LECTURE 3: CONCURRENT & DISTRIBUTED ARCHITECTURES

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- MIMD: Tight & Loose Coupling
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Intro to Architectures in Concurrent & Dist'd Systems: S/w V System Architectures

- Organizating concurrent & distributed systems is mostly about the software components making up the system.
- These *software architectures* (aka *Programming Models*) dictate the organization & interaction of the various s/w components .
- The actual realization of a system requires instantiating and placing software components on real machines.
- There are many different choices that can be made in doing so.
- The final instantiation of a software architecture is referred to as a *system architecture* (aka *Machine Model*).

SECTION 3.1: CONCURRENT ARCHITECTURES & PROGRAMMING MODELS

Aside on Writing Concurrent Code

1. Identify concurrency in task
   – Do this on a piece of paper
2. Expose the concurrency when writing the task
   – Choose a *programming model* and language that allow you to express this concurrency
3. Exploit the concurrency
   – Carefully choose a language & hardware that facilitate advantage to be taken of the concurrency (often one ⇔ another)

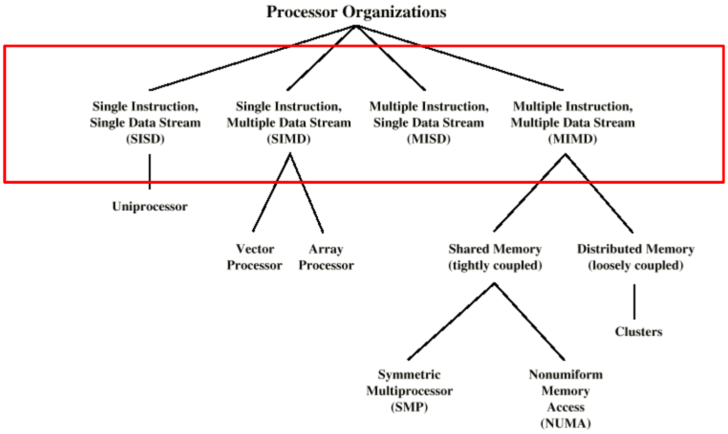
- Value of a programming model is judged on
  – *Generality*: how well a range of different problems can be expressed for a variety of different architectures,
  – *Performance*: how efficiently compiled programs can execute on these architectures.

Parallel Programming Model

- *Definition:* Programming model comprises languages & libraries that create an abstract view of the machine.
  – Control
    - What orderings exist between operations?
    - How do different threads of control synchronize?
  – Data
    - What data is private vs. shared?
    - How is logically shared data accessed or communicated?
  – Synchronization
    - What operations can be used to coordinate parallelism?
    - What are the atomic (indivisible) operations?

Concurrent Architecture Taxonomies

- As seen above, Michael Flynn in 1966 classified machines into a taxonomy by the number of instruction and data streams
- We examine these from standpoint of concurrent architectures



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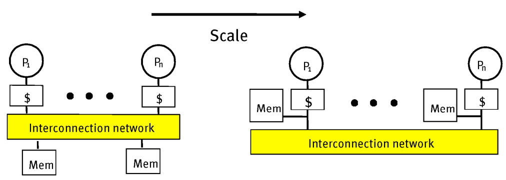
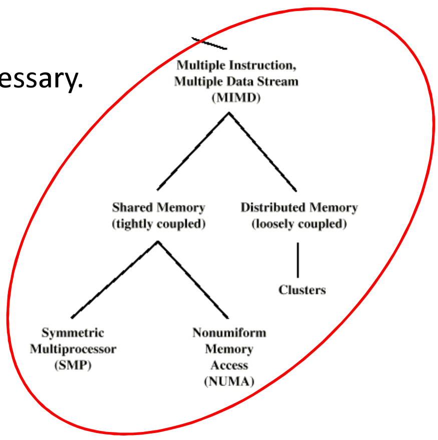
More on MIMD

- *MIMD*
- General purpose processor
- Each can process all instructions necessary.
- Further classified by method of processor communication:
  - *Tight Coupling*
  - *Loose Coupling*



Centralized Memory Distributed Memory



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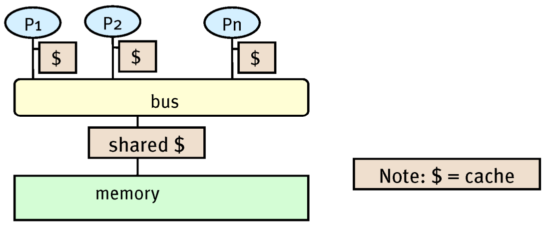
Concurrent Architectures

- *Machine Model #1: Shared Memory*
- Processors all connected to a large shared memory
  - Typically Symmetric Multiprocessors (SMPs e.g. IBM SMPs)
  - Multicore chips, except caches are often shared in multicores
  - But
    - Bus is a bottleneck (interconnect performance not scalable)
    - Also, shared memory can give issues with *race conditions*
    - Can be fixed by adding locks of some sort, at performance cost

