TCSS 558: APPLIED DISTRIBUTED COMPUTING

Distributed System Architectures – II, Middleware Organization

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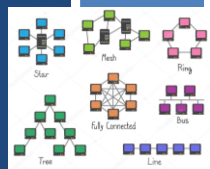

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OBJECTIVES – 1/18

- Questions from 1/16
- Assignment 0: Cloud Computing Infrastructure Tutorial
- Chapter 2: Distributed System Architectures:
  - Chapter 2.1 – Architectural Styles
  - Resource-centered architectures
    - Representational state transfer (REST)
  - Event-based
    - Publish and subscribe (Rich Site Summary RSS feeds)
- Class Activity: Architectural Styles
- Chapter 2.2: Middleware Organization
- Chapter 2.3: System Architectures
  - Centralized system architectures
  - Decentralized peer-to-peer architectures
  - Hybrid architectures

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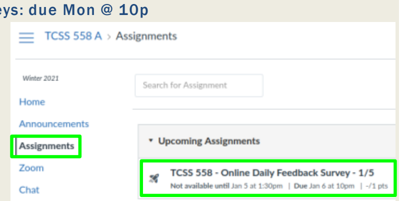
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by Wed @ 10p
- Thursday surveys: due Mon @ 10p



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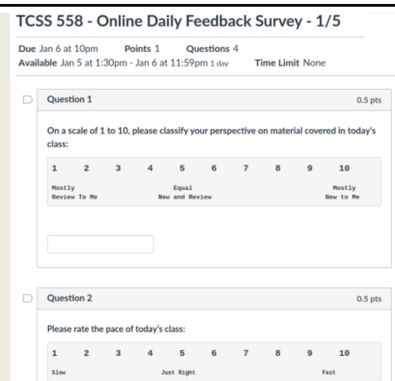

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (23 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 7.04** (↑ - *previous 5.63*)

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 6.09** (↑ - *previous 5.00*)

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FEEDBACK FROM 1/16

- ***As someone with no networking background, I'm a bit intimidated by all the protocols and layers***

- In lecture 4, we presented the Open Systems Interconnection **(OSI) model**, a conceptual model created by the International Organization for Standardization (ISO).
- The OSI model provides a common model that enables diverse communication systems to communicate using standard protocols.
- The OSI model provides an excellent example of a layered architecture with 7 layers.

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OSI MODEL LAYERS

7	Application Layer	Human-computer interaction layer, where applications can access the network services
6	Presentation Layer	Ensures that data is in a usable format and is where data encryption occurs
5	Session Layer	Maintains connections and is responsible for controlling ports and sessions
4	Transport Layer	Transmits data using transmission protocols including TCP and UDP
3	Network Layer	Decides which physical path the data will take
2	Data Link Layer	Defines the format of data on the network
1	Physical Layer	Transmits raw bit stream over the physical medium

Image credit: https://www.imperva.com/

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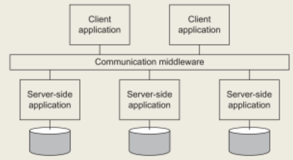
FEEDBACK - 2

- ***What are the key defining traits of a Distributed Information System that differentiates it from other system types?***
- Distributed Information Systems are client/server apps found in organizations which over time were integrated to form enterprise-wide information systems
- Key features include:
  - Multi-client/server
  - Use of atomic transactions
  - Separation into components
  - Remote integration
    - RPC, RMI, Message queues
- Some common SaaS apps are managed Dist Info Sys



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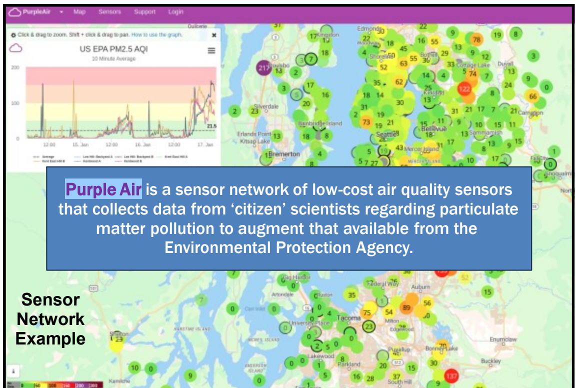

Purple Air is a sensor network of low-cost air quality sensors that collects data from 'citizen' scientists regarding particulate matter pollution to augment that available from the Environmental Protection Agency.

