Historically, parallel architectures tied to programming models

- Divergent architectures, with no predictable pattern of growth.
Current Trends In Parallel Architectures

• The extension of “computer architecture” to support communication and cooperation:
  – OLD: Instruction Set Architecture.
  – NEW: Communication Architecture.

• Defines:
  – Critical abstractions, boundaries, and primitives (interfaces).
  – Organizational structures that implement interfaces (hardware or software).

• Compilers, libraries and OS are important bridges today
Modern Parallel Architecture

Layered Framework

<table>
<thead>
<tr>
<th>CAD</th>
<th>Database</th>
<th>Scientific modeling</th>
<th>Parallel applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiprogramming</td>
<td>Shared address</td>
<td>Message passing</td>
<td>Data parallel</td>
</tr>
<tr>
<td>Compilation or library</td>
<td>Operating systems support</td>
<td>Communication abstraction</td>
<td>User/system boundary</td>
</tr>
<tr>
<td>Communication hardware</td>
<td></td>
<td>Hardware/software boundary</td>
<td></td>
</tr>
<tr>
<td>Physical communication medium</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- CAD
- Database
- Scientific modeling
- Parallel applications
- Programming models
- Communication abstraction
- User/system boundary
- Hardware/software boundary
- Communication hardware
- Physical communication medium
Programming Models

• Programming methodology used in coding applications
• Specifies communication and synchronization

• Examples:
  – Multiprogramming:
    No communication or synchronization at program level
  – Shared memory address space:
  – Message passing:
    Explicit point to point communication
  – Data parallel:
    More regimented, global actions on data
    • Implemented with shared address space or message passing
Communication Abstraction

• User-level communication primitives provided
  – Realizes the programming model.
  – Mapping exists between language primitives of programming model and these primitives

• Supported directly by hardware, or via OS, or via user software.

• Lot of debate about what to support in software and gap between layers.

• Today:
  – Hardware/software interface tends to be flat, i.e. complexity roughly uniform.
  – Compilers and software play important roles as bridges today.
  – Technology trends exert strong influence

• Result is convergence in organizational structure
  – Relatively simple, general purpose communication primitives.
Communication Architecture

\[ \text{Communication Architecture} = \text{User/System Interface} + \text{Implementation} \]

- **User/System Interface:**
  - Communication primitives exposed to user-level by hardware and system-level software.

- **Implementation:**
  - Organizational structures that implement the primitives: hardware or OS.
  - How optimized are they? How integrated into processing node?
  - Structure of network.

- **Goals:**
  - Performance
  - Broad applicability
  - Programmability
  - Scalability
  - Low Cost
Toward Architectural Convergence

- Evolution and role of software have blurred boundary:
  - Send/receive supported on SAS machines via buffers.
  - Can construct global address space on massively parallel (MP) message-passing machines by carrying along pointers specifying the process and local virtual address space.
  - Shared virtual address space in message-passing machines can also be established at the page level generating a page fault for remote pages handled by sending a message.

- Hardware organization converging too:
  - Tighter integration even for MP (low-latency, high-bandwidth):
    - Network interface tightly integrated with memory/cache controller.
    - Transfer data directly to/from user address space.
    - DMA transfers across the network.
  - At lower level, even hardware SAS passes hardware messages.

- Even clusters of workstations/SMPs are becoming parallel systems:
  - Emergence of fast system area networks (SAN): ATM, fiber channel ...

- Programming models distinct, but organizations converging:
  - Nodes connected by general network and communication assists.
  - Implementations also converging, at least in high-end machines.
Convergence of Scalable Parallel Machines: Generic Parallel Architecture

- A generic modern multiprocessor:
  - Node: processor(s), memory system, plus communication assist:
    - Network interface and communication controller.
    - Scalable network:
    - Convergence allows lots of innovation, now within framework
      - Integration of assist with node, what operations, how efficiently...
Understanding Parallel Architecture

• Traditional taxonomies not very useful.
• Programming models are not enough, nor hardware structures.
  – Can be supported by radically different architectures.
• *Architectural distinctions that affect software*
  – Compilers, libraries, programs.
• Design of user/system and hardware/software interface
  – Constrained from above by programming models and below by technology.
• Guiding principles provided by layers.
  – What primitives are provided at communication abstraction.
  – How programming models map to these.
  – How they are mapped to hardware.
Fundamental Design Issues

• At any layer, interface (contract) aspect and performance aspects:
  – **Naming**: How are logically shared data and/or processes referenced?
  – **Operations**: What operations are provided on these data.
  – **Ordering**: How are accesses to data ordered and coordinated to satisfy program threads dependencies?
  – **Replication**: How are data replicated to reduce communication overheads?
  – **Communication Cost**: Latency, bandwidth, overhead, occupancy.