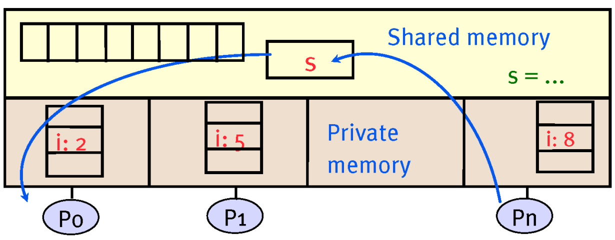


Programming Models

- *Programming Model # 1: Shared Memory*

  Program is a collection of threads of control.
  - Each thread has set of private variables, e.g., local stack variables

  & set of shared variables, e.g., static variables
  - Implicit comms between threads writing/reading shared variables
  - Threads coordinate by synchronizing on shared variables
  - Here model used by threads calculating the sum (S) of an array

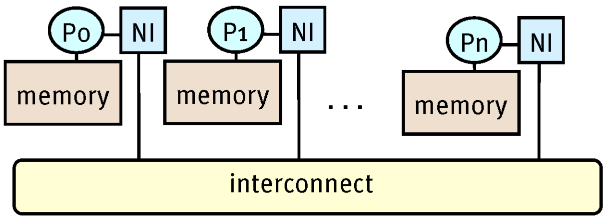


Concurrent Architectures (/2)

- *Machine Model #2: Distributed Memory*

Processors have own memory but typically fast interconnect

- Each processor has its own memory and cache but cannot directly access another processor's memory.
- Each "node" has a Network Interface (NI) for all communication and synchronization.
- Example: IBM SP2, Beowolf Cluster

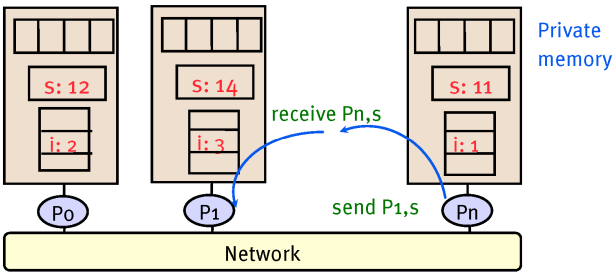


Programming Models (/2)

- *Programming Model # 2: Message Passing*

Program consists of a collection of named processes.

- Usually fixed at program startup time
- Thread of control plus local address space—NO shared data.
- Logically shared data is partitioned over local processes.
- Here, similar calculation as last time.

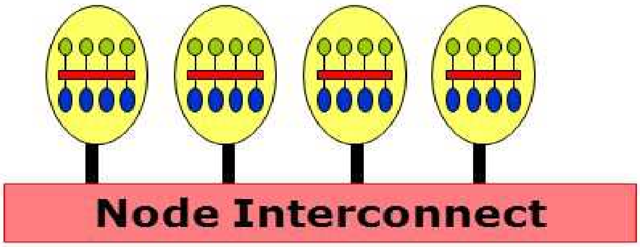


Concurrent Architectures (/3)

- *Machine Model #3: Clusters*

Used for computation-intensive purposes, (Vs for IO operations such as web service or DBs.)

- Emerged as result of trends e.g. availability of low-cost cores, high speed networks & s/w for high-performance distributed computing.
- Wide applicability from small biz clusters to fastest supercomputers
- Applications that can be done however, are nonetheless limited, since s/w needs to be purpose-built per task.



Programming Models (/3)

- *Programming Model # 3: Hybrids*

Need to run "same/similar computation" on many nodes very fast

- Common model: Hybrid MPI + OpenMP
  - Each SMP node = 1 MPI process, w MPI comm on node interconnect
  - OpenMP inside of each SMP node
- Maybe gives the highest performance?
  - Advantage: Could be good for heavyweight comms between nodes & lightweight threads within a node
  - Disadvantages:
    - Very difficult to start with OpenMP and modify for MPI
    - Very difficult to program, debug, modify and maintain
    - Generally, cannot do MPI calls within OpenMP parallel regions
    - Only people experienced in both should use this mixed prog model

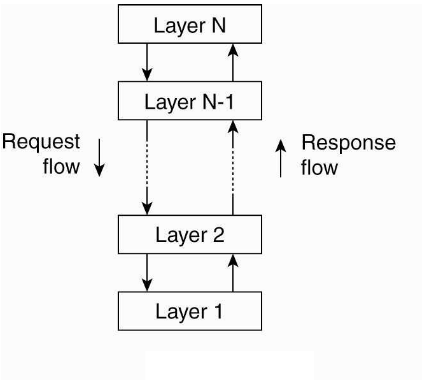
SECTION 3.2: ARCHITECTURES FOR DISTRIBUTED SYSTEMS

Architectures for *Distributed* Systems

- *Introduction*
- Examine traditional centralized *distributed systems* architectures where 1 server implements most s/w components (thus functionality)
- Remote clients access the server using simple communication means.
- Also consider decentralized architectures in which machines more or less play equal roles, as well as hybrid organizations.
- From Lecture 1, one aim of distributed systems is separating applications from underlying platforms by providing a m/w layer.
- Adopting such a layer is an important architectural decision, and its main purpose is to provide *distribution transparency*.
- However, trade-offs must be made to have transparency, leading to various techniques to make middleware adaptive.