Sensor Network Example

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ASSIGNMENT 1

- ***Preparing for Assignment 1: Intro to Cloud Computing Infrastructure and Load Balancing***
  - Establish AWS Account - Standard account
- Coming Soon - - PREVIEW:
  - Task 0 - Establish local Linux/Ubuntu environment
  - Task 1 –AWS account setup, obtain user credentials
  - Task 2 – Intro to: Amazon EC2 & Docker: create Dockerfile for Apache Tomcat
  - Task 3 – Create Dockerfile for haproxy (software load balancer)
  - Task 4 – Working with Docker-Machine
  - Task 5 – Submit Results of testing alternate server configs

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CH 2.1 - ARCHITECTURAL STYLES

- Layered — Lecture 4
- **Object-based**
  - Service oriented architecture (SOA)
- Resource-centered architectures
  - Representational state transfer (REST)
- Event-based
  - Publish and subscribe (Rich Site Summary RSS feeds)

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OBJECT-BASED ARCHITECTURES

- Enables loose and flexible component organization
- Objects == components
- Enable distributed node interaction via function calls over the network
- Began with C - Remote Procedure Calls (RPC)
  - Straightforward: package up function inputs, send over network, transfer results back
  - Language dependent
  - In contrast to web services, RPC calls originally were more intimate in nature
  - Procedures more "coupled", not as independent
  - The goal was not to decouple and widgetize everything

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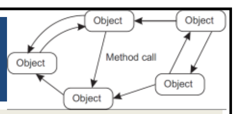
OBJECT-BASED ARCHITECTURES - 2



- Distributed objects Java- Remote Method Invocation (RMI)
  - Adds object orientation concepts to remote function calls
  - Clients bind to proxy objects
  - Proxy provide an object interface which transfers method invocation over the network to the remote host
- How do we replicate objects?
  - Object marshalling – serialize data, stream it over network
  - Unmarshalling- create an object from the stream
  - Unmarshall local object copies on the remote host
  - JSON, XML are some possible data formats

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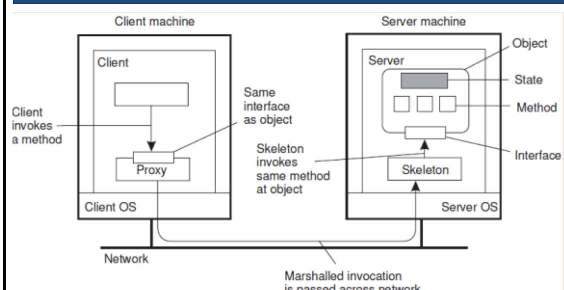
DISTRIBUTED OBJECTS



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DISTRIBUTED OBJECTS - 2

- A counterintuitive feature is that state is not distributed
- Each "remote object" maintains its own state
- Remote objects may not be replicated
- Objects may be "mobile" and move around from node to node
  - Common for data objects
- For distributed (remote) objects consider
  - Pass by value
  - Pass by reference .... *(does this make sense?)*

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CH 2.1 - ARCHITECTURAL STYLES

- Layered
- Object-based
  - **Service oriented architecture (SOA)**
- Resource-centered architectures
  - Representational state transfer (REST)
- Event-based
  - Publish and subscribe (Rich Site Summary RSS feeds)

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SERVICE ORIENTED ARCHITECTURE

- Services provide always-on encapsulated functions over the internet/web
- Leverage redundant cloud computing infrastructure
- Services may:
  - Aggregate multiple languages, libraries, operating systems
  - Include (wrap) legacy code
- Many software components may be involved in the implementation
  - Application server(s), relational database(s), key-value stores, in memory-cache, queue/messaging services

SERVICE ORIENTED ARCHITECTURE - 2

- Are more easily developed independently and shared vs. systems with distributed object architectures
- Less coupling
- An error while invoking a distributed object may crash the system
- An error calling a service (e.g. mismatching the interface) generally does not result in a system crash

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RESOURCE BASED ARCHITECTURES

- Motivation:
  - Increasing number of services available online
  - Each with specific protocol(s), methods of interfacing
  - Connecting services w/ different TCP/IP protocols → integration nightmare
    - Need for specialized client for each service that speaks the application protocol "language"...
- Need standardization of interfaces
  - Make services/components more pluggable
  - Easier to adopt and integrate
  - Common architecture

REST SERVICES

- Representational State Transfer (REST)
- Built on HTTP
- Four key characteristics:
  1. Resources identified through single naming scheme
  2. Services offer the same interface
     - Four operations: GET PUT POST DELETE
  3. Messages to/from a service are fully described
  4. After execution server forgets about client
     - Stateless execution

HYPERTEXT TRANSPORT PROTOCOL (HTTP)

- An ASCII-based request/reply protocol for transferring information on the web
- HTTP request includes:
  - request method (GET, POST, etc.)
  - Uniform Resource Identifier (URI)
  - HTTP protocol version understood by the client
  - headers—extra info regarding transfer request
- HTTP response from server
  - Protocol version & status code →
  - Response headers
  - Response body

HTTP status codes:
2xx — *all is well*
3xx — *resource moved*
4xx — *access problem*
5xx — *server error*

