LECTURE 3: CONCURRENT & DISTRIBUTED ARCHITECTURES

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Intro to Architectures in Concurrent & Dist’d Systems: S/w V System Architectures

- Organizing 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

More on MIMD

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

![Distributed Memory Diagram](image)

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.

![Message Passing Diagram](image)
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 thru 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.

![Diagram of Client-Server Interaction](image)
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](image)

  **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](image)
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 \((m\text{-bit identifier})\) to data item & random number \((m\text{-bit identifier})\) 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. \(\text{LOOKUP(key)} \equiv \text{returning network address of node responsible for that data item},\)
  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*

**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:

\[FT_1[1] = \text{succ}(1 + 2^0) = \text{succ}(2) = 4\]
\[FT_1[2] = \text{succ}(1 + 2^1) = \text{succ}(3) = 4\]
\[FT_1[3] = \text{succ}(1 + 2^2) = \text{succ}(5) = 7\]
\[FT_1[4] = \text{succ}(1 + 2^3) = \text{succ}(9) = 12\]

\[FT_1[1] = \text{succ}(4 + 2^0) = \text{succ}(5) = 7\]
\[FT_1[2] = \text{succ}(4 + 2^1) = \text{succ}(6) = 7\]
\[FT_1[3] = \text{succ}(4 + 2^2) = \text{succ}(8) = 12\]
\[FT_1[4] = \text{succ}(4 + 2^3) = \text{succ}(12) = 12\]

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

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 \(\text{succ}(id) = 32\), node responsible for looking after \(id\)
  – Next, node simply contacts \(\text{succ}(id)\) & its 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 \(\text{succ}(id)\).

• 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 $\text{succ}(k)$ 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 $FT_a[i]$ 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 ($\text{NodeId}$) generated randomly so each has same probability of being chosen
- Node with similar $\text{NodeId}$ may be geographically far apart
- Given a key, PASTRY can deliver a message to node with closest $\text{NodeId}$ to key within $\log_2 N$ 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 $|M|$ 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 \(\left\lfloor \log_2 N \right\rfloor \times (2^b - 1)\) columns table
  where \(\left\lfloor \log_2 N \right\rfloor\) 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 \(\left\lfloor \log_2 N \right\rfloor \times (2^b - 1)\) 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

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

- **Example Routing Table \(R\) in Pastry:**

  - \(N = 1024\) Nodes, \(b = 2\) so \(\left\lfloor \log_2 N \right\rfloor = 10\) 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

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>3320</td>
<td>2222</td>
</tr>
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<td>3031</td>
<td>3130</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>3201</td>
<td>-</td>
<td>3212</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>3210</td>
<td>3212</td>
</tr>
<tr>
<td>4</td>
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<td>-</td>
<td>3212</td>
</tr>
</tbody>
</table>
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

- 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

<table>
<thead>
<tr>
<th>Smaller NodeID's</th>
<th>Larger NodeID's</th>
</tr>
</thead>
<tbody>
<tr>
<td>32100</td>
<td>32023</td>
</tr>
<tr>
<td>32110</td>
<td>32121</td>
</tr>
<tr>
<td>32012</td>
<td>32022</td>
</tr>
<tr>
<td>32123</td>
<td>32120</td>
</tr>
</tbody>
</table>

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

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

(1) if ($L_{-L/2} \leq D \leq L_{L/2}$) then
(2) // $D$ is in the Leaf Node Set
(3) forward to $L_i$, such that $|D - L_i|$ is minimal, i.e. closest NodeID in $L$
(4) else
(5) // search for a node with longer shared prefix in the routing table
(6) Let $l = shl(D, A)$
(7) if ($R^D_l \neq null$) then
(8) forward to $R^D_l$, // entry in routing table row $l$, column $D_l$
(9) $D_l$ is the value of the $l$’s digit in the key $D$
(10) else
(11) // rarely
(12) forward to $T \in L \cup R \cup M$ such that
(13) $shl(T, D) \geq l, |T - D| < |A - D|$
(14) 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_1|, |a_i - b_1|\}

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)

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 Dataspaces

• 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