Distributed Systems

COMP3231 Operating Systems

2005 S2

Today

- Challenges in Distributed Systems
- Client Server Architecture
- Message Passing
- Remote Procedure Call
- Remote Method Invocation
- TCP/IP

There is an extra subject
Distributed Systems (COMP9243).

Distributed Systems

What is a distributed system?
- Andrew Tannenbaum defines it as follows:
  A distributed system is a collection of independent computers that appear to the users of the system as a single computer.
- Is there any such system? Hardly!
- You can learn about the challenges in building "true" distributed systems in COMP9243

For the time being, we would like a weaker definition of distributed systems:

A distributed system is a collection of independent computers that are used jointly to perform a single task or to provide a single service.

Examples of distributed systems
- Collection of Web servers: distributed database of hypertext and multimedia documents
- Distributed file system in a LAN (e.g., NFS as used at CSG)
- Point-of-sale system hooked up to a back office data center
- Domain Name Service (DNS)
- Cray T3E, UNICOS/mk
THE ADVANTAGES AND CHALLENGES OF DISTRIBUTED SYSTEMS

What are economic and technical reasons for having distributed system?

Cost. Better price/performance as long as commodity hardware is used for the component computers

Performance. By using the combined processing and storage capacity of many nodes, performance levels can be reached that are out of the scope of centralised machines

Scalability. Resources such as processing and storage capacity can be increased incrementally

Inherent distribution. Some applications like the Web are naturally distributed

Reliability. By having redundant components, the impact of hardware and software faults on users can be reduced

Which problems are there in the use and development of distributed systems?

Limited software. Distributed software is harder to develop than conventional software; hence, it is more expensive and there is fewer software available

New component: network. Networks are needed to connect independent nodes and are subject to performance limits and constitute another potential point of failure

Security. It is easier to compromise distributed systems

DISTRIBUTED SERVICES FROM NETWORK OSes TO DISTRIBUTED SYSTEMS

What is a Network OS?

→ Network of application systems
→ Configuration with one or more servers
→ Servers provide network wide services or applications
→ Network OS is adjunct to local OS which supports interaction between application machines and servers
→ User is aware of single machines, must deal with them explicitly

Network OSes provide the following:

→ Services for remote login (telnet, rsh, and ssh)
→ File transfer (ftp, rcp, and scp)

How far is a network OS away from a distributed system?

→ Network OS lacks a single image view for any of its services
→ Individual nodes are highly autonomous
→ All distribution of tasks is explicit to the user
With extra software, network OSes may provide some distributed services:

**Data sharing.** Common data needs to be accessed and updated (e.g., distributed file systems, Web)

**Device sharing.** Common peripherals need to be used remotely (e.g., printers)

**Flexibility.** Workloads can be distributed or moved to less loaded machines (e.g., remote login)

**Communication.** Email, IM, and so on

However, the user usually is aware of the distribution.

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**Distributed Systems and Parallel Computing**

- Parallel systems: improved performance by multiple processors per application
- There are two flavours:
  1. Shared-memory systems:
     - Multiple processor share a single bus and memory unit
     - SMP support in OS
     - Much simpler than distributed systems
     - Limited scalability
  2. Distributed memory systems:
     - Multiple nodes connected via a network
     - These are a form of distributed systems
     - Share many of the challenges discussed here
     - Better scalability & cheaper

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**Basic Problems and Challenges in Distributed Systems**

The distributed nature of these systems brings some inherent challenges:

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- Transparency ⇐
- Flexibility
- Reliability
- Performance
- Scalability ⇐

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**Basic Problems and Challenges in Distributed Systems**

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**Transparency:**

*Concealment of the separation of the components of a distributed system (single image view).*

There are different kinds of transparency

- Location: Users unaware of location of resources
- Migration: Resources can migrate without name change
- Replication: Users unaware of existence of multiple copies
- Failure: Users unaware of the failure of individual components
- Concurrency: Users unaware of sharing resources with others
- Parallelism: Users unaware of parallel execution of activities
Scalability:
- Centralised resources become performance bottlenecks:
  - components (single server),
  - tables (directories), or
  - algorithms (based on complete information).
- Bottleneck can be resources or communication with them.

Helpful design rules:
- Do not require any machine to hold complete system state
- Allow nodes to make decisions based on local info
- Algorithms must survive failure of nodes
- No assumption of a global clock

Scalability often conflicts with (small system) performance.