REST-FUL OPERATIONS

Operation	Description	
PUT	Create a new resource	(C)reate
GET	Retrieve state of a resource in some format	(R)ead
POST	Modify a resource by transferring a new state	(U)pdate
DELETE	Delete a resource	(D)elete

- Resources often implemented as objects in OO languages
- REST is weak for tracking state
- Generic REST interfaces enable ubiquitous *"so many"* clients

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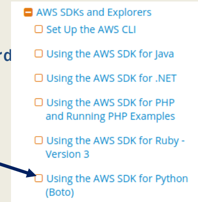
EXAMPLE: AMAZON S3

- Amazon S3 offers a REST-based interface
- Requires signing HTTP authorization header or passing authentication parameters in the URL query string
- REST: GET/PUT/POST/DELETE
- SOAP: 16 operations, moving toward deprecation
- Python boto ~50 operations (SDK for Python)
- SDKs for other languages



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REST - 2

- Defacto web services protocol
- Requests made to a URI – uniform resource identifier
- Supersedes SOAP – Simple Object Access Protocol
  - SOAP – application protocol specific to web services
- Access and manipulate web resources with a predefined set of stateless operations (known as web services)
- Responses most often in JSON, also HTML, ASCII text, XML, no real limits as long as text-based
- curl – generic command-line REST client: https://curl.haxx.se/

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```
// SOAP REQUEST – Book Store – Query Price

POST /InStock HTTP/1.1
Host: www.bookshop.org
Content-Type: application/soap+xml; charset=utf-8
Content-Length: nnn

<?xml version="1.0"?>
<soap:Envelope
xmlns:soap="http://www.w3.org/2001/12/soap-envelope"
soap:encodingStyle="http://www.w3.org/2001/12/soap-
encoding">
<soap:Body xmlns:m="http://www.bookshop.org/prices">
  <m:GetBookPrice>
    <m:BookName>The Fleamarket</m:BookName>
  </m:GetBookPrice>
</soap:Body>
</soap:Envelope>
```


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```
// SOAP RESPONSE – Book Store – Query Price

POST /InStock HTTP/1.1
Host: www.bookshop.org
Content-Type: application/soap+xml; charset=utf-8
Content-Length: nnn

<?xml version="1.0"?>
<soap:Envelope
xmlns:soap="http://www.w3.org/2001/12/soap-envelope"
soap:encodingStyle="http://www.w3.org/2001/12/soap-
encoding">
<soap:Body xmlns:m="http://www.bookshop.org/prices">
  <m:GetBookPriceResponse>
    <m: Price>10.95</m: Price>
  </m:GetBookPriceResponse>
</soap:Body>
</soap:Envelope>
```


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```
// Web Service Definition Language (WSDL)
// Service Definition – Day of Week Service

<?xml version="1.0" encoding="UTF-8"?>
<definitions  name ="DayOfWeek"
  targetNamespace="http://www.roguewave.com/soapworx/examples/DayOfWeek.wsdl"
  xmlns:tns="http://www.roguewave.com/soapworx/examples/DayOfWeek.wsdl"
  xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
  xmlns:xsd="http://www.w3.org/2001/XMLSchema"
  xmlns="http://schemas.xmlsoap.org/wsdl/">
  <message name="DayOfWeekInput">
    <part name="date" type="xsd:date"/>
  </message>
  <message name="DayOfWeekResponse">
    <part name="dayOfWeek" type="xsd:string"/>
  </message>
  <portType name="DayOfWeekPortType">
    <operation name="GetDayOfWeek">
      <input message="tns:DayOfWeekInput"/>
      <output message="tns:DayOfWeekResponse"/>
    </operation>
  </portType>
  <binding name="DayOfWeekBinding" type="tns:DayOfWeekPortType">
    <soap:binding style="document"
      transport="http://schemas.xmlsoap.org/soap/http"/>
    <operation name="GetDayOfWeek">
      <soap:operation soapAction="getdayofweek"/>
      <input>
        <soap:body use="encoded"
          namespace="http://www.roguewave.com/soapworx/examples"
          encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
      </input>
      <output>
        <soap:body use="encoded"
        namespace="http://www.roguewave.com/soapworx/examples"
        encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
      </output>
    </operation>
  </binding>
  <service name="DayOfWeekService" >
    <documentation>
      Returns the day-of-week name for a given date
    </documentation>
    <port name="DayOfWeekPort" binding="tns:DayOfWeekBinding">
      <soap:address location="http://localhost:8090/dayofweek/DayOfWeek"/>
    </port>
   </service>
</definitions>
```


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REST CLIMATE SERVICES EXAMPLE

- USDA Lat/Long Climate Service Demo
- Just provide a Lat/Long

