Networks and distributed computing

• Abstractions provided for networks

network card has fixed MAC address

deliver message to computer on LAN

machine-to-machine communication

unordered messages

unreliable messages

finite-sized messages

multiple computers

Machine-to-machine communication (IP) -> Process-to-process communication (sockets)

• Process abstraction: each process thinks it has its own:
  – Multiprocessor (threads)
  – Memory (address space)
  – Network interface cards (sockets)

• Socket
  – Virtual network interface card
  – Endpoint for communication
  – NIC named by MAC address; socket named by “port number” (via bind)
  – Programming interface: BSD sockets
Operating system multiplexes multiple sockets onto a single network interface card

- UDP (user datagram protocol): IP + sockets
- TCP (transmission control protocol): IP + sockets + reliable, ordered streams

Ordered messages

- Hardware interface: network can re-order messages sent by IP layer
  - Send A, B
  - Receive B, A
- Application interface: all messages are received in the order in which they were sent
- How to provide ordered messages?

- To have a notion of order, we must first have the notion of a network “connection” (so we know that a set of messages are related)
  - TCP: process opens connection (via `connect`), sends sequence of messages, then closes connection.
  - Sequence number of specific to a socket-to-socket connection
Reliable messages

- Hardware interface: networks can drop, duplicate, or corrupt messages
- Application interface: each message is delivered exactly once (without corruption)
- How to fix a dropped message?

- How does sender know message was dropped?

Reliable messages

- Duplicate messages
  - Detect by examining sequence #s
  - Fix by dropping the duplicate message

- Corrupted messages
  - Detect by adding redundant information (e.g., checksum)
  - Fix by dropping corrupted message

- Transform corrupted messages into dropped messages
- Transform potential dropped messages into potential duplicates
- Solve duplicates by dropping messages
Byte streams

- Hardware interface: send information over network in distinct messages
- Application interface: send data in a continuous stream (similar to reading/writing a file)
- TCP provides byte streams instead of distinct messages
- Sender sends messages of arbitrary size, which are combined into a single stream
- TCP implementation
  - Break up stream into fragments
  - Sends fragments as distinct messages
  - Reassembles fragments at destination

Message boundaries

- TCP has no message boundaries (in contrast, UDP preserves message boundaries)
  - E.g., sender sends 100 bytes, then 50 bytes. Receiver could receive 1-150 bytes.
- If receiver wants to receive a specific number of bytes, it can loop around receive call, or specify MSG_WAITALL
- How to know # of bytes to receive?
Client-server

- Different ways to structure a distributed application. Most common is client-server.
  - Server provides some centralized service
  - Client makes request to server, then waits for response
- E.g., web server
  - Server stores and generates web pages
  - Clients run web browsers
  - Requests are GET or POST
- E.g., producer-consumer with client-server
  - Server manages state associated with coke machine
  - Clients call client_produce() or client_consume(). These send request to the server and return when done.
  - Client calls may block at the server if request cannot be satisfied immediately.

Producer-consumer as a client-server distributed application

```c
client_produce()
{
    send produce request to server
    wait for response
}

server()
{
    receive request
    if (produce request) {
        add coke to machine
    } else {
        take coke out of machine
    }
}
```

- Problems?
- How to fix?
Producer-consumer as a client-server distributed application

server()
{
    receive request
    if (produce request) {
        create thread that calls server_produce()
    } else {
        create thread that calls server_consume()
    }
}

server_produce()
{
    lock
    while (machine is full) {
        wait
    }
    put coke in machine
    send response to client
    unlock
}

Producer-consumer as a client-server distributed application

• This creates a new thread for each request. How to lower the overhead of creating threads?

• Other ways to structure the server
  – Polling (via select)
  – Signals
RPC

• We’ve been using send/receive to communicate between client and server
  – Client sends request to server
  – Server receives and processes request, then sends response to client
  – Client receives response from server
  – This exposes the distributed nature of the system to the programmer
  – Would like to make building a distributed application more similar to
    building a local application.
• What else in programming is similar to making a request to a server and
  getting a response?

RPC

• How to make message send/receive look like function call/return to both
  the client and the server?
  – Client wants the sending of its request to look like calling a function,
    and wants the reply from the server to look like returning from the
    function call.
  – Server wants the receiving of a request from the client to look
    receiving a function call, and wants the send of the response to look
    like returning to the caller.
Providing RPC abstraction via stub functions on client and server

RPC stubs

- Client stub
- Server stub
Producer-consumer using RPC

- Use reliable datagrams (not TCP)
- Client stub (name is produce)
  
  ```c
  int produce (int n) 
  {
    int status;
    send (sock, &n, sizeof(n));
    recv (sock, &status, sizeof(status));
    return(status);
  }
  ```

- Server stub (name is arbitrary)
  
  ```c
  void produce_stub ()
  { 
    int n;
    int status;
    recv (sock, &n, sizeof(n));
    status = produce(n);
    send (sock, &status, sizeof(status));
    return(status);
  }
  ```

- Client and server stubs can be generated automatically. What information do you need to generate a stub?