Client-Server Architecture

Basic architectural building block for distributed systems:

- Simple, connectionless request-reply protocol is sufficient
- Support in the form of stub generators etc. is possible

What is middleware?
- Abstraction layer in the middle, between OS and applications
- Less OS dependencies in the applications
- Varying degrees of transparency
- Typically two components: communications abstraction & services

The three most common communications abstractions:

1. Message passing:
   - Simple, light-weight
   - Application has to do a lot of tedious work (e.g., marshalling)
   - Sockets, Message Passing Interface (MPI)

2. Remote Procedure Call (RPC):
   - The idea: remote access appears as a local procedure call
   - The called procedure is executed on the server
   - Often stub generators or similar tool supported is available
   - SUN RPC, XML-RPC, Simple Object Access Protocol (SOAP)

3. Remote Method Invocation (RMI):
   - The idea:
     - Server is a remote object
     - remote access appears as a local method invocation
   - IDL compiler or other form of stub generation supported
   - CORBA, Java RMI, DCOM
MESSAGE PASSING

- Messaging layer supports send and receive operations
- The application has to implement marshalling:
  - Conversion of in-memory to on-wire representation of data structures
  - Bridging architectural variants, e.g., byte order
- The application may also have to handle naming:
  - Bind names to remote services
  - Resolve names: name → location of service
  - Migration of services

Example: socket interface:

```c
int socket (int domain, int type, int protocol);
int send (int s, const void *msg, size_t len, int flags);
int recv (int s, void *buf, size_t len, int flags);
```

---

Sample message format:
```c
define struct {
    nodeid_t source;  // system supplied */
    nodeid_t dest;   // receiver identity */
    int opcode;      // which operation */
    int count;       // data size */
    char object[N_NAME];  // name of target object */
    char data[BUF_SIZE];  // data to be transferred */
};
```

Sample send code:
```c
#define struct massage{
    msg source = me();
    msg dest = somewhere();
    msg, opcode = SO_SOMETHING, GOOL;
    msg, count = N;
    strcopy(msg, object, "My cool object", N_NAME);
    marshall_data(msg, data, whatever, BUF_SIZE);
    send (m, &msg, sizeof (msg));
```

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There are different flavors of point-to-point communication:

- Blocking versus non-blocking communication
- Reliable versus unreliable communication
- Buffered versus unbuffered messages

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<table>
<thead>
<tr>
<th>Name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF_UNIX, PF_LOCAL</td>
<td>Local communication</td>
</tr>
<tr>
<td>PF_INET</td>
<td>IPv4 Internet protocols</td>
</tr>
<tr>
<td>PF_INET6</td>
<td>IPv6 Internet protocols</td>
</tr>
<tr>
<td>PF_IPX</td>
<td>IPX * Novell protocols</td>
</tr>
<tr>
<td>PF_NETLINK</td>
<td>Kernel user interface device</td>
</tr>
<tr>
<td>PF_BSC</td>
<td>ITU-T X.25 / ISO-8208 protocol</td>
</tr>
<tr>
<td>PF_AX25</td>
<td>Amateur Radio AX.25 protocol</td>
</tr>
<tr>
<td>PF_ATM</td>
<td>Access to raw ATM PVCs</td>
</tr>
<tr>
<td>PF_APPLETALK</td>
<td>AppleTalk</td>
</tr>
<tr>
<td>PF_PACKET</td>
<td>Low level packet interface</td>
</tr>
</tbody>
</table>
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**Blocking versus non-blocking communication:**
- **Blocking (synchronous):**
  - Client blocked until reply arrives
  - Delivery guarantee
  - Latency can be significant (infinite?)
- **Non-blocking (asynchronous):**
  - Client can perform other processing
  - Client must not modify message buffer until transmitted
  - Kernel buffers message
  - Kernel interrupts client when buffer processed

**Several factors may influence a decision:**
- Blocked client not a problem if multitasked/multithreaded
- Kernel buffering is overhead
- Interrupts are overhead, and tricky to program

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**Reliable versus unreliable communication**
- Generally, messages may get lost (network failure, node down, server crashed, . . .)
- **Unreliable communication:**
  - Messaging layer does not make any guarantees
  - Application has to handle message loss
- **Reliable communication:**
  - Messaging layer guarantees delivery if possible
  - **Advantage:**
    - Application code gets simpler
  - **Disadvantage:**
    - Application-specific protocol properties cannot be exploited
    - Often more expensive