```
// REST/JSON
// Request climate data for Washington

{
 "parameter": [
  {
    "name": "latitude",
    "value":47.2529
  },
  {
    "name": "longitude",
    "value":-122.4443
  }
  ]
}
```


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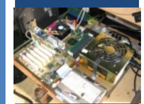
WE WILL RETURN AT 4:50PM



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PUBLISH-SUBSCRIBE ARCHITECTURES: EVENT-BASED

- Enables separation between processing and coordination
- Types of coordination:

	Temporally coupled (at the same time)	Temporally decoupled (at different times)
Referentially coupled (*dependent on name*)	**Direct** Explicit synchronous service call	**Mailbox** Asynchronous by name (address)
Referentially decoupled (*name not required*)	**Event-based** Event notices published to shared bus, w/o addressing	**Shared data space** Processes write tuples to a shared data space

Publish and subscribe architectures

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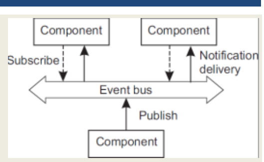
PUBLISH-SUBSCRIBE ARCHITECTURES - 2

- **Event-based coordination**
- Processes do not know about each other explicitly



- **Processes:**
  - **Publish:** a notification describing an event
  - **Subscribe:** to receive notification of specific kinds of events
- Assumes subscriber is presently up (*temporally coupled*)
- Subscribers must actively **MONITOR** event bus

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PUBLISH-SUBSCRIBE ARCHITECTURES: SHARED DATA SPACE

- Enables separation between processing and coordination
- Types of coordination:

	Temporally coupled (at the same time)	Temporally decoupled (at different times)
Referentially coupled (*dependent on name*)	**Direct** Explicit synchronous service call	**Mailbox** Asynchronous by name (address)
Referentially decoupled (*name not required*)	**Event-based** Event notices published to shared bus, w/o addressing	**Shared data space** Processes write tuples to a shared data space

Publish and subscribe architectures

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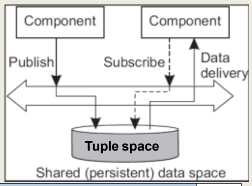
PUBLISH SUBSCRIBE ARCHITECTURES - 3

- **Shared data space**
- Full decoupling (name and time)
- Processes publish "tuples" to shared dataspace (publish)
- Processes provide search pattern to find tuples (subscribe)
- Subscribers are notified of matches (both existing and newly published tuples)
- **Key characteristic:** Processes have no explicit reference to each other



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PUBLISH SUBSCRIBE ARCHITECTURES - 4

- Subscriber describes events interested in
- Complex descriptions are intensive to evaluate and fulfil
- **Middleware will:**
- Publish matching notification and data to subscribers
  - Common if middleware lacks storage
- Publish only matching notification
  - Common if middleware provides storage facility
  - Client must explicitly fetch data on their own
- Publish and subscribe systems are generally scalable
- **What would reduce the scalability of a publish-and-subscribe system?**

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IN-CLASS ACTIVITY: ARCHITECTURAL STYLES

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CLASS ACTIVITY 2

- We will form groups of ~2-3
  - On Zoom breakout rooms will be created
- Each group will complete a MS Doc worksheet
- Add names to the Doc as they appear in Canvas
- Once completed, **one person** submits a PDF to Canvas
- Instructor will score all group members based on the uploaded PDF file
- To get started – link is under Class Activity 2 in Canvas:
  - Log into your *** **UW NET ID** ***
  - Link to shared doc file on Canvas
  - Follow link: https://canvas.uw.edu/files/114972397/

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DISTRIBUTED SYSTEM GOALS TO CONSIDER

- **Consider how the architectural change may impact:**
- Availability
- Accessibility
- Responsiveness
- Scalability
- Openness
- Distribution transparency
- Supporting resource sharing
- Other factors…

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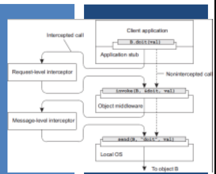

CH 2.2: MIDDLEWARE ORGANIZATION

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MIDDLEWARE ORGANIZATION

- Relies on two important design patterns:
  - Wrappers
  - Interceptors
- Both help achieve the goal of openness

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MIDDLEWARE: WRAPPERS

- Wrappers (also called adapters)
  - WHY?: Interfaces available from legacy software may not be sufficient for all new applications to use
  - WHAT: Special "frontend" components that provide interfaces for clients
