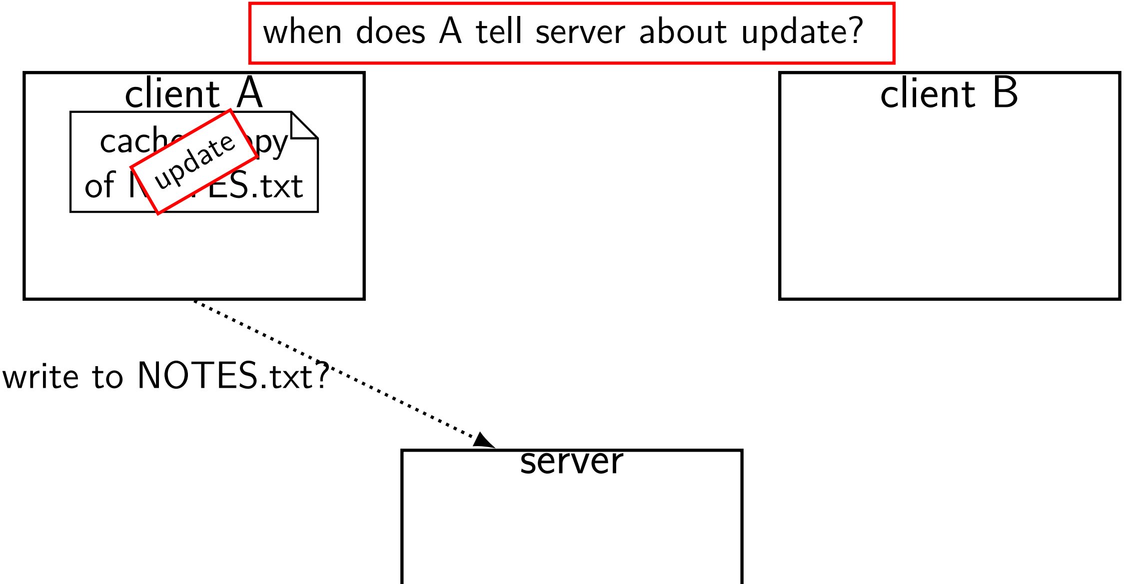


how does A's copy get updated?

one solution: A checks on every read

still allows stateless server

updating cached copies?



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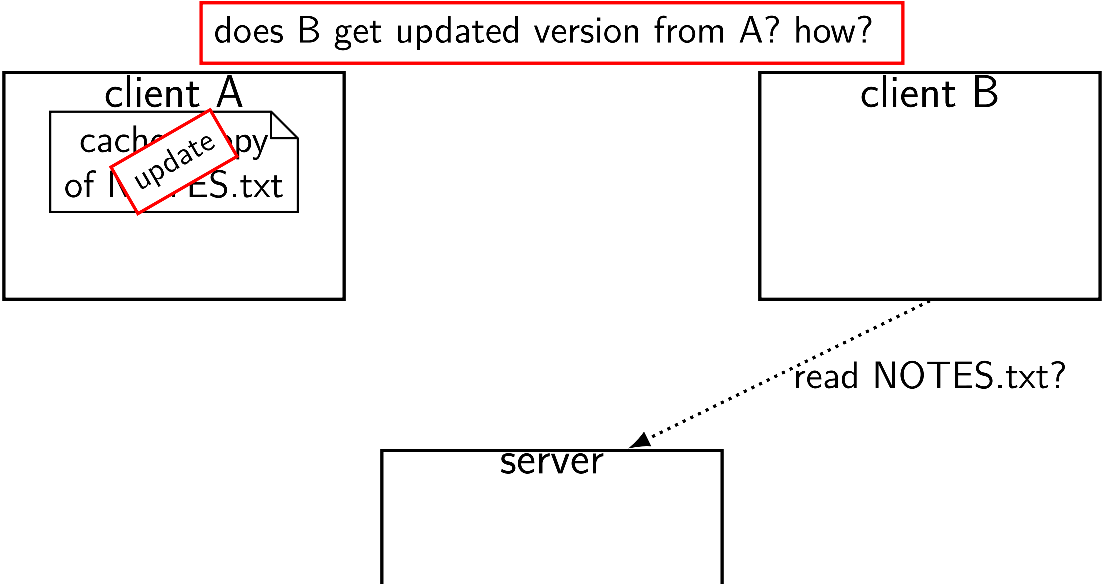

does B get updated version from A? how?

client A

cach py

of N ES.txt

update

client B

read NOTES.txt?

server

consistency with stateless server

always check server before using cached version

write through *all* updates to server

consistency with stateless server

always check server before using cached version

write through *all* updates to server

allows server to not remember clients

- no extra code for server/client failures, etc.

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…but kinda destroys benefit of caching

- many milliseconds to contact server, even if not transferring data

consistency with stateless server

always check server before using cached version

write through *all* updates to server

allows server to not remember clients

- no extra code for server/client failures, etc.

...but kinda destroys benefit of caching

- many milliseconds to contact server, even if not transferring data

NFSv3's solution: allow inconsistency

typical text editor/word processor

typical word processor:

opening a file:

open file, read it, load into memory, close it

saving a file:

open file, write it from memory, close it

two people saving a file?

have a word processor document on shared filesystem

Q: if you open the file while someone else is saving, what do you expect?

Q: if you save the file while someone else is saving, what do you expect?

two people saving a file?

have a word processor document on shared filesystem

Q: if you open the file while someone else is saving, what do you expect?

Q: if you save the file while someone else is saving, what do you expect?

observation: not things we really expect to work anyways

most applications don't care about accessing file while someone has it open

open to close consistency

a compromise:

opening a file checks for updated version

    otherwise, use latest cache version

closing a file writes updates from the cache

    otherwise, may not be immediately written

open to close consistency

a compromise:

opening a file checks for updated version

- otherwise, use latest cache version

closing a file writes updates from the cache

- otherwise, may not be immediately written

idea: as long as one user loads/saves file at a time, great!

an alternate compromise

application opens a file, read it a day later, result?