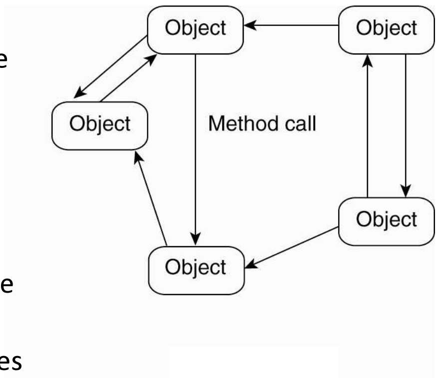
Distributed Architectural Styles

- *#1 Layered Architectures*
  - Basic idea is simple: components are organized in a layered fashion
  - Component at layer N is allowed to call components at underlying layer $N-1$ (but not vice versa)
  - This is shown in the diagram
  - This model has been widely adopted by the networking community
  - A key observation is that control generally flows from layer to layer
  - E.g. requests go down the hierarchy whereas the results flow upward.



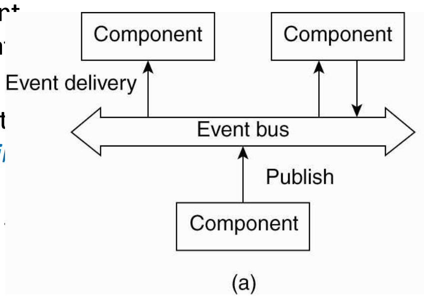
Distributed Architectural Styles (/2)

- *#2 Object-Based Architectures*
  - A far looser organization is followed in object-based architectures,
  - Each object corresponds to what we have defined as a component,
  - These components are connected through a *(remote) procedure call* mechanism.
  - This software architecture matches the client-server system architecture (described below).
  - Layered & object-based architectures still form the most important styles for large s/w systems



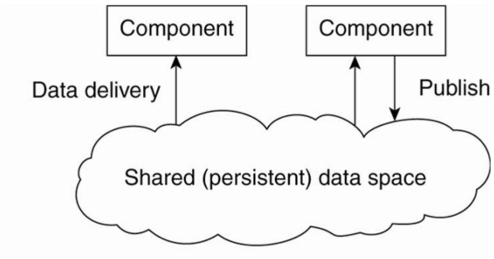
Distributed Architectural Styles (/3)

- *#3 Event-Based Architectures*
  - Here, processes communicate thro event propagation, optionally also carrying data
  - For distributed systems, event propagation has generally been associated with what are known as *publish/subscribe*
  - Idea: processes publish events & m/w ensures that only processes subscribed to the events receive them.
  - The main advantage of such systems is that processes are *loosely coupled.*
  - Needn't refer to each other explicitly.
  - This is also referred to as being *decoupled in space*, or *referentially decoupled*.



Distributed Architectural Styles (/4)

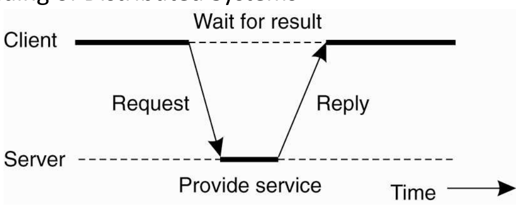
- *#4 Shared Data-Space Architectures*
  - Event-based architectures can be combined w data-centered architectures
  - Gives what is also known as *shared data spaces.*
  - Essence: processes now also *decoupled in time*
  - Thus need not both be active when communication takes place.
  - Also, many shared data spaces use a SQL-like interface to shared repository.
  - Means data can be accessed using a description rather than an explicit ref, as per files.



