CSCE 455/855
Distributed Operating Systems

Real-Time Systems

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Real-Time Systems

- Conventional programming model
  - » Independent processes using independent processors
  - » Independent *virtual* processors executing in *virtual* time
  - » Computation time does not affect *correctness*
- Why was this model created?
  - » Simplified sharing a physical machine among many computations
  - » Simplified improving *average case* performance in countless situations

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Real-Time Systems

- Real-Time systems have different goals, require different assumptions, producing different designs & implementations
- In a real-time system, *when* the answer is produced is part of the answer's *correctness*
  - Example: Can an air-traffic control solution created *after* the plane has crashed be correct?
    - Time dependent computation semantics
- Real-time computations must produce solutions which are *logically correct* and *timely*
  - Timeliness means completion by a *deadline*

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Real-Time Systems

- Key Design Question:
  - Must this system be able to *guarantee* that one or more computations will complete by a deadline
  - NO
    - No problem, this is not a real-time system
    - Conventional designs and approaches apply
  - YES
    - OK, but we have a problem because *guaranteeing* that computations will complete by deadlines depends on *worst* case assumptions and behaviors

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Real-Time Systems
Assumption Assault

- Decades of hardware and software design decisions have used *average* case performance metrics
  - » Bad: explicit design assumptions can become invalid
  - » Worse: *implicit* design assumptions can become invalid

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Real-Time Systems
Assumption Assault

- Explicit
  - » Computation time doesn't matter
    - Now we need to know *worst case execution time*
  - » Computations can be treated independently
    - They affect one another's completion time
  - » Algorithms treating computations fairly are good
    - Unfair is preferred if it increases deadline satisfaction
- Implicit
  - » Caching is good
    - Not if it decreases *average* access time by increasing *worst case* access time

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Real-Time Systems
Requirements

- Timeliness
  - » System must ensure that real-time tasks satisfy their deadlines
- Simultaneity
  - » More than one event may occur at the same time
  - » Deadlines of computations serving events must be met
- Predictability
  - » Real-time system must service all events predictably
- Adaptability to handle
  - » Increased load (short term state changes)
  - » Configuration changes (long term)

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Real-Time Systems
Computation Characteristics

- Resource Use
  - » CPU
  - » Shared resources implying execution constraints
- Precedence Relations
  - » Among components of a computation
- Concurrency Constraints
  - » Arising from resource use or precedence relations
  - » Should permit maximum concurrency
- Communication Relations
  - » Time constrained communication among computations and components$\rightarrow$ precedence relations

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Real-Time Systems
Computation Characteristics

- Importance
  - » Different tasks have different levels of importance
  - » Application semantics' influence on scheduling
- Fault tolerance
  - » Critical tasks must be fault tolerant
  - » How critical and how tolerant must be specified and then dealt with appropriately
- Placement constraints
  - » Hardware dependencies for device control
  - » Separation on different HW elements for fault tolerance

Classification

- Deadline Classification
  - » Hard: infinite cost for a missed deadline
  - » Soft: non-zero but tolerable cost
  - » Firm: non-zero and less tolerable cost
- Periodic/Aperiodic
  - » Can a computation be handled with periodic attention
- Event triggered vs. Time triggered
  - » Is the system best described as a set of computations scheduled at particular times or computations executing in response to external events

Hard Real-Time

- HRT computation failure causes terrible consequences
  - » Air traffic control, fly-by-wire, machine controllers
  - » Late results are useless
- Often low level operations and combined with fault tolerance requirements
- Often designed as separate components of a distributed system to simplify analysis
  - » Isolate HRT components on dedicated resources
- Design Challenge
  - » Correctly distinguish hard from not-so-hard computations
  - » Redesign components to reduces "hardness"