- day-old version of file

modification 1: check server/write to server after an amount of time

doesn't need to be much time to be useful

- word processor: typically load/save file in $<$ second

AFSv2

Andrew File System version 2

uses a stateful server

also works file at a time — not parts of file
- i.e. read/write entire files

but still chooses consistency compromise
- still won't support simulatenous read+write from diff. machines well

stateful: avoids repeated 'is my file okay?' queries

NFS versus AFS reading/writing

NFS reading: read/write block at a time

AFS reading: always read/write *entire file*

exercise: pros/cons?
- efficient use of network?
- what kinds of inconsistency happen?
- does it depend on workload?

AFS: last writer wins

on client A	on client B
open NOTES.txt	
	open NOTES.txt
write to cached NOTES.txt	
	write to cached NOTES.txt
close NOTES.txt	
AFS: write whole file	
	close NOTES.txt
	AFS: write whole file

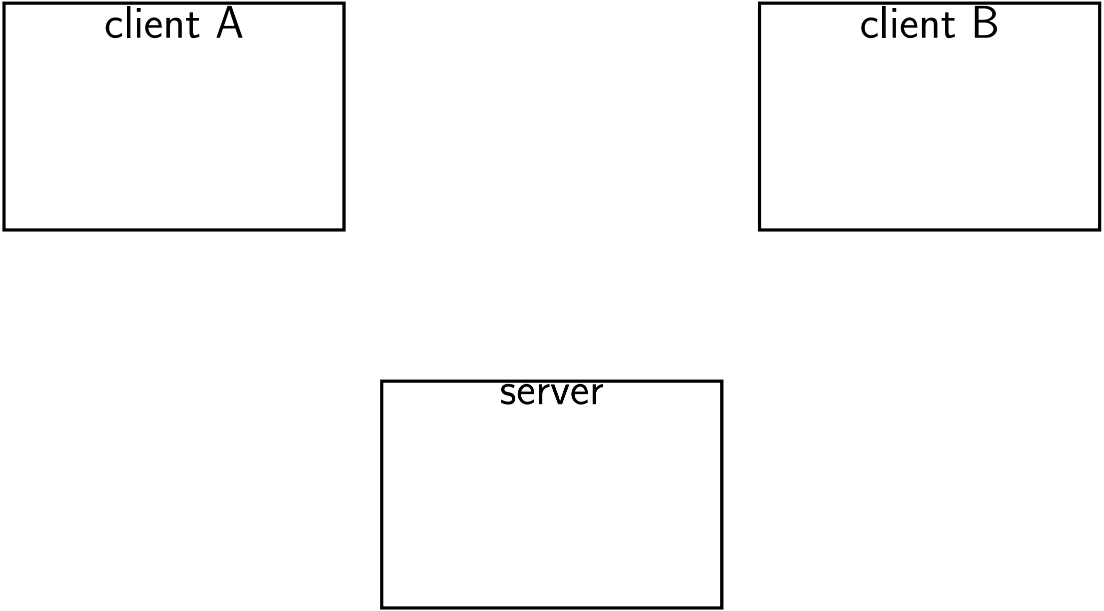
last writer wins

NFS: last writer wins per block

on client A	on client B
open NOTES.txt	
	open NOTES.txt
write to cached NOTES.txt	
	write to cached NOTES.txt
close NOTES.txt	
NFS: write NOTES.txt block 0	
	close NOTES.txt
	NFS: write NOTES.txt block 0
	NFS: write NOTES.txt block 1
NFS: write NOTES.txt block 1	
NFS: write NOTES.txt block 2	
	NFS: write NOTES.txt block 2