**Remote Procedure Call (RPC)**

**Idea:** Replace I/O oriented message passing model by execution of a procedure call on a remote node:
- Based on blocking messages
- Message-passing details hidden from application
- Procedure call parameters used to transmit data
- Client calls local “stub” which does messaging and marshalling

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**Local stub**

**Remote server**

**Local procedure calls**

**Remote procedure call**

**Local response**

**Local application or operating system**

**RPC mechanism**
Sample Stub: often generated from a high-level specification

```c
read(int fd, void *buf, size_t count) {
    int result;
    msg.dest = htonl(FS_SERVER_ID);
    msg.opcode = htonl(FS_READ);
    msg.count = htonl(2*sizeof(int));
    ((int*)msg.data)[0] = fd;
    ((int*)msg.data)[1] = htonl(count);
    send (&msg, sizeof(msg)); /* send request */
    recv (&msg, sizeof(msg)); /* receive reply */
    result = *((int *) msg.data);
    if (result > 0)
        bcopy(msg.data[1], buf, result);
    return result;
}
```

Application side:
- Just calls
- The procedure call hides all the marshalling and messaging complexity

Parameter Marshalling
- stub must pack (“marshal”) parameters into message structure
- message data must be pointer free
- by-reference data must be passed by-value
- may have to perform other conversions:
  - byte order (big endian vs little endian)
  - floating point format...
  - convert everything to standard (“network”) format, or
  - message indicates format, receiver converts if necessary
- stubs may be generated automatically from interface specs

Possible Problems with RPC
RPC can fail in ways not possible for “real” procedure calls:
- Cannot locate service (down, wrong version, migrating)
- request lost
- reply lost
- server crash
- client crash
- Need error values for functions that cannot fail locally.
  - Limits the illusion of “procedure call” (lack of transparency)
- Disjoint address space:
  - Concurrent access to global program variables (errors)
  - Need for stub to know size of all parameters (open arrays)
  - Arbitrary (pointer) data structures cannot be marshalled
Remote Message Invocation (RMI)

The transition from Remote Procedure Call (RPC) to Remote Method Invocation (RMI) is a transition from the server metaphor to the object metaphor.

Why is this important?
- There is no inherent link between procedure calls and issuing server requests, but
- There certainly is an intimate link between method invocations and the use of objects.
- RPC: explicit handling of host identification to determine the destination
- RMI: addressed to a particular state-encapsulating entity (object)
- Objects are first-class citizens
- More natural resource management and error handling
- But still only a small evolutionary step

References:
- Objects are identified by object references
- Distributed objects are identified by remote object reference
- The latter are more difficult to implement (why?)

Interfaces:
- Access to objects is controlled by interfaces
- Which contain the signatures of a set of methods
- Signatures include argument and result types of a method

Tasks of an ORB:
- Find object implementation
- Prepare object implementation (activation)
- Communicate data

The Architecture of CORBA

- The concept of an Object Request Broker (ORB) is the centerpiece of OMG's Common Object Request Broker Architecture (CORBA).

Drawbacks:
- Each object is located on a single server only
- Mostly used on small scale systems
**Data Consistency**

Common problem in distributed systems: data consistency:
- Consistency of virtual shared-memory systems
- Consistency of distributed file services
- Consistency of naming information
- Consistency of a snapshot of the global state of a system

**Why do these consistency problems arise?**
- Absence of strict central control
- Presence of caches
- Replication of data

**Central control:**
- Central bottleneck
- Does not scale

**Concrete Examples**

Let’s look at the consistency problem in
- distributed shared memory and
- distributed file systems.
Distributed Shared Memory (DSM)

- A set of processes on different hosts share part of their address space
- DSM system guarantees that updates by one process are available to others
- Data exchange often at the granularity of individual memory pages
- Easy to use (no marshalling, but synchronisation primitives required)

How does it work?

- Virtual memory management is extended
- In case of a page fault, the page may be requested from a remote node
Consistency problem:
- Concurrent write access to the same page
- Simplest solution: multiple-reader/single-writer policy
- Lock whole page ⇒ expensive
- Access maybe to same page, but different memory location

Distributed File Systems (DFS)

In a DFS
- multiple clients share
- multiple file servers, which may support
- differing types of file systems.

The client-side structure of the file system may
- consist of mixture of directories & files from local & remote devices and
- be different for each client.

Semantics of file access:

UNIX semantics:
- A READ after a WRITE returns the value just written
- When two writes follow in quick succession, the second persists
- Trivial with a single file server and without caching, but...