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Soft Real-Time

- Much less obvious temporal constraints
  - » More complex cost/benefit tradeoff
  - » "Fast Enough" is often heard but is not specific enough
- Rising cost (decreasing value) with lateness
  - » Deadline violation rate
  - » Value function: value of completed computation
- Examples: Vending Machines, Transaction Servers
- Continuum with "fast" conventional systems
- Often created by adding time-aware scheduling to a conventional system
  - » Limited value when many sub-systems are designed for the average case (Solaris)

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Firm Real-Time

- Emerging and growing class of systems
  - » Most deadlines must be met accurately
  - » Occasional misses can be handled
    - ❖ Fail-safe computation semantics required
- HRT/SRT compromise
  - » Intermediate time constraint granularity
  - » Intermediate deadline violation tolerance
- Examples
  - » Video on demand and Multi-Media conferencing
  - » Multi-player gaming
  - » Automated manufacturing

RT System Characteristics

- Often a mixed set of computations (hard, firm, soft)
  - » One reason for distribution or Multi-CPU
- RT used to be limited to embedded applications
  - » No longer
- Often motivated by desire to use a single CPU to support more than one computation
  - » Move beyond embedded/dedicated model
  - » How many CPUs are in a high end BMW?
    - ❖ 55 in 1990 (one for each wheel in ABS)
    - ❖ Move to shared bus and multi-processor architecture
    - ❖ Wiring cost more important than CPU cost

RT System Characteristics

- Fast Context Switch
  - » Low system overhead
- Small size
  - » Embedded application influence
- Minimal Functionality
  - » Traditionally accepted to achieve small size
  - » Generalizes to “configurable” OS where developer includes abilities required, leaving others out
- Fast Interrupt Service
  - » Desired for typical embedded control applications
  - » Generalizes to low latency event service

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RT System Characteristics

- No Virtual Memory
  - » Traditional for cost and speed
  - » Combines VM and Logical Address Space concepts
  - » No page faults makes sense
  - » No MMU is not as sensible
    - MMUs now are cheap
- Able to lock code and data in memory
  - » Related to no VM
  - » Eliminates unpredictable page-fault latency
- Real-Time Clock
  - » User computations often use absolute and elapsed time

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RT System Characteristics

- System provides alarms and timeouts
  - User interface for the system’s real-time clock
- Tasks interface to describe scheduling requirements
- Traditional RT systems used methods which must become
  - More adaptive
  - More scalable
  - More complex
  - More dynamic
  - More distributed
- Major growth and employment opportunity

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Misconceptions

- Sometimes arise from “sticker shock”
  - Profound nature and extent of changes required
  - Requirements can suddenly change when cost is known
- Real-time is about device drivers in assembly language on bare processors
  - Many years ago this was true
  - Real-time constraints are arising in a wide range of applications and device drivers now live inside systems
- Real-time is the same as *fast*
  - Must be able to predict behavior to guarantee a deadline
  - Fast computers often work OK for the *wrong reasons*

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Misconceptions

- All I have to do is buy a fast enough computer
  - » People (and managers) often want to simplify by drowning a problem in CPU cycles
  - » Sometimes works
  - » Leaves the system *brittle* since it can stop working abruptly and catastrophically if things change
    - Without deadline awareness everything can be late
  - » Never a substitute for *thought* and *understanding* of the problem

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Misconceptions

- There will always be a fast enough computer
  - » There are always problems where adequate resources exist without a sufficient surplus to permit sloppiness
  - » Corollary: using existing resources *well* can often reveal a wide variety of new possibilities
- We should get it working *logically* first and then worry about how fast it is
  - » Evil - even backwards
  - » Temporal constraints *must* be considered as first class design constraints
  - » Otherwise many average case vs. worst case assumptions and vulnerabilities will creep in

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Misconceptions

- Real-Time systems cannot use MMUs
  - » Embedded systems traditionally use CPUs with extra device control, timers, and other features without MMU
  - » Crucial distinction between VM and LM
    - Page faults are unpredictable and huge
  - » Logical → Physical address mapping can be done predictably
    - Explicitly manage the TLB
    - "Innovation" in real-time systems
    - Process compilation and protection simplifications
  - » Current RT systems commonly have a single huge physical address space → no protection