Problems with RPC

- RPC tries to make request/response to remote server look like a function call/return, but some differences remain
Making a distributed system look like a local system

- RPC: make request/response look like function call/return
- DSM: make multiple memories look like a single memory
- DFS: make disks on multiple computers look like a single file system
- Parallelizing compilers: make multiple CPUs look like one CPU
- Process migration (and RPC): allow users to easily use remote processors

Building distributed applications

- Why build distributed applications?
  - Performance
    - Aggregate performance of many computers can be faster than the performance of a single computer (even a fast one)
  - Reliability
    - Try to provide continuous service, even if some computers fail
    - Try to preserve data, even if some storage systems fail
Concurrency and distribution

• Distributed programs are multi-threaded, since each computer has at least one thread
• Need two mechanisms to write multi-threaded programs
  – Atomic primitive to synchronize threads
  – A way to share data between threads
• But neither of these mechanisms work for distributed applications
  – No shared memory

Send/receive as communication primitive

• No shared data; can only communicate information through message send/receive
• Can race conditions exist without shared data?
Send/receive as synchronization mechanism

• What atomic primitive does the network hardware provide?
  – Send/receive a packet on the network
  – If packets A and B are sent to the same receiver, the receiver will receive A, B, or neither (but not a mixture of A and B)

• OS builds up from the hardware atomic primitive
  – If incoming packets from multi-packet messages are interleaved, the OS can separate the packets to form a whole message
  – OS ensures that a packet contains the correct data (e.g., not mixed up from several messages)

Structuring a concurrent system

• One multi-threaded process on one computer

• Several multi-threaded process on several computers
Structuring a concurrent system

• Several multi-threaded process on each of several computers

![Diagram of send and receive](image)

• Why separate threads on one computer into separate address spaces, then use send/receive to communicate and synchronize?

• Microkernels
  – Operating system structure that separates OS functionality into several server processes, each in its own address space

Case study: distributed file systems

• Distributed file systems separates the storage of the data from the clients that use the data, but make it look as though all storage is local

• Benefits
  – Share data and resources between people
  – Enables uniform view from different computers

• Examples
  – AFS
  – SMB (Windows)
  – Dropbox
  – Google docs
  – WWW

• Basic implementation is simple
  – Send each request to server (classic client/server)
  – But poor performance. How to improve?
Client-side caching

• Assume many clients issuing requests to the file server
• Where will the bottleneck be?

• Use caching at clients to improve performance
  – Latency and throughput
  – Server scalability
  – Reduce network traffic
  – Availability?

Client-side caching

• Implementation #1: transfer sole copy of file from server to client cache
  – Problems?

• Implementation #2: client cache stores a copy of the file
  – What happens if the client modifies its copy?
  – How to address the problem?
State of a client’s copy of a file

Partitioning a file server across multiple servers

- To scale to a large number of clients, we can distribute the files across multiple file servers
- How to divide files between servers?

- Who knows which server holds a particular file?
Replication across multiple servers

- With more servers, likelihood of server failure increases
- Replication is the fundamental technique for tolerating failures
  - Store a file on multiple servers
  - E.g., primary + backup
    - Write data by writing to both primary and backup
    - Read data by reading from primary or backup
- What happens when a server fails?

  - How to survive more than 1 failure (say, $F$ failures)?

  - Assumptions about how a server fails?

Fault models

- Fail stop
  - Machine stops executing
  - You can detect the failure
- Byzantine
  - Server may send erroneous messages
  - Server could be malicious
Byzantine generals

• E.g., 1 commander (C), 2 lieutenants (L1, L2)
• Generals want to agree on a joint course of action (attack or retreat). All loyal generals must agree.
• Generals communicate with reliable (but unsigned messages). Recipient can tell who sent message (but not the true origin of that message).

• Solution #1
  – C sends to L1, L2
  – L1 and L2 follow C’s orders
  – How can this break?

Byzantine generals

• Solution #2
  – L1, L2 send each other the message each got from C
  – All generals follow majority vote

  – E.g.,
  • C -> L1: attack
  • C -> L2: attack
  • L1 -> L2: attack
  • L2 -> L1: retreat

  • What should L1 do?
Byzantine generals

- Need 4 generals to handle 1 traitor (in general, needs 3F+1 generals to deal with F traitors)
- If L3 is traitor
  C -> L1: attack
  C -> L2: attack
  C -> L3: attack

  L1 -> L2: attack
  L1 -> L3: attack

  L2 -> L1: attack
  L2 -> L3: attack

  L3 -> L1: retreat
  L3 -> L2: retreat

L1 and L2 each get 2 messages to attack and 1 message to retreat

Byzantine generals

- Need 4 generals to handle 1 traitor (in general, needs 3F+1 generals to deal with F traitors)
- If C is traitor
  C -> L1: attack
  C -> L2: attack
  C -> L3: retreat

  L1 -> L2: attack
  L1 -> L3: attack

  L2 -> L1: attack
  L2 -> L3: attack

  L3 -> L1: retreat
  L3 -> L2: retreat

L1, L2, L3 each get 2 messages to attack and 1 message to retreat