SECTION 3.3: SYSTEM ARCHITECTURES: CENTRALIZED & DECENTRALIZED ARCHITECTURES

System Architectures: Centralized Architectures

- *Basic Client–Server Model Characteristics*
  - There are processes offering services (*servers*)
  - There are processes that use services (*clients*)
  - Clients and servers can be on different machines
  - Sometimes Clients can be servers & vice versa
  - Clients follow request/reply model with respect to using services
  - Thinking in terms of Clients requesting Services from Servers aids in the understanding of Distributed Systems

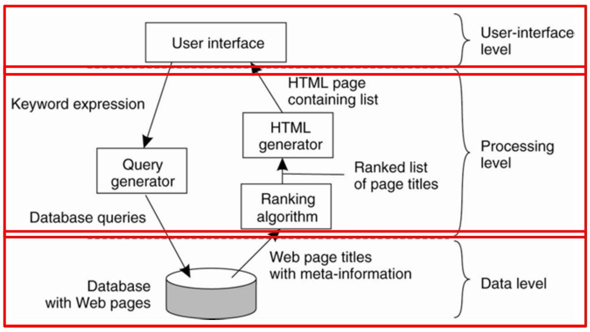


Plain Ol' Client-Server

System Architectures (/2):

- *Application Layering: Traditional three-layered view*
  1. *User-interface layer* contains units for an application's user interface
  2. *Processing layer* contains the functions of an application, i.e. no specific data
  3. *Data layer* contains data client wants to process thro application components
  - Found in many distributed info systems, using traditional DB technology and accompanying applications.

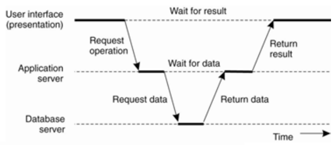
Typical Web Browser Architecture

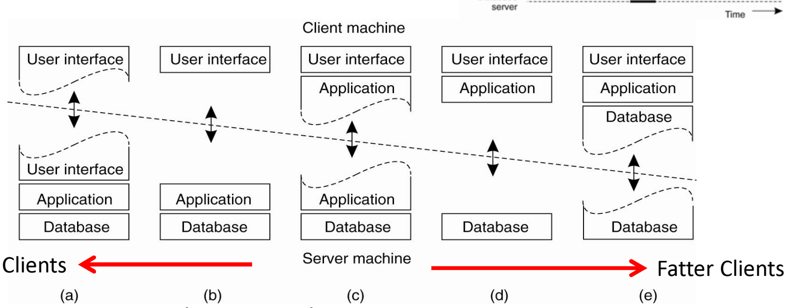


Core Functionality Transforming user keywords into DB queries & ranking results on return

System Architectures: Centralized Architectures (/3)

- *Multi-Tiered Architectures: Variations on traditional 3-layered view*
  1. *Single-tiered*: dumb terminal/mainframe configuration
  2. *Two-tiered*: client/single server configuration
  3. *Three-tiered*: each layer on separate machine (server may act as client)





Alternative Client-Server Organizations

System Architectures: Decentralized Architectures

- In multi-tiered architectures, the different tiers correspond directly to logical organization of applications – called *Vertical distribution*
- In *horizontal distribution* Client or Server may be split into logically equivalent parts each with own part of data set
- In the last couple of years there has been a tremendous growth in such *peer-to-peer (P2P)* systems:
  - *Structured P2P*: nodes are organized following a specific distributed data structure (usually a Distributed Hash Table)
  - *Unstructured P2P*: nodes have randomly selected neighbours. Each node has a list of neighbours which is constructed in a random way.
  - *Hybrid P2P*: some nodes are appointed special functions in a well-organized fashion

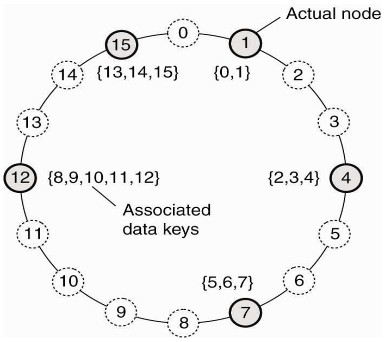
Decentralized Architectures (/2): Structured P2P Systems

- In virtually all cases, have *overlay networks*
  - This is n/w where nodes are processes & links are communication channels
  - Data is routed over connections setup between nodes.
- As processes can't communicate directly with others, available communication channel must be used (a.k.a. *Application-level Multicasting*)
  - ALM is offered by middleware (in contrast to low-level TCP/IP Multicasting)
  - Basic idea is to organize nodes in a structured overlay n/w such as a logical ring.
  - Specific nodes are made responsible for services based only on their ID.
  - Random key is assigned to a data item from a large (eg 128 bit) identifier space
  - The system provides an operation *LOOKUP(key)* that will efficiently route the lookup request to the associated node.
  - When the key is returned, the network address of node responsible for the data (known as the *successor*) item stored is returned.