NOTES.txt: 0 from B 1 from A 2 from B

AFS caching

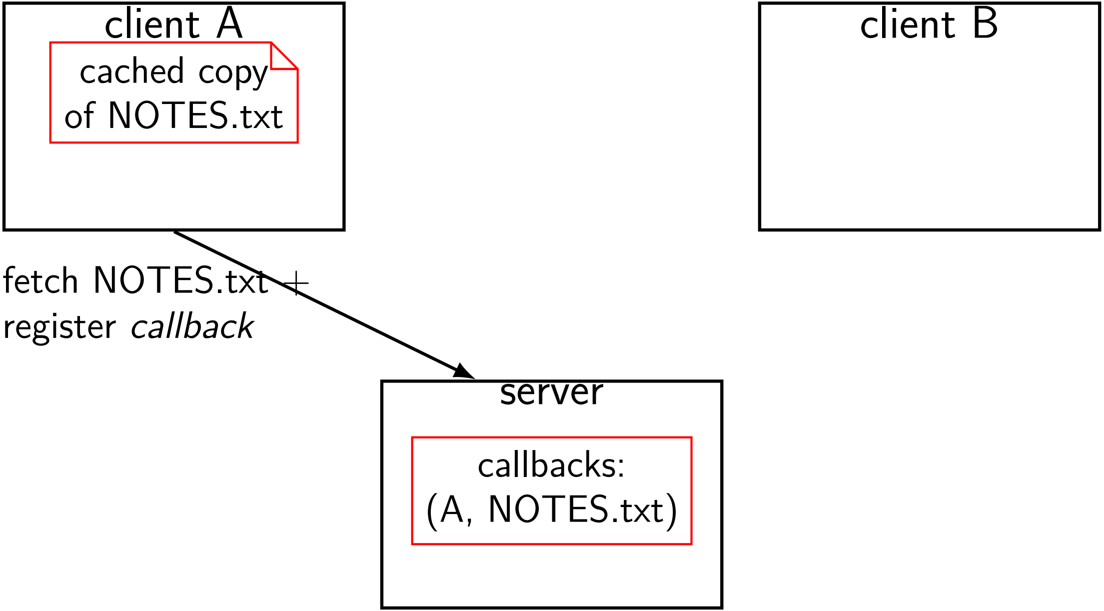


client A

client B

server

AFS caching



client A

cached copy of NOTES.txt

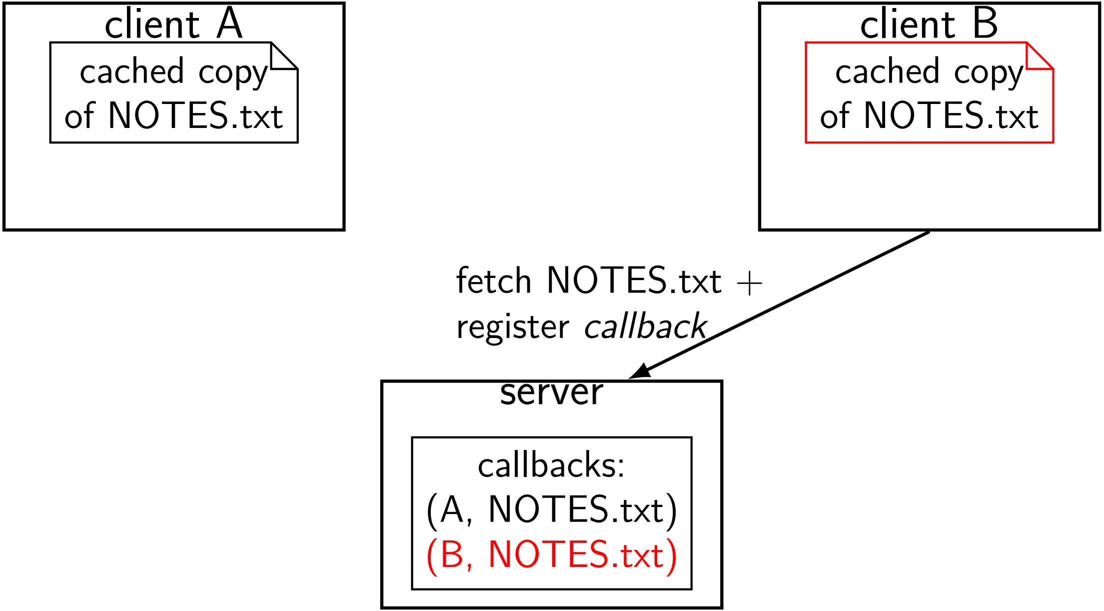
client B

fetch NOTES.txt + register *callback*

server

callbacks:
(A, NOTES.txt)

AFS caching



client A

cached copy of NOTES.txt

client B

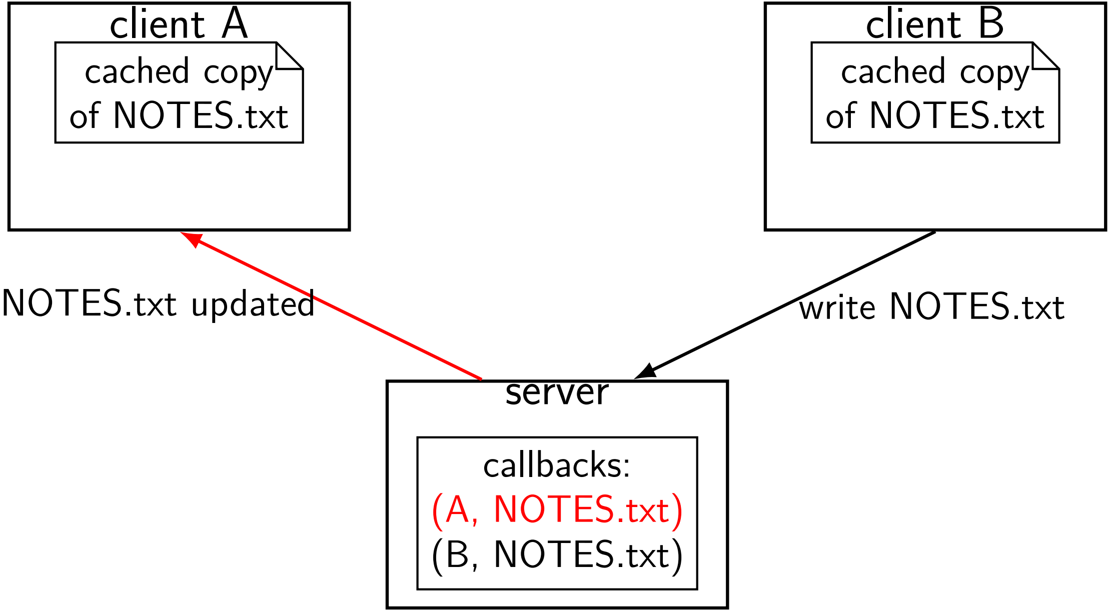
cached copy of NOTES.txt

fetch NOTES.txt +
register *callback*

server

callbacks:
(A, NOTES.txt)
(B, NOTES.txt)

AFS caching



client A

cached copy of NOTES.txt

client B

cached copy of NOTES.txt

NOTES.txt updated

write NOTES.txt

server

callbacks:

(A, NOTES.txt)