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Scheduling

- Goal: Organize process (task) execution so that each completes before its deadline
- Notice that this is a difference performance metric than
  - » Throughput
  - » Fairness
  - » Average response time
- Must consider: deadline, precedence, resource use
- Processor utilization is still an issue but we often must tolerate lower levels to ensure guarantees
  - » Code (almost) never follows the worst case path

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Scheduling

- Value or penalty function is often used (at least conceptually) to decrease task value after a deadline
  - » HRT: step function
  - » SRT: gentle slope
  - » FRT: steep slope and often more complex constraints
    - Miss deadlines of no more than 1 in N iterations
- The function describes how the "value" of completing a computation varies with time
  - » Describe several important characteristics of a task

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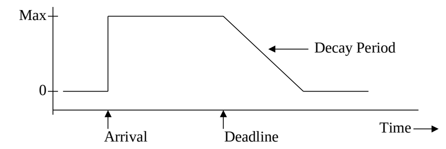
Scheduling
Value Functions

- Hard RT
  - » Decay period 0 and decays to 0
- Soft → Firm RT
  - » Decay period extended and decays to 0



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Scheduling Value Functions

- Theoretically we could use complex value functions
- Scheduler would have the job of maximizing the "value" produced by the system within various periods
- Classic Design Scenario
  - » Theoretically attractive
  - » Impractical for several reasons
- Problems
  - » Value functions become too elaborate and expensive
  - » Scheduler takes too long to evaluate situation
- Classic solution: Simple is better

Scheduling

- Schedulers assume some set of information about tasks
  - » Deadline
  - » WCET
  - » Resource use (shared, exclusive)
  - » Communication and precedence relations

Scheduling

- Scheduler characteristics
  - » Preemptive and non-preemptive
  - » Static and Dynamic
  - » Centralized and Distributed
- Popular Methods
  - » Earliest Deadline First (EDF)
  - » Rate Monotonic
  - » Explicit Plan

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Preemptive vs. Non-Preemptive

- Can the execution of a task be stopped and restarted
- Preemption stops one process and starts another
  - » This is the behavior assumption of a conventional OS
  - » Usually done at I/O operations but also at time quantum
  - » Consistent with "virtual time" assumption
- Consider resource use and synchronization
  - » Preemption while holding a resource leaves it locked
- Good idea for average case behavior and fairness but RT systems do not care about average case or fairness
  - » Still a good idea sometimes but care is required
  - » Some task sets can only be scheduled preemptively

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Preemptive vs. Non-Preemptive

- Generally, the highest priority task is run
- If a higher priority task arrives or makes the state transition Blocked → Runnable
  - » Current lower priority task is preempted
    - ❖ Running → Runnable
    - ❖ Preempted tasks continue to hold all resources
- Scheduling decision is thus reduced to selecting the runnable process with the highest priority
  - » O(N) operation to select maximum (best) value
  - » Assumes a *total* order on the set of processes
- Attractive because it is familiar and simple
  - » How do we know how to assign the priorities?

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Schedulability

- RT system designers must constantly ask and answer:
  - » Can this system meet all of its constraints?
- Conventional system designers do not face this question because *execution time* is not part of *correctness*
- It is for RT systems
  - » Example: Event requiring 50 ms execution time occurs 30 times per second (33.3 ms period)
  - » Get a (much) faster CPU
- This depends on the notion of *guarantee*
  - » Must have sufficient CPU and other resources to meet worst case behavior