Decentralized Architectures (/3): Structured P2P Systems: Chord Case Study

- *Details of Chord Algorithm*

1. Assign random key *(m-bit identifier)* to data item & random number *(m-bit identifier)* to node in system,
2. Implement an efficient & deterministic system to map a data item to a node based on some distance metric,
3. This means that data item should physically be as close to node as possible
4. *LOOKUP(key)* ≡ returning network address of node responsible for that data item,
5. Do this by routing a request for the data item to responsible node (*successor*).
6. Node with key k falls under the jurisdiction of node with smallest $id \geq k$
7. This process of looking up node's name (& any info stored there) called *name resolution*



Decentralized Architectures (/3): Structured P2P Systems: Chord Case Study

- *Principle of Operation of Chord*
- Membership management in Chord doesn't follow a logical organization of nodes in a ring as shown in diagram (previous).
- Lookups on keys can be done in $O(\log_2 N)$ steps.
- Each node p maintains a finger table $FT_p[i]$ with at most m entries:

$$FT_p[i] = succ(p + 2^{i-1})$$

- Note: $FT_p[i]$ points to the first node succeeding p by at least 2^{i-1}
- This is because Chord is an algorithm based on binary (will look at higher order algorithms later)
- To look up a key k, node p forwards the request to node with index j satisfying

$$q = FT_p[j] \leq k < FT_p[j+1]$$

- If $p < k < FT_p[1]$ the request is also forwarded to $FT_p[1]$

Decentralized Architectures (/4): Structured P2P Systems: Chord Case Study

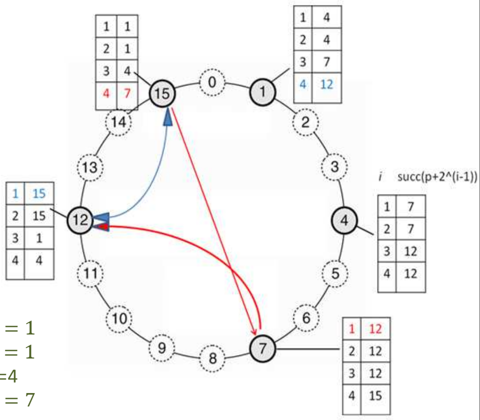
- *Building Finger Tables in Chord*

Some calculations for Finger tables in the diagram:

$FT_1[1] = succ(1 + 2^0) = succ(2) = 4$
$FT_1[2] = succ(1 + 2^1) = succ(3) = 4$
$FT_1[3] = succ(1 + 2^2) = succ(5) = 7$
$FT_1[4] = succ(1 + 2^3) = succ(9) = 12$

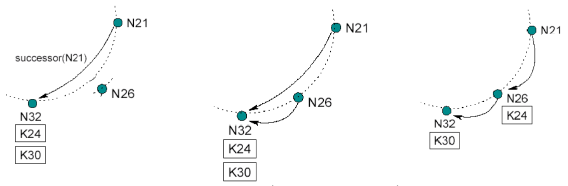
$FT_4[1] = succ(4 + 2^0) = succ(5) = 7$
$FT_4[2] = succ(4 + 2^1) = succ(6) = 7$
$FT_4[3] = succ(4 + 2^2) = succ(8) = 12$
$FT_4[4] = succ(4 + 2^3) = succ(12) = 12$

$FT_{15}[1] = succ(15 + 2^0) = succ(16) = succ(0) = 1$
$FT_{15}[2] = succ(15 + 2^1) = succ(17) = succ(1) = 1$
$FT_{15}[3] = succ(15 + 2^2) = succ(19) = succ(3) = 4$
$FT_{15}[4] = succ(15 + 2^3) = succ(23) = succ(7) = 7$



Decentralized Architectures (/5): Structured P2P Systems: Chord Case Study

- *Principle of Joining a System in Chord*
- Node wanting to join system starts by generating random identifier $id = 26$.
  - Then node simply contacts an arbitrary node & does a lookup on id,
  - Returns address of $succ(id) = 32,$ node responsible for looking after id
  - Next, node simply contacts $succ(id)$ & it's predecessor & inserts self in ring
  - This consists of updating the finger tables.
  - Insertion also yields that each data item whose key is now associated with node id, is transferred from $succ(id)$.
- Chord scheme requires that each node also stores info on its predecessor.



Decentralized Architectures (/6): Structured P2P Systems: Chord Case Study

- *Problems in Chord*
- Logical organization of overlay nodes may lead to erratic msg transfers in underlying Internet: node k, node $\mathrm{succ}(k)$ may be far apart.
  - *Topology-aware node assignment:*
    - When assigning an ID to a node, make sure that nodes close in the ID space are also close in the network.
    - Can be very difficult.
  - *Proximity routing:*
    - Maintain more than one possible successor, and forward to the closest.
    - Example: in Chord $FT_p[i]$ points to first node in $[p + 2^{i-1}, p + 2^i - 1]$.
    - Node p can also store pointers to other nodes in the interval.
  - *Proximity neighbour selection:*
    - When there is a choice of selecting who your neighbour will be (not in Chord), pick the closest one.