(B, NOTES.txt)

callback inconsistency (1)

on client A	on client B
open NOTES.txt	
(AFS: NOTES.txt fetched)	
read from cached NOTES.txt	
	open NOTES.txt
	(NOTES.txt fetched)
	read from NOTES.txt
write to cached NOTES.txt	
	read from NOTES.txt
write to cached NOTES.txt	
close NOTES.txt	
(write to server)	
	(AFS: callback: NOTES.txt changed)

callback inconsistency (1)

on client A	on client B
open NOTES.txt	
(AFS: NOTES.txt fetched)	
read from cached NOTES.txt	
	open NOTES.txt
	(NOTES.txt fetched)
	read from NOTES.txt
write to cached NOTES.txt	
	read from NOTES.txt
write to cached NOTES.txt	
close NOTES.txt	
(write to server)	
	(AFS: callback: NOTES.txt changed)

problem with close-to-open consistency

same issue w/NFS: B can't know about write because server doesn't

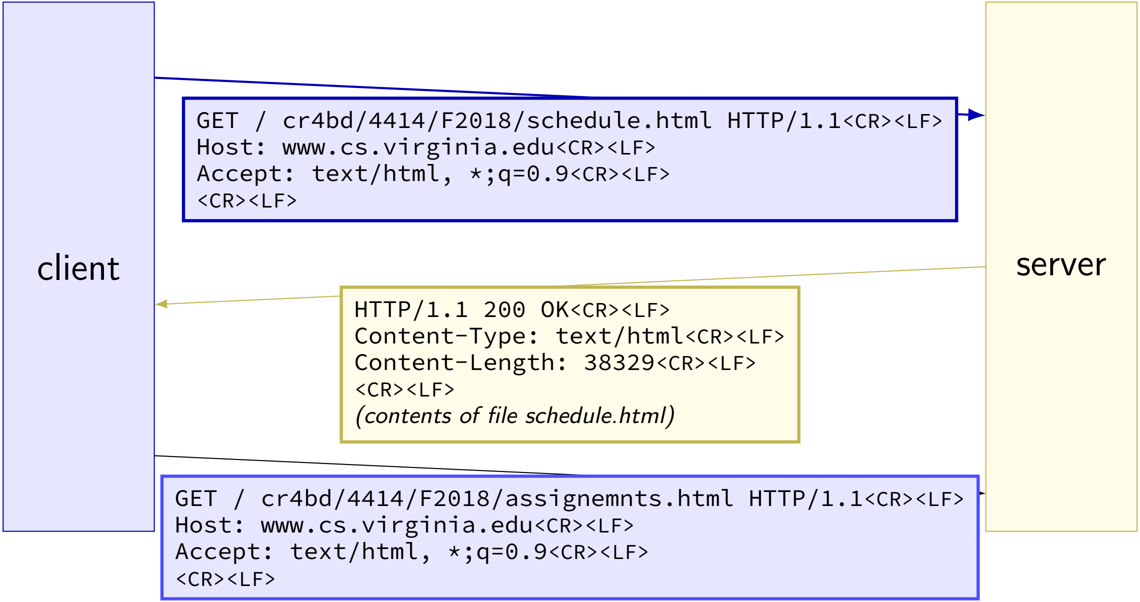
(could fix by notifying server earlier)

callback inconsistency (1)

on client A	on client B
open NOTES.txt	
(AFS: NOTES.txt fetched)	
read from cached NOTES.txt	
	open NOTES.txt
	(NOTES.txt fetched)
	read from NOTES.txt
write to cached NOTES.txt	
	read from NOTES.txt
write to cached NOTES.txt	
close NOTES.txt	
(write to server)	
	(AFS: callback: NOTES.txt changed)

close-to-open consistency assumption:
are not accessing file from two places at once

HTTP protocol (simplified)



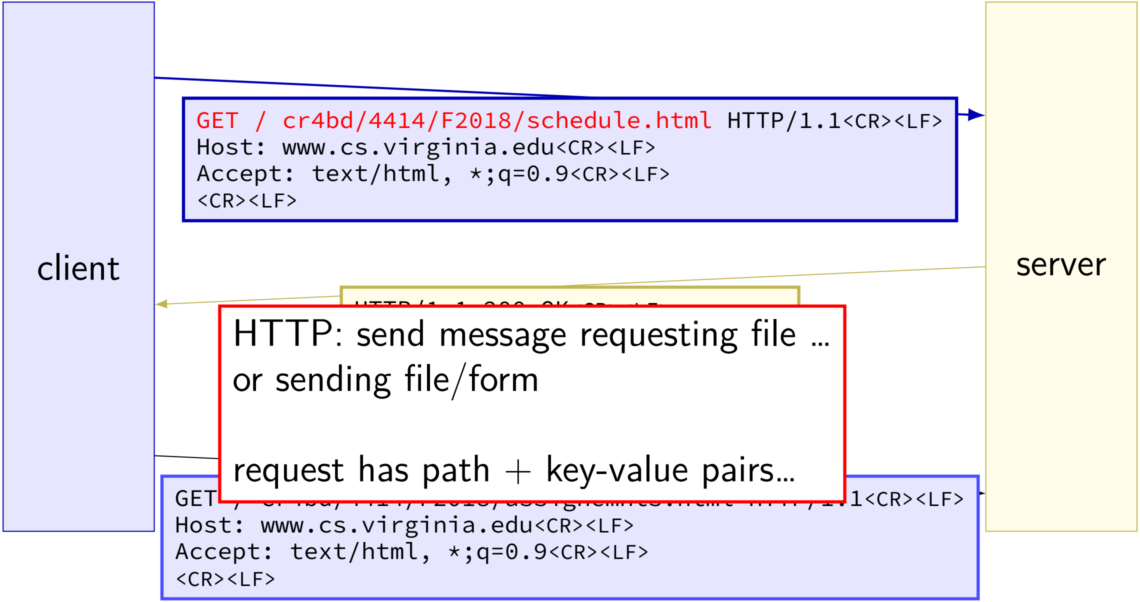
```
GET / cr4bd/4414/F2018/schedule.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

```
HTTP/1.1 200 OK<CR><LF>
Content-Type: text/html<CR><LF>
Content-Length: 38329<CR><LF>
<CR><LF>
```

(contents of file schedule.html)