• Understand at programming model level first, since that sets requirements from lower layers.

• Other issues:
  – **Node Granularity**: How to split between processors and memory?
  – ...

Sequential Programming Model

Contract

– Naming: Can name any variable in virtual address space
  • Hardware (and perhaps compilers) does translation to physical addresses.
– Operations: Loads and Stores.
– Ordering: Sequential program order.

Performance

– Rely on dependencies on single location (mostly): dependence order.
– Compilers and hardware violate other orders without getting caught.
– Compiler: reordering and register allocation
– Hardware: out of order, pipeline bypassing, write buffers
– Transparent replication in caches
SAS Programming Model

- **Naming:** Any process can name any variable in shared space.

- **Operations:** Loads and stores, plus those needed for ordering and thread synchronization.

- **Simplest Ordering Model:**
  - Within a process/thread: sequential program order.
  - Across threads: some interleaving (as in time-sharing).
  - Additional orders through synchronization.
  - Again, compilers/hardware can violate orders without getting caught.
  - Different, more subtle ordering models also possible.
Synchronization

Mutual exclusion (locks):
- Ensure certain operations on certain data can be performed by only one process at a time.
- Room that only one person can enter at a time.
- No ordering guarantees.

Event synchronization:
- Ordering of events to preserve dependences
  - e.g. producer —> consumer of data
- 3 main types:
  - point-to-point
  - global
  - group
Message Passing Programming Model

- **Naming:** Processes can name private data directly.
  - No shared address space.
- **Operations:** Explicit communication through `send` and `receive`
  - Send transfers data from private address space to another process.
  - Receive copies data from process to private address space.
  - Must be able to name processes.
- **Ordering:**
  - Program order within a process.
  - Blocking `send` and `receive` can provide point to point synchronization between processes.
  - Mutual exclusion inherent.
- **Can construct global address space:**
  - Process number + address within process address space
  - But no direct operations on these names at the communication abstraction level.
Design Issues Apply at All Layers

• Prog. model’s position provides constraints/goals for the system.

• In fact, each interface between layers supports or takes a position on:
  – Naming model.
  – Set of operations on names
  – Ordering model.
  – Replication.
  – Communication performance.

• Any set of positions can be mapped to any other by software.

• Let’s see issues across layers:
  – How lower layers can support contracts of programming models.
  – Performance issues.
Lower Layers Support of Naming and Operations

- Naming and operations in programming model can be directly supported by lower levels, or translated by compiler, libraries or OS
  - Example: Shared virtual address space in programming model

- Hardware interface supports *shared physical address space*
  - Direct support by hardware through virtual-to-physical mappings, no software layers.

- Hardware supports independent physical address spaces:
  - Can provide SAS through OS, in system/user interface
    - v-to-p mappings only for data that are local.
    - Remote data accesses incur page faults; brought in via page fault handlers.
    - Same programming model, different hardware requirements and cost model.
  - Or through compilers or runtime, so above sys/user interface
    - shared objects, instrumentation of shared accesses, compiler support.
Lower Layers Support of Naming and Operations

Example: Implementing Message Passing

- Direct support at hardware interface:
  - But message matching and buffering benefit from the added flexibility provided by software.

- Support at sys/user interface or above in software (almost always)
  - Hardware interface provides basic data transport (well suited).
  - Send/receive built in sw for flexibility (protection, buffering).
  - Choices at user/system interface:
    - All messages go through OS each time: expensive
    - OS sets up once/infrequently, then little software involvement each time for simple data transfer operations.
    - Or lower interfaces provide SAS, and send/receive built on top with buffers and loads/stores.

- Need to examine the issues and tradeoffs at every layer
  - Frequencies and types of operations, costs.
Lower Layers Support of Ordering

• Message passing: No assumptions on orders across processes except those imposed by send/receive pairs.