Decentralized Architectures (/7): Structured P2P Systems: Pastry Case Study

- *Properties of Pastry:*
- *PASTRY* is an implementation of a Distributed Hash Table (DHT) algorithm for P2P routing overlay
- Salient features:
  - Fully decentralized
  - Scalable
  - High fault tolerance
- Each node is identified by a unique 128 bit node id (*NodeId*) generated randomly so each has same probability of being chosen
- Node with similar *NodeId* may be geographically far apart
- Given a *key*, PASTRY can deliver a message to node with closest *NodeId* to key within $\log_{2^b} N$ steps,

  where b is a configuration parameter (usually $b = 4$)

  and N is the number of nodes

Decentralized Architectures (/8): Structured P2P Systems: Pastry Case Study (/2)

- *Pastry Routing Algorithm:*
- Given want to find PASTRY n/w node with *NodeId* closest to given *key*
  - Note that *NodeId* & *key* are both 128 bit sequences
  - Both *NodeId* & *key* can be thought as sequence of digits with base 2^b

- *Routing idea:*
  1. Each routing step, node normally forwards message to a node whose *NodeId* shares with *key* a prefix min. 1 digit longer than *key* shares with present node.
  2. If such a node unknown, message is forwarded to a node that shares same prefix of actual node but its *NodeId* is numerically closer to *key*

Decentralized Architectures (/9): Structured P2P Systems: Pastry Case Study (/3)

- *State of a Node in Pastry:*
- Each PASTRY node has a *state* consisting of:
  - A *routing table* R
    - used in the first phase of the routing (*long distances*)
  - A *neighbourhood set* M
    - contains *NodeId* & IP addresses of the $|M|$ nodes which are *closest* (according to a *metric*, e.g. geog. or ping distance) to considered node
  - A *leaf set* L
    - contains *NodeId* & IP addresses of $|L|/2$ nodes with *NodeId numerically closest on* smaller side of present *NodeId*,
    - and $|L|/2$ nodes with *NodeId numerically closest on the* larger side of present *NodeId*.
    - L usually taken to be 16

Decentralized Architectures (/10): Structured P2P Systems: Pastry Case Study (/4)

- *Routing table in Pastry:*
- This is a $\lceil \log_{2^b} N \rceil$ rows $\times (2^b - 1)$ columns table

  where $\lceil \log_{2^b} N \rceil$ is the max number of hops between any pair of nodes

  b is the configuration parameter (usually 4) and

  N is the number of PASTRY nodes in the network
- The $2^b - 1$ entries at row n each refer to a node whose *NodeId* shares the present node *NodeId* in the first n digits
- However the $(n+1)$th digit has one of the $2^b - 1$ possible values other than $(n+1)$th digit digit in the present node id.
- The choice of b is a choice between the size of the populated part of the Routing table ($\lceil \log_{2^b} N \rceil \times (2^b - 1)$ entries) & max number of hops.
  - e.g. a value of $b = 4$ and $N = 10^6$ nodes gives ~75 entries and ~5 hops
  - while $b = 4$ and $N = 10^9$ Nodes gives ~105 entries and ~7 hops

Decentralized Architectures (/11): Structured P2P Systems: Pastry Case Study (/5)

- *Example Routing Table R in Pastry:*
- $N = 1024$ Nodes, $b = 2$ so $\lceil \log_{2^b} N \rceil = 5$ rows, $2^b - 1 = 3$ columns
  - Row i: Holds ids of Nodes whose IDs share an i digit prefix with Node
  - Column j: digit $(i+1) = j$
  - Contains topologically closest node that meets these criteria

Shared prefix length with *NodeID*

Digit at position *i+1*

These entries match node 32101's *ID*

Topologically closest with **prefix length *i* & digit *(i+1)=j***

i *j*	0	1	2	3
0	01230	13320	22222	
1	30331	31230	-	33123
2	32012	-	32212	32301
3	-	32110	32121	32131
4	32100	-	32102	32103

Possible node 33xyz 33123 is topologically closest node

Decentralized Architectures (/12): Structured P2P Systems: Pastry Case Study (/6)

- *Example Routing in Pastry: $N = 1024$ Nodes, $b = 2, L = 8$*
- Leaf Table L for *NodeID* 32101
  - $L/2$ smaller, $L/2$ larger
  - Fixed maximum size
  - Similar to Chord's finger table
  - Used for routing and recovery from departures of nodes

Smaller *NodeID's*		Larger *NodeId's*	
32100	32023	32110	32121
32012	32022	32123	32120

- Neighbour Set M
  - Contains nearby nodes (based on some scalar proximity metric e.g. geography, latency, IP hops etc
  - Fixed maximum size
  - Irrelevant for routing

Decentralized Architectures (/13): Structured P2P Systems: Pastry Case Study (/7)