  - Interface wrappers transform client requests to "implementation" (i.e. legacy software) at the component-level
  - Can then provide modern service interfaces for legacy code/systems
  - Components encapsulate (i.e. abstract) dependencies to meet all preconditions to operate and host legacy code
  - Interfaces parameterize legacy functions, abstract environment configuration (i.e. make into black box)
- Contributes towards system **OPENNESS**
- **Example: Amazon S3:** S3 HTTP REST interface
- GET/PUT/DELETE/POST: requests handed off for fulfillment

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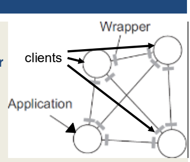
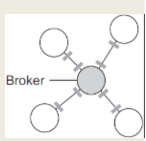
MIDDLEWARE: WRAPPERS - 2

- Inter-application communication
  - Applications may provide unique interface for every client application
- Scalability suffers
  - N applications → $O(N^2)$ wrappers



- **ALTERNATE: Use a Broker**
  - Provide a common intermediary
  - Broker knows how to communicate with every application
  - Applications only know how to communicate with the broker



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MIDDLEWARE: INTERCEPTORS

- **Interceptor**
- Software construct, breaks flow of control, allows other application code to be executed
- Interceptors send calls to other servers, or to ALL servers that replicate an object while abstracting the ***distribution*** and/or ***replication***
  - Used to enable remote procedure calls (RPC), remote method invocation (RMI)
- Object A calls method belonging to object B
  - Interceptors route calls to object B regardless of location

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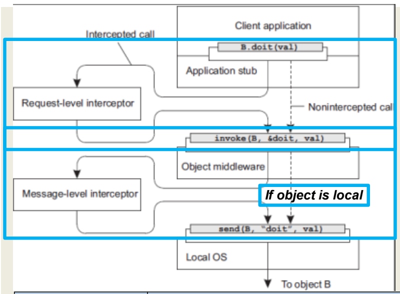
MIDDLEWARE: INTERCEPTORS - 2



Request-level interceptor transforms:
`B.doit(val)`
into generic call:
`invoke(B,&doit,val)`

Message-level interceptor in middleware sends message through OS (TCP/IP socket) to transfer data:
`send(B,"doit",val)`

Non-intercepted:

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MIDDLEWARE INTERCEPTION - METHOD

- **MIDDLEWARE**: Provides local interface matching Object B to Object A
- Object A calls Object B's method provided by local interface
- A's call is transformed into a "*generic object invocation*" by **request-level interceptor**
- "*Generic object invocation*" is transformed into a **message** by **message-level interceptor** and sent over Object A's network to Object B
- Interception automatically routes calls to all object replicas

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MODIFIABLE MIDDLEWARE

- **GOAL:** It should be possible to modify middleware without loss of availability
  - *Software components can be replaced at runtime*
- Component-based design
  - Modifiability through composition
  - Systems may have static or dynamic configuration of components
  - Dynamic configuration requires ***late binding***
  - Components can be changed at runtime
- Component based software supports modifiability at runtime by enabling components to be swapped out.
- **Does a microservices architecture (e.g. AWS Lambda) support modifiability at runtime ?**

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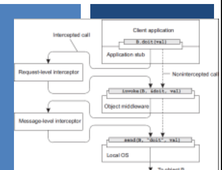

CH 2.3: SYSTEM ARCHITECTURES

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OBJECTIVES – 1/18

- Questions from 1/16
- Assignment 0: Cloud Computing Infrastructure Tutorial
- Chapter 2: Distributed System Architectures:
  - Chapter 2.1 – Architectural Styles
  - Resource-centered architectures
    - Representational state transfer (REST)
  - Event-based
    - Publish and subscribe (Rich Site Summary RSS feeds)
- Class Activity: Architectural Styles
- Chapter 2.2: Middleware Organization
- **Chapter 2.3: System Architectures**
  - Centralized system architectures
  - Decentralized peer-to-peer architectures
  - Hybrid architectures

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SYSTEM ARCHITECTURES

- Architectural styles (or patterns)
- General, reusable solutions to commonly occurring system design problems
- Expressed as a logical organization of ***components*** and ***connectors***
- Deciding on the system components, their interactions, and placement is a "realization" of an ***architectural style***
- System architectures represent designs used in practice

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TYPES OF SYSTEM ARCHITECTURES

- Centralized system architectures
  - Client-server
  - Multitiered
- Decentralized peer-to-peer architectures
  - Structured
  - Unstructured
  - Hierarchically organized
- Hybrid architectures

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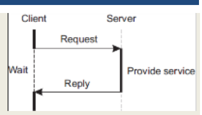
CENTRALIZED: SIMPLE CLIENT-SERVER ARCHITECTURE