```
GET / cr4bd/4414/F2018/assignemnts.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

HTTP protocol (simplified)



```
GET / cr4bd/4414/F2018/schedule.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

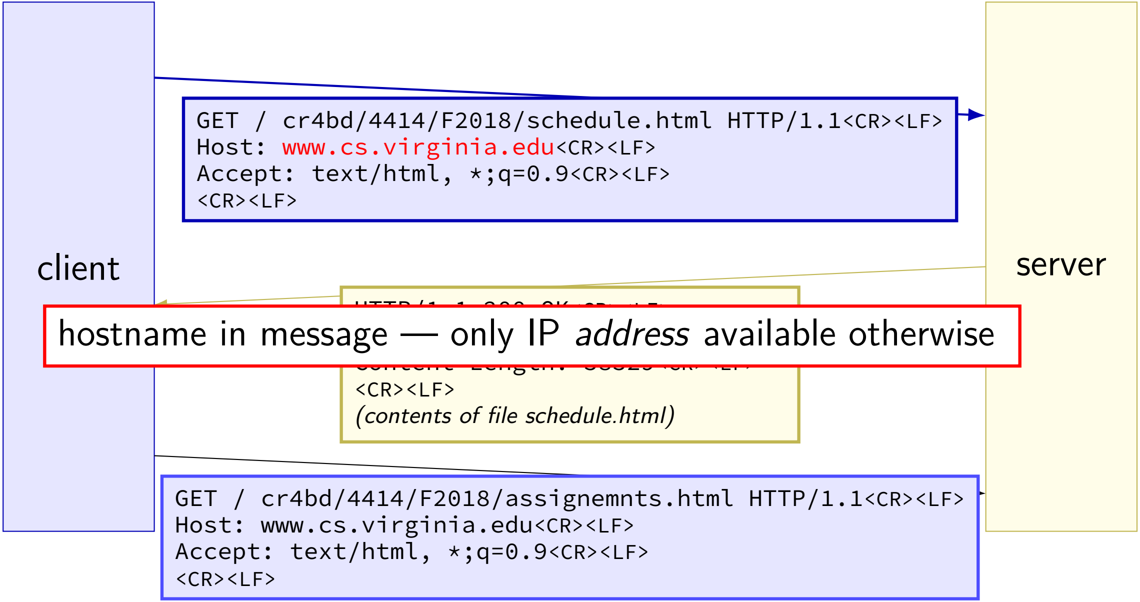
```
HTTP/1.1 200 OK<CR><LF>
```

HTTP: send message requesting file ...
or sending file/form

request has path + key-value pairs...

```
GET / cr4bd/4414/F2018/assignments.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

HTTP protocol (simplified)



```
GET / cr4bd/4414/F2018/schedule.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

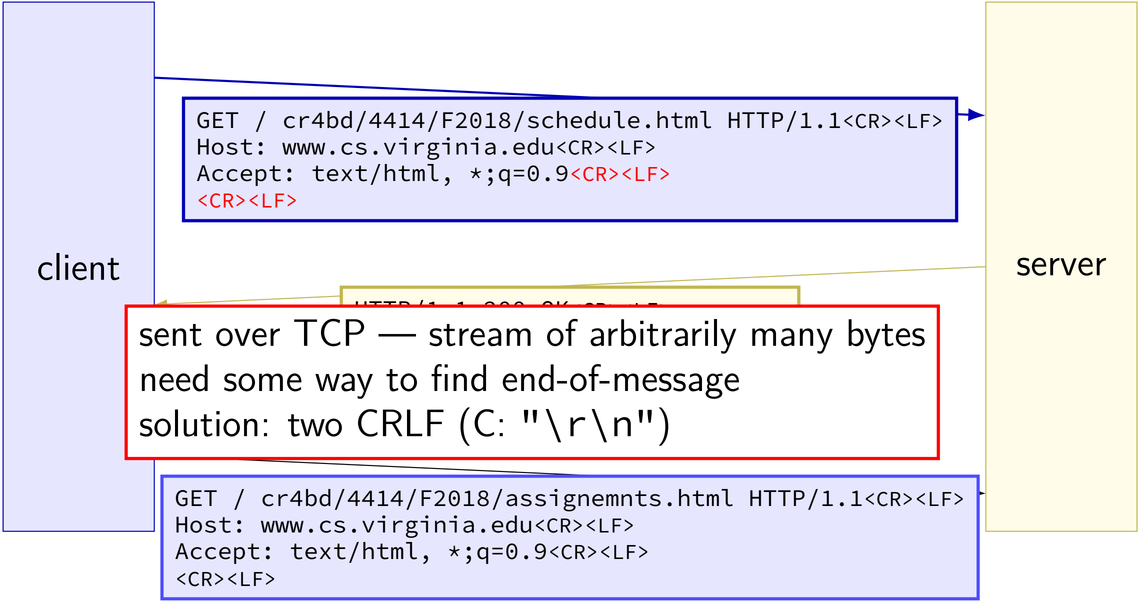
```
HTTP/1.1 200 OK<CR><LF>
Content-Length: 33925<CR><LF>
<CR><LF>
```

(contents of file schedule.html)

hostname in message — only IP *address* available otherwise

```
GET / cr4bd/4414/F2018/assignemnts.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

HTTP protocol (simplified)