- *Routing Algorithm of Packet with NodeID A, key D (both 128 bit):*

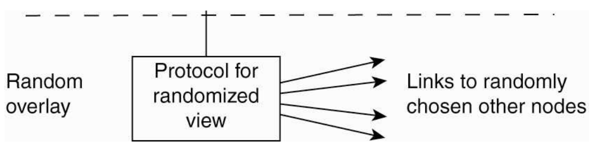
if $\left(L_{-|L|/2} \leq D \leq L_{|L|/2}\right)$ then
    // D is in the Leaf Node Set
    forward to L_i, such that $|D - L_i|$ is minimal, i.e. closest *NodeID* in L
else
    // search for a node with longer shared prefix in the routing table
    Let $l = shl(D, A)$
    if $\left(R_l^{D_l} \neq null\right)$ then
        forward to $R_l^{D_l}$ // entry in routing table row l, column D_l
        D_l is the value of the l's digit in the key D
    else
        // rarely
        forward to $T \in L \cup R \cup M$ such that
        $shl(T, D) \geq l, |T - D| < |A - D|$
        search for node T with longest prefix out of merged set

Decentralized Architectures (/14): Unstructured P2P Systems

- Many unstructured P2P systems try to maintain a random graph
- Basic principle is for each node is required to contact a randomly selected other node:
  - Let each peer maintain a partial view of the network, consisting of c other nodes
  - Each node P periodically selects a node Q from its partial view
  - P and Q exchange information and exchange members from their respective partial views
- It turns out that, depending on the exchange, randomness, but also robustness of the network can be maintained.

Decentralized Architectures (/15): Unstructured P2P Systems (/2)

- *Topology Management of Overlay Networks*
- Basic idea is to distinguish two layers:
  1. maintain random partial views in lowest layer;
  2. be selective on who you keep in higher-layer partial view.



- Lower layer feeds upper layer with random nodes; upper layer is selective when keeping references (e.g. based on distance).

Decentralized Architectures (/16): Unstructured P2P Systems (/3)

- *Topology Management of Overlay Networks (cont'd)*
- To construct a torus, Consider a $N \times N$ grid.

  Keep only refs to nearest neighbours:

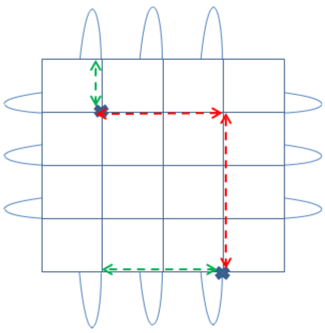
$$\|(a_1, a_2) - (b_1 - b_2)\| = d_1 + d_2$$
$$d_i = \min\{N - |a_i - b_i|, |a_i - b_i|\}$$

Decentralized Architectures (/17): Unstructured P2P Systems (/4)

- *Topology Management of Overlay Networks (cont'd)*
- To construct a torus, Consider a $N \times N$ grid.

  Keep only refs to nearest neighbours:

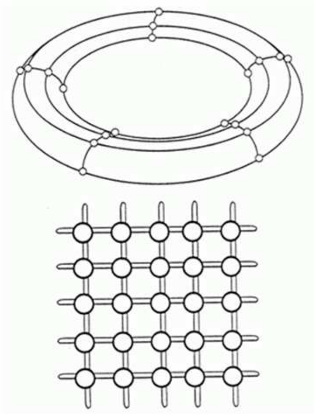
$$\|(a_1, a_2) - (b_1, b_2)\| = d_1 + d_2$$
$$d_i = \min\{N - |a_i - b_i|, |a_i - b_i|\}$$



Here, there are two points:
$(a_1, a_2) = (1,3)$ and $(b_1, b_2) = (3,0)$
hence
$d_1 = \min\{4 - 2,2\} = 2$ (both paths same length)
and
$d_2 = \min\{4 - 3,3\} = 1$(green path is shorter)

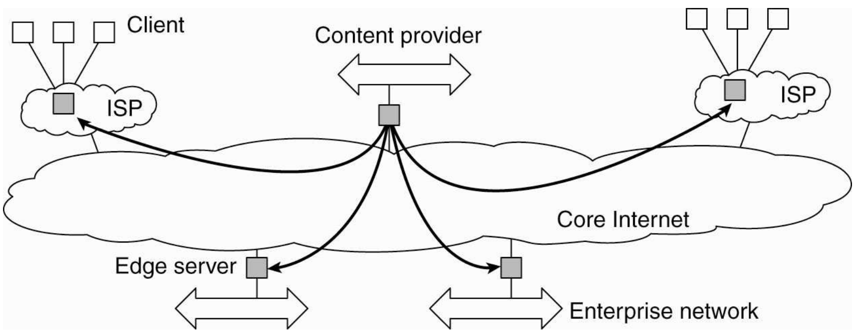
Decentralized Architectures (/18): Unstructured P2P Systems (/5)

- *Topology Management of Overlay Networks (cont'd)*
- Explanation
  - With minimum distance condition, a toroidal shape emerges.



Decentralized Architectures (/19): Hybrid Architectures: C-S combined with P2P

- Example: *Edge-server* architectures, which are often used for *Content Delivery Networks*



Viewing the Internet as consisting of a collection of edge servers.