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Schedulability

- Basic relationship makes the calculation on CPU cycles
  - » Every task T_i has a period P_i and a computation time C_i
  - » Utilization (μ) of the processor(s) must be feasible
  - » CPU utilization of a single task T_i is: $\frac{C_i}{P_i}$
  - » For a set of *m* tasks on *N* processors satisfaction of the following equation is a *necessary* but not *sufficient* condition:

$$\mu = \sum_{i=1}^{m} \frac{C_i}{P_i} \leq N$$

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Schedulability

- Preemption may be required
  - » Consider a simple set of three tasks T_1 ,T_2 and T_3
  - » Assume that $P_1 = 2P_2 = 4P_3$
    - This means that T_2 executes twice for every execution of T_1 and T_3 executes four times for every execution of T_1
  - » Now consider what happens if:

$$C_1 > P_2 - C_2 - 2C_3$$

- The task set is not schedulable unless the execution of T_1 is split into two pieces through preemption
  - » Because T_1 cannot complete execution before T_3 must begin executing again

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Schedulability

- Note that this analysis provides a *lower bound* on the CPU resources required to support a task set
- Ignores many sources of overhead, delay, and other constraints on scheduling
  - » Context switching
  - » Interrupt service routines not associated with a task
  - » Message transmission latency
  - » Resource use
- Some increase CPU requirements, others constrain the minimum period of some computations
  - » Constraints can be subtle

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Dynamic vs. Static

- Dynamic scheduling algorithms make decisions at run time
- Static algorithms simply consult a predefined table to determine task context switches
  - » Static algorithms clearly have lower overhead
- Conventional systems us priority driven preemptive dynamic scheduling with no priority re-computation
  - » Familiar and very successful BUT
  - » *Mechanism* not a *Policy*
- Static schedule satisfying all scheduling constraints
  - » Is correct and sufficient
  - » This is often lost in the complexity of design debates

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Dynamic vs. Static

- Dynamic algorithms are familiar and attractive in theory because they are:
  - » Simple
  - » Provably *optimal* in uni-processor system
- They often do not take system overhead or resource use into account
  - » When they do, they are not nearly as simple
- Common dynamic scheduling techniques include
  - » Earliest Deadline First (EDF)
  - » Least Laxity First (LLF)
  - » Rate Monotonic (RM)

Optimality

- Important but dangerous term
  - » Optimal means, colloquially, "as good as any and better than most"
  - » No algorithm can produce better results
- Important questions
  - » What is the performance metric?
    - Algorithms are optimal "with respect to" some measure
  - » How much does this optimality cost?
  - » How does it do with respect to other measures?
  - » How close to optimal do simpler algorithms come?
  - » How robust is the algorithm?

Earliest Deadline First (EDF)

- Simple and Fast
  - » Keep a list of tasks sorted by deadline
  - » Always run the task with the earliest (lowest) deadline
- Optimal for a single CPU and tasks with no ordering or mutual exclusion (exclusive resource use) constraints
  - » Many RT systems meet these criteria
- Ignores context switching costs
- Brittle with respect to assumption violation
  - » If any WCET or period assumption is violated the whole system can crash → no tasks meet their deadlines
  - » Every task almost makes it

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Least Laxity First (LLF)

- Also simple and fast
  - » Laxity is the difference between the time remaining until the deadline and the computation time
  - » Interesting because this metric combines aspects of deadline and computation time
  - » Execute the task with least laxity at any given moment
- Optimal for single CPU and independent tasks
- Brittle
  - » Assumption violation can leave all tasks almost finishing
- When problems occur it can also be difficult to figure out why they happened → cascade failures

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Rate Monotonic (RM)

- Classic result by Liu and Layland assigns priorities according to the task period
  - » A task T_i has WCET C_i and a period P_i
  - » Tasks with shorter periods get better priorities
- Result is classic because
  - » Proved optimal for single CPU and independent tasks
  - » Provides a utilization bound
    - Roughly .69 in theory but higher in practice
  - » Uses familiar priority driven scheduling
- Brittle with respect to assumption violation
  - » Difficult failure analysis and cascade failure

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Rate Monotonic (RM)