- **Clients** request services
- **Servers** provide services
- Request-reply behavior



- **Connectionless protocols (UDP)**
- Assume stable network communication with no failures
- Best effort communication: No guarantee of message arrival without errors, duplication, delays, or in sequence. No acknowledgment of arrival or retransmission
- Problem: How to detect whether the client request message is lost, or the server reply transmission has failed
- Clients can resend the request when no reply is received
- ***But what is the server doing?***

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CLIENT-SERVER PROTOCOLS

- **Connectionless cont'd**
- Is resending the client request a good idea?
- Examples:
  Client message: "transfer $10,000 from my bank account"
  Client message: "tell me how much money I have left"
- **Idempotent** – repeating requests is safe
- **Connection-oriented (TCP)**
- Client/server communication over wide-area networks (WANs)
- When communication is inherently reliable
- Leverage "reliable" TCP/IP connections

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CLIENT-SERVER PROTOCOLS - 2

- **Connection-oriented cont'd**
- Set up and tear down of connections is relatively expensive
- Overhead can be amortized with longer lived connections
  - Example: database connections often retained
- Ongoing debate:
- How do you differentiate between a client and server?
- Roles are ***blurred***
- **Blurred Roles Example:** Distributed databases
- DB nodes both **service** client requests, *and* ***submit*** new requests to other DB nodes for replication, synchronization, *etc.*

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TCP/UDP

TCP	UDP
Reliable	Unreliable
Connection-oriented	Connectionless
Segment retransmission and flow control through windowing	No windowing or retransmission
Segment sequencing	No sequencing
Acknowledge segments	No acknowledgement

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CONNECTIONLESS VS CONNECTION ORIENTED

	Connectionless (UDP) *stateless*	Connection-oriented (TCP) *stateful*
Advantages		
Disadvantages		

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CONNECTIONLESS VS CONNECTION ORIENTED

	Connectionless (UDP) *stateless*	Connection-oriented (TCP) *stateful*
Advantages	• Fast to communicate (no connection overhead) • Broadcast to an audience • Network bandwidth savings	• Message delivery confirmation • Idempotence not required • Messages automatically resent - if client (or network) is temporarily unavailable • Message sequences guaranteed
Disadvantages	• Cannot tell difference of request vs. response failure • Requires idempotence • Clients must be online and ready to receive messages	• Connection setup is time-consuming • More bandwidth is required (protocol, retries, multinode-communication)

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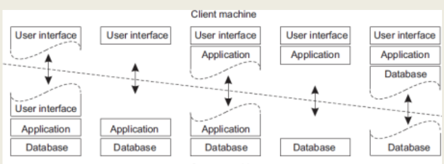
MULTITIERED ARCHITECTURES

- Where should functionality be distributed?
  - At the client?
  - At the server?



- **Why should we consider component composition?**

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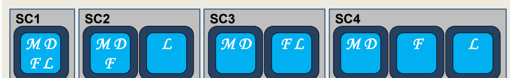
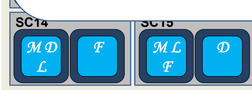


Bell's Number:

k: number of ways n components can be distributed across containers

n	k
4	15
5	52
6	203
7	877
8	4,140
9	21,147
n	. . .



M: Tomcat Application Server
D: Postgresql DB
F: nginx file server
L: Logging server (high O/H)

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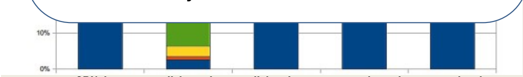
Resource utilization profile changes from component composition

M-bound RUSLE2 – Soil Erosion Model Webservice
- Box size shows absolute deviation (+/-) from mean
- Shows *relative* magnitude of performance variance

Two application variants tested
- M-bound: Standard service, M is compute bound
- D-bound: Modified service, D is compute bound

Disk sector writes:	21.8%	111.1%
Network bytes received:	144.9%	145%
Network bytes sent:	143.7%	143.9%



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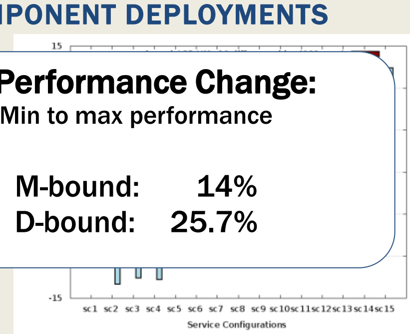
PERFORMANCE IMPLICATIONS OF COMPONENT DEPLOYMENTS



∆ Performance Change:
Min to max performance

M-bound: 14%
D-bound: 25.7%

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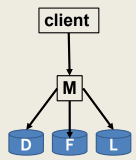
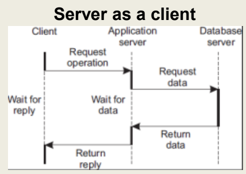
MULTITIERED ARCHITECTURES - 2

- **M D F L** architecture
- **M** – is the application server
- **M** – is also a client to the database (D), fileserver (F), and logging server (L)





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MULTITIERED RESOURCE SCALING

- **Vertical distribution**
- The distribution of "M D F L"