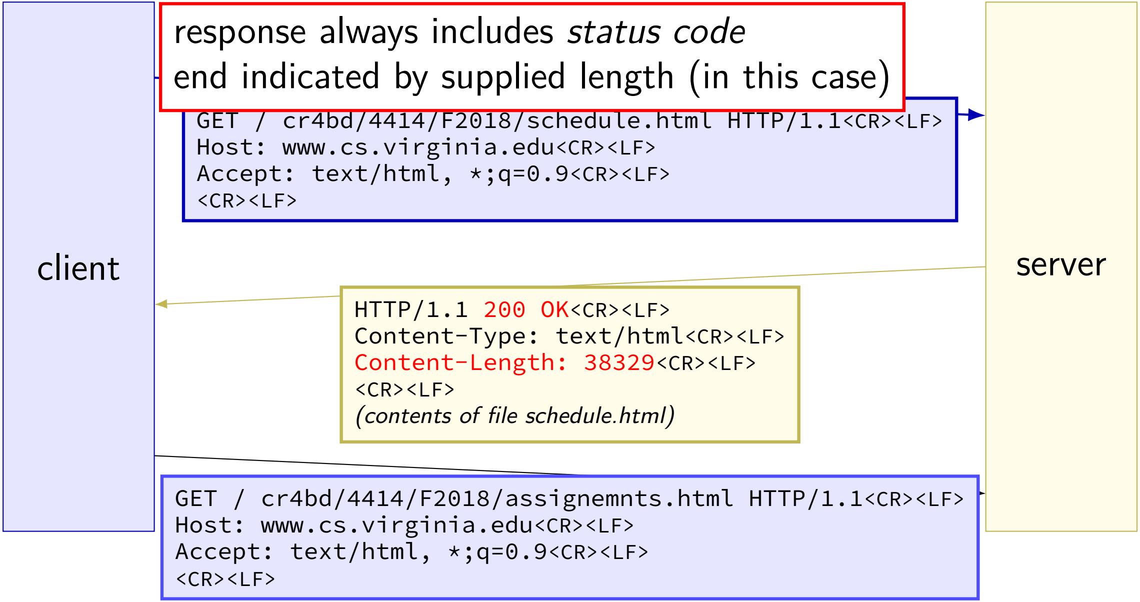
```
GET / cr4bd/4414/F2018/schedule.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

```
HTTP/1.1 200 OK<CR><LF>
```

sent over TCP — stream of arbitrarily many bytes
need some way to find end-of-message
solution: two CRLF (C: `"\r\n"`)

```
GET / cr4bd/4414/F2018/assignemnts.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

HTTP protocol (simplified)



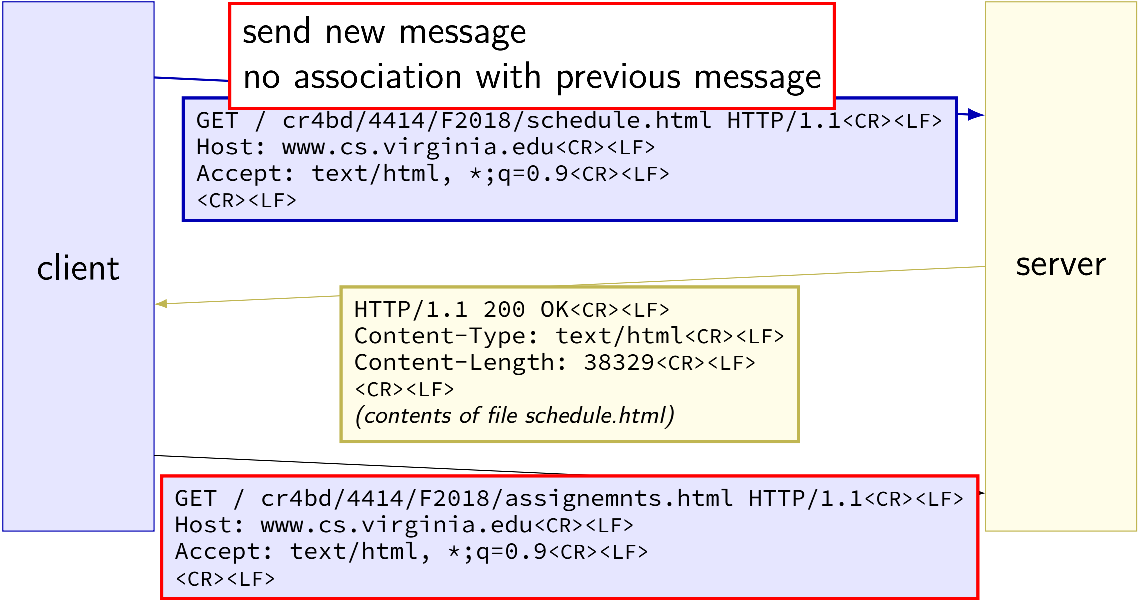
response always includes *status code*
end indicated by supplied length (in this case)

```
GET / cr4bd/4414/F2018/schedule.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

```
HTTP/1.1 200 OK<CR><LF>
Content-Type: text/html<CR><LF>
Content-Length: 38329<CR><LF>
<CR><LF>
```
(contents of file schedule.html)

```
GET / cr4bd/4414/F2018/assignemnts.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

HTTP protocol (simplified)



send new message
no association with previous message

client

server

```
GET / cr4bd/4414/F2018/schedule.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

```
HTTP/1.1 200 OK<CR><LF>
Content-Type: text/html<CR><LF>
Content-Length: 38329<CR><LF>
<CR><LF>
(contents of file schedule.html)
```