- Caches are needed for performance & write-through is expensive
- Multiple file servers aggravate the problem
  ⇒ transparency for a Unix system is problematic
How can we solve this problem?

1. We stay faithful to the semantics and compromise on performance, or
2. We search for an alternative semantics that can be implemented more efficiently.

- The second alternative is quite popular (NFS & CODA)
- What are feasible semantics?

Session semantics:

- Changes to an open file are only locally visible
- When a file is closed, changes are propagated to the server (and other clients)
- Easy to implement, but there are tradeoffs. For example,
  - parent and child processes cannot share file pointers if running on different machines.

Consistency of Global State

Why is determining the global state of a system difficult?

- Lack of global clock/synchronisation
- Messages may be in the network

Implementation of session semantics:

- Upload/download model

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C
B
A
D
E
F
G

Remote access

Upload/download

- Download the whole file to the client (often more efficient)
- Update in cache
- Upload file to server on close()

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% cat twoecho
#!/bin/sh
/bin/echo "a"
/bin/echo "b"
% twoecho >output
% cat output
a
b
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(a) Total = $100
SA = $100
SB = $0
3:00

(b) Total = $0
SA = $0
SB = $0
3:00
3:00
3:01
2:59

(g) Clocks are not synchronised
Sum at 3:00 is $200

What can we do?
- Define a notion of consistent global state
- Make sure we only take consistent distributed snapshots

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- Message currently in transit
- Sum at 3:00 is $0

What can we do?
- Include record of transfers
- Check against receipts

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- Clocks are not synchronised
- Sum at 3:00 is $200

What can we do?
- Define a notion of consistent global state
- Make sure we only take consistent distributed snapshots

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When is a distributed snapshot consistent?
- Snapshot of a process includes all messages that have been sent or received since the last snapshot
- Distributed snapshot is a collection of snapshots, one for each process
A distributed snapshot is consistent

- If any message recorded as received
- Is recorded as sent by the originating process

Physical Layer:
Covers physical interface between data transfer device (computer) and transmission medium (network):
- Specifies characteristics of network
- Data transfer rate
- Nature of signals
- Data rate

No messages out of thin air!

TCP/IP Protocol Architecture
Collection of protocols issued as Internet standard by the Internet Activity Board

TCP/IP Layers:
- Physical Layer
- Network access layer
- Internet Layer
- Host-to-host (transport-) layer
- Application layer

Network access layer:
Exchange of data between server/workstation and network
- Sender provides network with address of receiver
- Sender may invoke network services (e.g., priorities)
- Type of network determines software used at this layer:
  - Circuit switching
  - Packet switching
  - LAN
- Upper layers need not be concerned about network specifics
Internet Layer:
- Internet Protocol (IP) provides routing functions across multiple networks
- Protocol implemented in end systems (server/workstations) and routers
- Router: processor
  - which connects two networks
  - relays data from one network to the other

TCP
- applications send data stream
- TCP chops it up into packages
- packages then passed to IP layer
- TCP checks to avoid package loss
- waits for acknowledgement, otherwise resends
- uses checksum to ensure correct transmission of package

TCP header:
- Source Port | Destination Port |
- Sequence Number |
- Acknowledgment Number |
- Header Len. | Res. | Window |
- Options | Padding |
- Data |
**User Datagram Protocol (UDP)**

- small protocol overhead
- no guaranteed delivery
- no guaranteed preservation of sequence
- no protection against duplication
- Example application: SNMP (Simple Network Management Protocol)

**IP and IPv6**

- IPv4 is version 4 of the Internet Protocol (IP)
- first widely used IP version
- first published 1981
- IPv4 uses 32-bit addresses
- address space too limited

**TCP/IP Operation**

Process on Host A associated with Port 3 wants to send data to Process on host B, Port 2:

1. **Process A**
   - hands down message to TCP layer
   - instructs it to send to Host B, Port 3

2. **TCP**
   - chops message up, if necessary
   - adds control information to each package (TCP header)
   - hands it down to IP layer
   - instructs it to send to Host B

3. **IP**
   - adds control information (IP header)
   - hands it down to Network layer (e.g., Ethernet logic)
   - instructs it to send it to router
Network
• adds control information (Network header)

IP module in router directs package to Host B

Network strips off network header, passes it to IP layer

IP layer strips off IP header, passes it to TCP

TCP strips off TCP header, passes it to application