- RM is among the most popular RT scheduling algorithms
  - » Software Engineering Institute support and documentation
- Provides an easy way to adapt essentially conventional systems to real-time
- Important extensions for
  - » Aperiodic event server
  - » Handling tasks which use resources creating *mutual exclusion* scheduling constraints
  - » Even distributed systems
- Good, popular, and has equations
  - » Not a law of the universe

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Rate Monotonic (RM)

- Resource use in real-time priority driven systems makes things more complicated
- Resource use in exclusive mode creates execution constraints which the priority driven scheduler cannot see
- Sharing of a mutual exclusion resource among tasks with different priorities can lead to *priority inversion*
  - » A lower priority task can block the execution of a higher priority task
- Handling priority inversion substantially increases system complexity
  - » Implementation, analysis, *and* performance evaluation

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Rate Monotonic
Priority Inversion Example

- Consider three tasks T_1, T_2, and T_3
  - » T_1 has the shortest period and thus the highest priority
  - » T_3 has the longest period and thus the lowest priority
- T_1 and T_3 share a resource R
- T_3 holds R when T_2 becomes runnable
  - » Scheduler preempts T_3 to execute T_2
- T_1 then becomes runnable preempting T_2 but T_1 blocks when it tries to get R because T_3 still holds R
- T_1 blocking makes T_2 the highest priority process
  - » T_2 thus keeps T_3 from running and thus freeing R
  - » T_2 thus keeps T_1 from running → *Priority Inversion*

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Rate Monotonic
Priority Inheritance

- Priority Inversion is handled by implementing *priority inheritance*
  - We assume we know resource use by each task
  - Preprocessing is performed on the set of tasks after priorities are assigned to determine what lower priority tasks can potentially block higher priority tasks
  - Table of *resource priorities* is constructed
    - Records highest priority use of each resource
  - System *raises* priority of a task to the *resource priority* while it uses the resource
  - Lower priority task *inherits* a higher priority
- Significantly complicates schedulability analysis

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Explicit Plan Scheduling

- Classic scheduling algorithms are often called *myopic* because they make decisions based on limited information
  - They are nearsighted
- Important to realize that *all* scheduling algorithms are NP-Complete for multiple CPU/Distributed systems
  - Optimality and theoretical advantage evaporates

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Explicit Plan Scheduling

- Simply pre-compute when tasks will execute
  - » Ability to find such a schedule is not guaranteed
  - » When you have one you are done
  - » Searching for a feasible schedule is NP-Complete
  - » Heuristics are used
- Plan can be constructed using any of a number of methods and can consider all task constraints
  - » Resource use - mutual exclusion
  - » Precedence Relations
  - » Communication relations
  - » Context switching and other system overhead

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Explicit Plan Scheduling

- Disadvantage is that we have no *guarantee* that we can find a feasible schedule
  - » Cannot distinguish *infeasible* task set from failure to find a feasible schedule
- More of a theoretical than a practical problem
  - » Off-line schedule search task can run for a *long time*

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Explicit Plan Scheduling

- Spring system at Umass-Amherst
  - » Used explicit plan scheduling
    - Task precedence relations
    - Resource use (shared, exclusive)
    - Explicit delay
    - Communication relations
- Computations written as groups of interacting processes
  - » Scheduled as sets of tasks with known WCET, resource use, precedence and communication relations
  - » Compiler extensively analyzed process representation during compilation and constructed a task representation of the process *execution time behavior*

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Explicit Plan Scheduling

- Less popular for no clear reason
  - » Strength of CMU and SEI reputation and advocacy of RMS
  - » Lure of mathematical analysis and optimality
    - Largely illusory
- Considerable duality in these methods
  - » RM analysis effectively constructs a "worst case" execution plan
  - » The task set is thus feasible even in the worst case
  - » Texas Instruments then used this as an explicit schedule
- All explicit schedules satisfying execution constraints are solutions to the scheduling problem - regardless of source