```
GET / cr4bd/4414/F2018/assignemnts.html HTTP/1.1<CR><LF>
Host: www.cs.virginia.edu<CR><LF>
Accept: text/html, *;q=0.9<CR><LF>
<CR><LF>
```

HTTP protocol

standard(s) for...

format of messages, identifying length of messages

meaning of key-value pairs

replies for messages for success or failure

on connections and how they fail

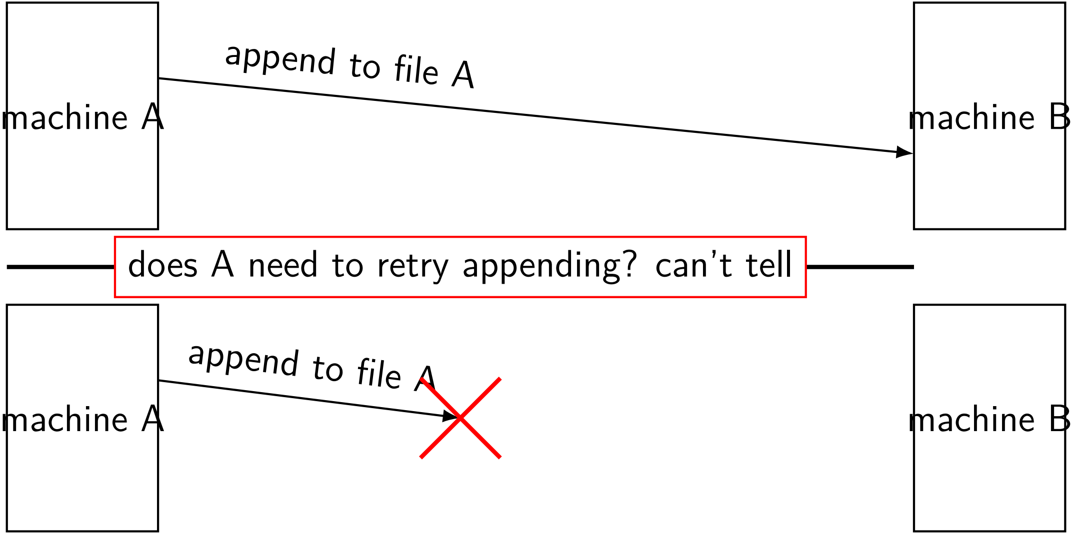
for the most part: don't look at details of connection implementation

…but will do so to explain how things fail

why? important for designing protocols that change things

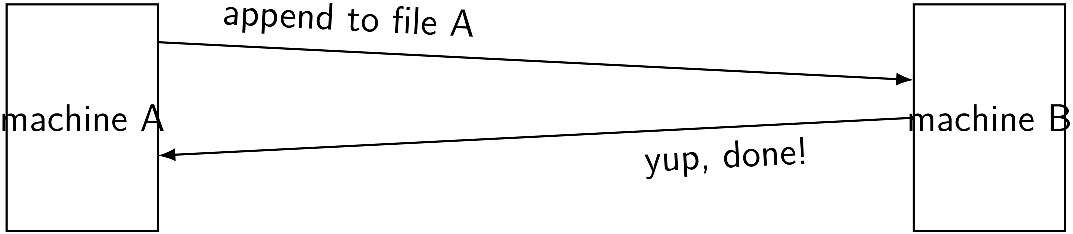
- how do I know if any action took place?

dealing with network failures

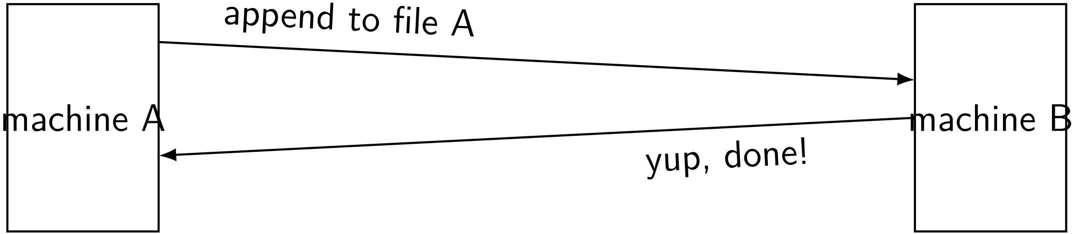


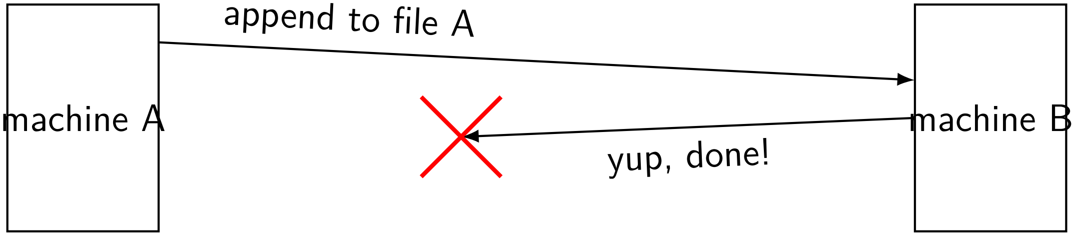
does A need to retry appending? can't tell

handling failures: try 1

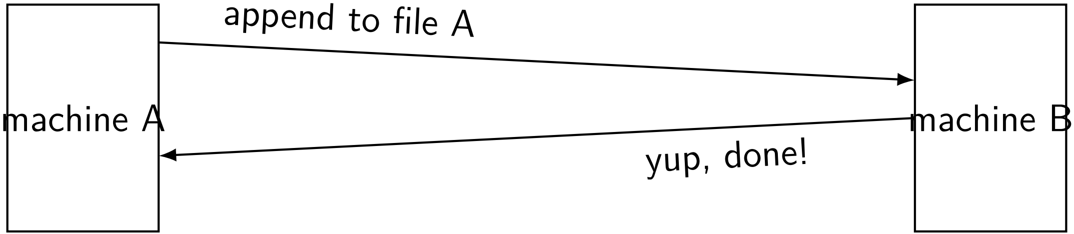


handling failures: try 1





handling failures: try 1



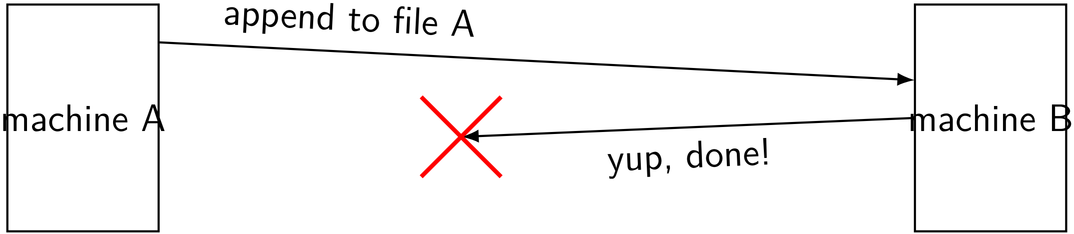
append to file A

machine A

machine B

yup, done!

does A need to retry appending? *still* can't tell



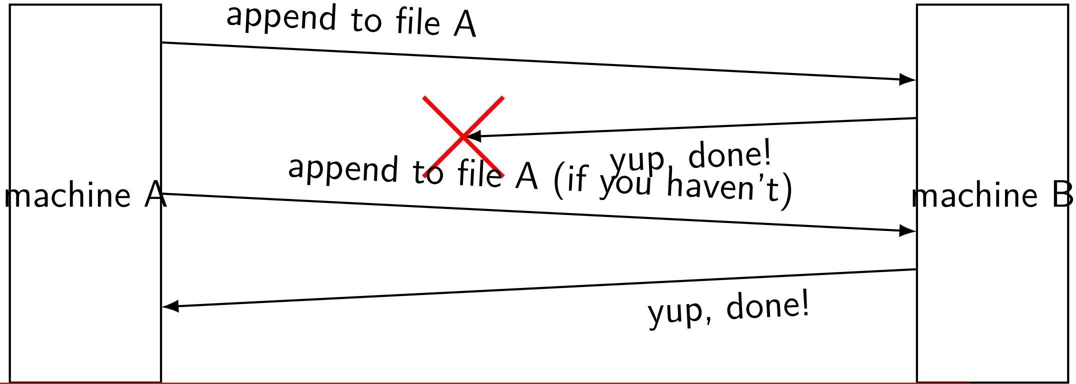
append to file A

machine A

machine B

yup, done!

handling failures: try 2



retry (in an idempotent way) until we get an acknowledgement
basically the best we can do, but when to give up?

dealing with failures

real connections: acknowledgements + retrying

but have to give up eventually

means on failure — can't always know what happened remotely!

- maybe remote end received data
- maybe it didn't
- maybe it crashed
- maybe it's running, but it's network connection is down
- maybe our network connection is down

also, connection knows *whether program received data*

- not whether program did whatever commands it contained

supporting offline operation

so far: assuming constant contact with server

someone else writes file: we find out

we finish editing file: can tell server right away

good for an office

- my work desktop can almost always talk to server

not so great for mobile cases

- spotty airport/café wifi, no cell reception, …

AFS: last writer wins

on client A	on client B
open NOTES.txt	
	open NOTES.txt
write to cached NOTES.txt	
	write to cached NOTES.txt
close NOTES.txt	
AFS: write whole file	
	close NOTES.txt
	AFS: (over)write whole file

probably losing data!

usually wanted to merge two versions

Coda FS: conflict resolution

Coda: distributed FS based on AFSv2 (c. 1987)

supports offline operation with conflict resolution

while offline: clients remember *previous version ID of file*

clients include version ID info with file updates

allows detection of conflicting updates

Coda FS: conflict resolution

Coda: distributed FS based on AFSv2 (c. 1987)

supports offline operation with conflict resolution

while offline: clients remember *previous version ID of file*

clients include version ID info with file updates

allows detection of conflicting updates

and then…ask user? regenerate file? …?

Coda FS: what to cache

idea: user specifies list of files to keep loaded

when online: client synchronizes with server

- uses version IDs to decide what to update

Coda FS: what to cache

idea: user specifies list of files to keep loaded

when online: client synchronizes with server

- uses version IDs to decide what to update

DropBox, etc. probably similar idea?

version ID?

not a version number?

actually a *version vector*

version number for each machine that modified file

- number for each server, client

allows use of multiple servers

- if servers get desync'd, use version vector to detect
- then do, uh, something to fix any conflicting writes

file locking

so, your program doesn't like conflicting writes

what can you do?

if offline operation, probably not much…

otherwise file locking

except it often doesn't work on NFS, etc.

advisory file locking with fcntl