- Application is scaled by placing "tiers" on separate servers
  - M – The application server
  - D – The database server
- Vertical distribution impacts "network footprint" of application
- Service isolation: each component is isolated on its own HW
- **Horizontal distribution**
- Scaling an individual tier
- Add multiple machines and distribute load
- Load balancing

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MULTITIERED RESOURCE SCALING - 2

- **Horizontal distribution cont'd**
  - Sharding: portions of a database map" to a specific server
  - Distributed hash table
  - Or replica servers

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DECENTRALIZED PEER-TO-PEER ARCHITECTURES

- Client/server:
  - Nodes have specific roles
- Peer-to-peer:
  - Nodes are seen as ***all equal…***
- **How should nodes be organized for communication?**

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STRUCTURED PEER-TO-PEER

- Nodes organized using specific ***topology*** (e.g. ring, binary-tree, grid, etc.)
  - Organization assists in data lookups
- Data indexed using "semantic-free" indexing
  - Key / value storage systems
  - Key used to look-up data
- Nodes store data associated with a subset of keys

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DISTRIBUTED HASH TABLE (DHT)

- Distributed hash table (DHT) *(ch. 5)*
- Hash function

  `key(data item) = hash(data item's value)`

- Hash function "generates" a unique key based on the data
- No two data elements will have the same key (hash)
- System supports data lookup via key
- ***Any*** node can receive and resolve the request
- Lookup function determines which node stores the key

  `existing node = lookup(key)`

- Node forwards request to node with the data

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FIXED HYPERCUBE EXAMPLE

- Example where topology helps ***route*** data lookup request
- Statically sized 4-D hypercube, every node has 4 connectors
- 2 x 3-D cubes, 8 vertices, 12 edges
- Node IDs represented as 4-bit code (0000 to 1111)
- Hash data items to 4-bit key (1 of 16 slots)
- Distance (number of hops) determined by identifying number of varying bits between neighboring nodes and destination

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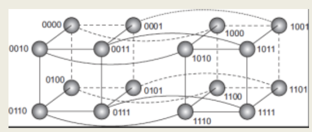
FIXED HYPERCUBE EXAMPLE - 2

- **Example:** *fixed hypercube* node **0111** (7) retrieves data from node **1110** (14)
- Node **1110** is not a neighbor to **0111**
- **Which connector leads to the shortest path?**



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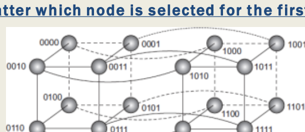
WHICH CONNECTOR LEADS TO THE SHORTEST PATH?

- **Example:** node **0111** (7) retrieves data from node **1110** (14)
- Node **1110** is not a neighbor to **0111**

[0111] Neighbors:
1111 (1 bit different than **1110**) **0011** (3 bits different– bad path)
0110 (1 bit different than **1110**) **0101** (3 bits different– bad path)

- **Does it matter which node is selected for the first hop?**



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DYNAMIC TOPOLOGY

- Fixed hypercube requires static topology
  - Nodes cannot join or leave
- Relies on symmetry of number of nodes
- Can force the DHT to a certain size
- Chord system – DHT (again in ch.5)
  - Dynamic topology
  - Nodes organized in ring
  - Every node has unique ID
  - Each node connected with other nodes (shortcuts)
  - Shortest path between any pair of nodes is ~ order O(log N)
  - N is the total number of nodes

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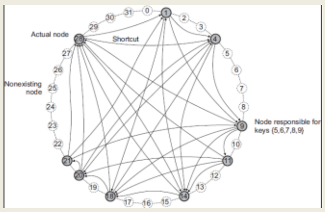
CHORD SYSTEM

- Data items have m-bit key
- Data item is stored at closest "successor" node with ID ≥ key k
- Each node maintains finger table of successor nodes
- Client sends key/value lookup to ***any*** node
- Node forwards client request to node with m-bit ID closest to, but not greater than key k
- Nodes must continually refresh finger tables by communicating with adjacent nodes to incorporate node joins/departures



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UNSTRUCTURED PEER-TO-PEER

- **No topology:** ***How do nodes find out about each other?***
- Each node maintains adhoc list of neighbors
- Facilitates nodes frequently joining, leaving, adhoc systems
- **Neighbor:** node reachable from another via a network path
- Neighbor lists constantly refreshed
  - Nodes query each other, remove unresponsive neighbors
- Forms a "random graph"
- Predetermining network routes not possible
  - How would you calculate the route algorithmically?
- Routes must be discovered

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SEARCHING FOR DATA: UNSTRUCTURED PEER-TO-PEER SYSTEMS