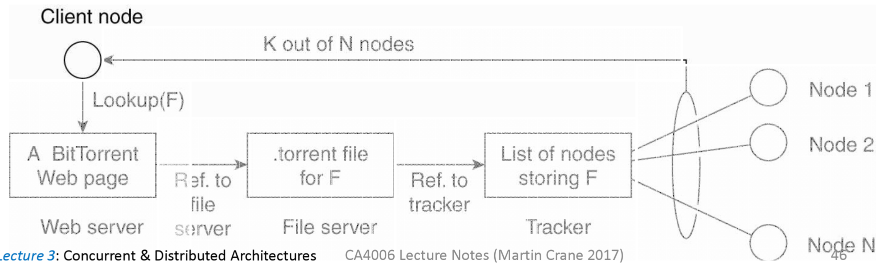
Decentralized Architectures (/20): Hybrid Architectures: C-S with P2P (/2)

- *Internet as consisting of a collection of edge servers*
- An important class of distributed systems that is organized according to a hybrid architecture is formed by *edge-server systems*.
- Such systems are deployed on the Internet where servers are placed "at the edge" of the network.
  - Edge is formed by boundary between enterprise n/ws and actual Internet, (for example, as provided by an ISP).
  - Likewise, where end users at home connect to the Internet through their ISP, the ISP can be considered as residing at edge of Internet.
  - Edge-Server thus serves content and optimises delivery
- *Content Delivery Networks* offers storage of copies of webpages for rapid reaccessing.

Decentralized Architectures (/21): Hybrid Architectures: C-S combined with P2P

- *Example: Hybrid Architectures: C/S with P2P – BitTorrent*
- *Basic Idea*: *Tracker* (server with list of active nodes to download chunks of file) gives single copy (*seed*) of file (F), *swarm* is all nodes with some/all of F
- *Steps*:

1. Client Node does a Lookup on F,
2. BT webpage gives ref to file server with `.torrent` file for F (with Tracker).
3. BT Client s/w talks to tracker to find other BT Nodes with whole/part of F.
4. Tracker identifies swarm (i.e. connected peers sending/receiving) F.
5. Tracker helps client trade pieces of F needed with others in swarm.



Architecture V Middleware

- *Architecture and Middleware*
- Considering the architectural issues above, a question that comes to mind is where middleware fits in.
- Important aim is to give a degree of distribution transparency, i.e. try to hide data distribution, processing, and control from applications.
- What is commonly seen in practice is that middleware systems actually follow a specific architectural style.
- The chosen style may not be optimal in all cases.
- So may need to (dynamically) adapt behaviour of the middleware.

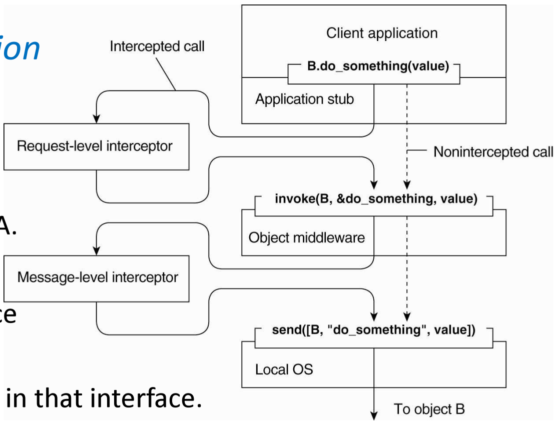
Interceptors

- These intercept usual flow of control when invoking a remote object.
- Thus they allow other (application specific) code to be executed.
- This is demonstrated in the diagram (over)

Architecture V Middleware : Interceptors (2)

- *Remote Object Invocation*
- Basic idea:

Object A can call a method belonging to object B, living on a different machine to A.



- Steps:
  1. A offered a local interface (same as B's).
  2. A calls method available in that interface.
  3. A's call transformed into a generic object invocation, enabled thro a general object-invocation interface offered by m/w at A's machine.
  4. Finally, GOI is transformed into a message sent thro the transport-level network interface offered by A's local operating system.

Summary

- Flynn's Taxonomy is a classic but still useful way to classify architectures:
  - SISD, SIMD, MIMD can still be identified in supercomputers today
  - MIMD can be split into Tight & Loose Coupling
- Software Architectures for Distributed Systems divide into:
  - Layered, Object-/Event-based, Shared Dataspace Architectures
- System Architectures
  - Centralized Architectures:
    - 2 & multi-tiered architectures
    - Fat & Thin Clients
  - Decentralized Architectures can be divided into
    - Structured P2P Systems (e.g. Chord & Pastry Routing algorithms)
    - Unstructured P2P Systems
    - Hybrid Systems (e.g. BitTorrent)
- Middleware can sometimes be used to fill in for architecture