```
int fd = open(...);
struct flock lock_info = {
    .l_type = F_WRLCK,  // write lock; RDLOCK also available
    // range of bytes to lock:
    .l_whence = SEEK_SET, l_start = 0, l_len = ...
};
/* set lock, waiting if needed */
int rv = fcntl(fd, F_SETLKW, &lock_info);
if (rv == -1) { /* handle error */ }
/* now have a lock on the file */

/* unlock --- could also close() */
lock_info.l_type = F_UNLCK;
fcntl(fd, F_SETLK, &lock_info);
```

advisory locks

fcntl is an *advisory* lock

doesn't stop others from accessing the file…

unless they always try to get a lock first

POSIX file locks are horrible

actually two locking APIs: fcntl() and flock()

fcntl: *not* inherited by fork

fcntl: closing any fd for file release lock
    even if you dup2'd it!

fcntl: maybe sometimes works over NFS?

flock: less likely to work over NFS, etc.

fcntl and NFS

seems to require extra state at the server

typical implementation: separate *lock server*

not a stateless protocol

lockfiles

use a separate *lockfile* instead of “real” locks

- e.g. convention: use `NOTES.txt.lock` as lock file

lock: create a *lockfile* with `link()` or `open()` with `O_EXCL`

- can’t lock: link()/open() will fail “file already exists”
- for current NFSv3: should be single RPC calls that always contact server
- some (old, I hope?) systems: link() atomic, open() O_EXCL not

unlock: remove the lockfile

- annoyance: what if program crashes, file not removed?