• SAS: How processes see the order of other processes’ references defines semantics of SAS:
  – Ordering is very important and subtle.
  – Uniprocessors play tricks with orders to gain parallelism or locality.
  – These are more important in multiprocessors.
  – Need to understand which old tricks are valid, and learn new ones.
  – How programs behave, what they rely on, and hardware implications.
Lower Layers Support of Replication

- Very important for reducing data transfer/communication.
- Again, depends on naming model.
- Uniprocessor: caches do it automatically
  - Reduce communication with memory.
- Message Passing naming model at an interface:
  - A receive replicates, giving a new name; subsequently use new name.
  - Replication is explicit in software above that interface
- SAS naming model at an interface
  - A load brings in data transparently, so can replicate transparently
  - Hardware caches do this, e.g. in shared physical address space
  - OS can do it at page level in shared virtual address space, or objects
  - No explicit renaming, many copies for same name: coherence problem
  - In uniprocessors, “coherence” of copies is natural in memory hierarchy.
Communication Performance

• Performance characteristics determine usage of operations at a layer:
  – Programmer, compilers etc. make choices based on this
• Fundamentally, three characteristics:
  – *Latency*: time taken for an operation.
  – *Bandwidth*: rate of performing operations.
  – *Cost*: impact on execution time of program.
• If processor does one thing at a time: bandwidth $\propto 1/\text{latency}$
  – But actually more complex in modern systems.
• Characteristics apply to overall operations, as well as individual components of a system, however small
• We’ll focus on communication or data transfer across nodes.
Simple Communication Cost Example

• Component performs an operation in 100ns.
• Simple bandwidth: 10 M operations
• Internally pipeline depth 10 => bandwidth 100 Mops
  – Rate determined by slowest stage of pipeline, not overall latency.
• Delivered bandwidth on application depends on initiation frequency.
• Suppose application performs 100 M operations. What is cost?
  – op count * op latency gives 10 sec (upper bound)
  – op count / peak op rate gives 1 sec (lower bound)
    • assumes full overlap of latency with useful work, so just issue cost
  – if application can do 50 ns of useful work before depending on result of op, cost to application is the other 50ns of latency
Linear Model of Data Transfer Latency

Transfer time \((n) = T_0 + n/B\)

- \(T_0 = \text{Start-up cost}\)
- \(B = \text{Transfer rate}\)
- \(n = \text{Amount of data}\)

- useful for message passing, memory access, vector ops etc.

- As \(n\) increases, bandwidth approaches asymptotic rate \(B\)
- How quickly it approaches depends on \(T_0\)
- Size needed for half bandwidth (half-power point):
  \[n_{1/2} = T_0 / B\]

- But the linear model is not enough:
  - When can next transfer be initiated? Can cost be overlapped?
  - Need to know how the transfer is performed.
Communication Cost Model

Comm Time per message(n) = Overhead + Occupancy + Network Delay

= Overhead + Occupancy + Network Latency + Size/Bandwidth + Contention

= \( o_v + o_c + l + \frac{n}{B} + T_c \)

Overhead = Time for the processor to initiate the transfer.
Occupancy = The time it takes data to pass through the slowest component on the communication path. Limits frequency of communication operations.

\( l + \frac{n}{B} + T_c \) = Total Network Delay, can be hidden by overlapping with other processor operations.

• Overhead and assist occupancy may be \( f(n) \) or not.
• Each component along the way has occupancy and delay
  – Overall delay is sum of delays.
  – Overall occupancy (1/bandwidth) is biggest of occupancies.
Communication Cost Model

Comm Cost = frequency * (Comm time - overlap)

Frequency of Communication:
- The number of communication operations per unit of work in the program.
- Depends on many program and hardware factors.
  - Hardware may limit transfer size increasing comm. Frequency.
- Also affected by degree of hardware data replication and migration.

The Overlap:
- The portion of the communication operation time performed concurrently with other useful work including computation and other useful work.
- Reduction of effective communication cost is possible because much of the communication work is done by components other than the processor including:
  - Communication assist, bus, the network, remote processor or memory.
Summary of Design Issues

• Functional and performance issues apply at all layers

• Functional: Naming, operations and ordering.

• Performance: Organization, latency, bandwidth, overhead, occupancy.

• Replication and communication are deeply related:
  – Management depends on naming model.

• Goal of architects: design against frequency and type of operations that occur at communication abstraction, constrained by tradeoffs from above or below.
  – Hardware/software tradeoffs.