- **Flooding**
- `[Node u]` sends request for data item to all neighbors
- `[Node v]`
  - Searches locally, responds to u (or forwarder) if having data
  - Forwards request to **ALL** neighbors
  - Ignores repeated requests
- Features
  - High network traffic
  - Fast search results by saturating the network with requests
  - Variable # of hops
  - Max number of hops or time-to-live (TTL) often specified
  - Requests can "retry" by gradually increasing TTL/max hops until data is found

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SEARCHING FOR DATA - 2

- **Random walks**
- `[Node u]` asks a randomly chosen neighbor `[node v]`
- If `[node v]` does not have data, forwards request to a random neighbor
- Features
  - Low network traffic
  - Akin to sequential search
  - Longer search time
  - `[node u]` can start "n" random walks simultaneously to reduce search time
  - As few as n=16..64 random walks sufficient to reduce search time (LV et al. 2002)
  - Timeout required - need to coordinate stopping network-wide walk when data is found…

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SEARCHING FOR DATA - 3

- **Policy-based search methods**
- Incorporate history and knowledge about the adhoc network ***at the node-level*** to enhance effectiveness of queries
- Nodes maintain lists of preferred neighbors which often succeed at resolving queries
- Favor neighbors having highest number of neighbors
  - Can help minimize hops

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HIERARCHICAL PEER-TO-PEER NETWORKS

- **Problem:** Adhoc system search performance does not scale well as system grows
- Allow nodes to assume **ROLES** to improve search
- Content delivery networks (CDNs) *(video streaming)*
  - Store (cache) data at nodes local to the requester (client)
  - Broker node – tracks resource usage and node availability
    - Track where data is needed
    - Track which nodes have capacity (disk/CPU resources) to host data
- Node roles
  - Super peer –Broker node, routes client requests to storage nodes
  - Weak peer – Store data

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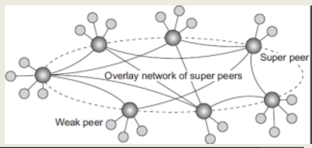
HIERARCHICAL PEER-TO-PEER NETWORKS - 2

- Super peers
  - Head node of local centralized network
  - Interconnected via overlay network with other super peers
  - May have replicas for fault tolerance
- Weak peers
  - Rely on super peers to find data
- Leader-election problem:
  - Who can become a super peer?
  - What requirements must be met to become a super peer?



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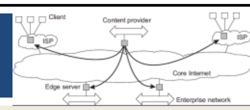
HYBRID ARCHITECTURES



- Combine centralized server concepts with decentralized peer-to-peer models
- **Edge-server systems:**
- Adhoc peer-to-peer devices connect to the internet through an edge server (origin server)
- Edge servers (provided by an ISP) can optimize content and application distribution by storing assets near the edge
- **Example:**
- AWS Lambda@Edge: Enables Node.js Lambda Functions to execute "at the edge" harnessing existing CloudFront Content Delivery Network (CDN) servers
- **https://www.infoq.com/news/2017/07/aws-lambda-at-edge**

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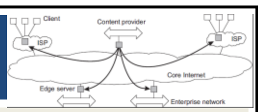
HYBRID ARCHITECTURES - 2



- **Fog computing:**
- Extend the scope of managed resources beyond the cloud to leverage compute and storage capacity of end-user devices
- End-user devices become part of the overall system
- Middleware extended to incorporate managing edge devices as participants in the distributed system
- Cloud → in the sky
  - *compute/resource capacity is huge, but far away…*
- Fog → (devices) on the ground
  - *compute/resource capacity is constrained and local…*

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COLLABORATIVE DISTRIBUTED SYSTEM EXAMPLE

- **BitTorrent Example:**
  File sharing system – users must contribute as a file host to be eligible to download file resources
- Original implementation features hybrid architecture
- Leverages idle client network capacity in the background
- User joins the system by interacting with a central server
- Client accesses global directory from a ***tracker*** server at well known address to access torrent file
- Torrent file tracks nodes having chunks of requested file
- Client begins downloading file chunks and immediately then participates to reserve downloaded content **or network bandwidth is reduced!!**
- Chunks can be downloaded in parallel from distributed nodes

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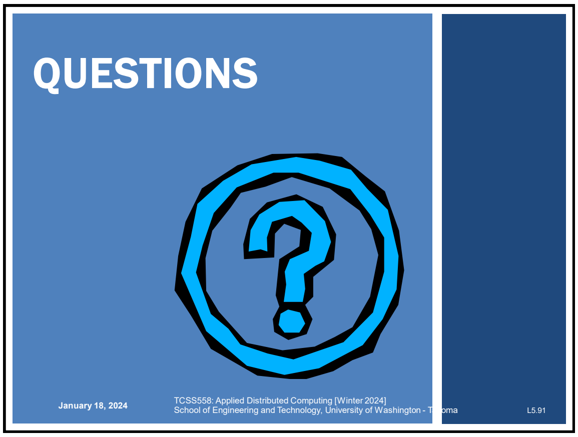
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