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Periodicity and Guarantees

- Mathematically based methods (RMS) are often popular because of perceived reliability and optimality
  - » Often optimal in that they succeed if any method succeeds, *not* that they have the best CPU utilization
- All methods are based on behavioral assumptions
  - » WCET
  - » Period
  - » Resource use
  - » Communication patterns

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Periodicity and Guarantees

- Customers, and designers, often want to combine issues
  - » Guarantee and best effort
- Priority driven scheduling is attractive because it is familiar and because the highest priority task is always run
  - » BUT: the guarantee of system correctness is based on a assumption about every process being periodic
  - » Fairness and minimizing response time *are not relevant*
  - » Executing every task according to the periodic assumptions *must* be OK or the analysis is bogus

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Periodicity and Guarantees

- Many developers simplify their problem by providing periodic servers for all events
  - » Then executing then according to a specific plan
  - » Minimize aperiodic ISR execution time
- This approach *must* be OK or everything is nonsense

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Language and Compiler Support

- All approaches to RT scheduling assume non-trivial information about tasks is available
  - » WCET
  - » Resource use
  - » Precedence relations
  - » Various attributes depending on scheduling method
- None of this information is known or used *a priori* by conventional systems

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Language and Compiler Support

- Language and compiler support are required to enable the compiler to provide required information about task behavior and to have that information be reliable
  - » Reliable execution behavior predictions
- As RT constraints become more and more important to a wider range of applications the ability to express time and behavior constraints and to make predictions will become more and more important

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Language and Compiler Support

- RT semantics are creeping into many applications without the developers or users realizing the implications
- CORBA researchers and developers are considering applications with RT constraints
  - » Adding behavioral assertions and constraints to the IDL
- Opportunity because RT is likely to become important “suddenly” from the point of view of many industry segments and types of users
  - » Those positioned to help will benefit greatly

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Network Support

- Real-time applications are increasingly distributed
  - » Distributed applications exhibit RT constraints with increasing frequency
- Network support is a component of distributed computations
  - » Predictability of network behavior thus affects the predictability of computation behavior
- Networks are traditionally designed to reduce cost through
  - » Statistical multiplexing
  - » Probabilistic resource allocation → paradigm conflict
    - Significant source of difficulty
    - providers are having figuring out how to support new services economically

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Real-Time Communication

- Different from communication in other distributed systems
- High performance is nice, but predictability and determinism are *required*!
  - » Ethernet does not provide a known upper bound on transmission time.
  - » Token ring and Time Division Multiple Access (TDMA) protocols do.

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Real-Time Communication

- Communication protocols are often very different from other distributed systems.
  - » QoS specification is common
  - » Time-Triggered Protocol (TTP)
- Unusual properties of TTP
  - » detection of a lost packet implies failed sender
  - » CRC on the packet plus global state
  - » automatic group communication membership protocol
  - » the way clock synchronization is achieved

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Real-Time Communication
Time-Triggered Protocol

- Used in MARS real-time system
  - » consists of a single layer that handles
    - end-to-end data transport,
    - clock synchronization, and
    - membership management.
- All nodes are connected by two reliable and independent TDMA broadcast networks
- All packets are sent on both networks in parallel
- Expected loss rate is one packet every 30 million years!

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Current Trends

- Time constraints are emerging in more and more areas
  - » Not from specialized to general computations
  - » But from general applications to real-time
- Distribution is becoming more and more common
- COTS hardware is developing such a dominant price/performance ration that it may dominate
  - » wearables.stanford.edu
  - » Matchbox size 66 MHz 486 w/16 MB
  - » KU Real-Time modifications to Linux
- Distributed virtual environments and multimedia may be sufficient to drive networks toward RT - maybe not

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Emerging Applications

- Time constrained transaction systems
- Multimedia
  - » On-demand video/audio
  - » Multi-media conferencing (harder because of lower latency constraint) → Games
- Smart appliances
- Complex distributed control
  - » Houses, Cars
  - » Traffic control
    - Cars, Trains, Ships, Planes, Elevators → turbo lifts
  - » Aegis Cruisers

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