The Distributed Real-Time Specification for Java

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Outline

- Java and “real-time Java”
- JSR-50 the Distributed Real-Time Specification for Java
- Distributed Control Flow
- Distribution Design Choices
- Conclusion

The raison d'être of real-time computing is predictability of collective thread timeliness

- **Informally, a property is *predictable* to the degree that it is known in advance**
- **Predictability is a continuum**
- **One end point of the predictability scale is *determinism*, in the sense that the property is known exactly in advance**
- **The other end point is maximum entropy, in the sense that nothing at all is known in advance about the property**
- **In stochastic systems (which include hard real-time ones as a special case), one way to measure predictability is coefficient of variation C_ν = variance/mean^2**
  - **the maximum predictability end point is the deterministic distribution, whose $C_\nu = 0$**
  - **at the minimum end point is the extreme mixture of exponentials distribution, whose $C_\nu = \infty$**

Timeliness predictability generally must be traded off against other properties

- **Predictability of timeliness generally just be traded off against**
  - **other real-time timeliness properties, particularly optimality of timeliness – e.g.,**
    - **better number of missed deadlines, mean tardiness, etc., but worse predictability of those**
    - **worse number of missed deadlines, mean tardiness, etc., but better predictability of those**
  - **other non-real-time performance properties, such as throughput**
  - **resource utilization**
- **These trade-offs are application-specific**
- **The programmers and users must be able to reason about these trade-offs**

There have been many “real-time” programming languages

- However, none have been commercially successful in the sense of being significantly adopted in that domain
  - many were academic research projects
  - most did not focus on the core real-time issues of managing computing resources in order to satisfy application timeliness optimality and predictability requirements
- Instead, they typically emphasized
  - the orthogonal (albeit important) topic of concurrency
  - and other topics important to the whole field of embedded computing systems (of which real-time computing systems are a subset)

Ada 95 has been the most successful real-time programming language

- Ada 95, including its Real-Time Systems Annex, has been the most successful real-time language, in terms of both adoption and real-time technology
- One reason is that Ada is unusually effective (among real-time languages and also operating systems) across the real-time computing system spectrum
  - from programming-in-the-small in traditional device-level control subsystems
  - to programming-in-the-large in enterprise command and control systems
- Despite that achievement, a variety of non-technical factors crippled Ada's commercial success (including in defense applications)

JSR-50:
the Distributed Real-Time Specification for Java

- There is strong pull (e.g., in the defense, industrial automation, telecom, and financial markets) for "distributed real-time Java"
- JSR-50 is to extend the RTSJ to include distributed real-time systems – the DRTSJ

JSR-50:
the Distributed Real-Time Specification for Java

- Java Specification Request written by Jensen (MITRE); supported by IBM and seven other organizations
- Sun approved JSR-50 in April 2000
- Sun appointed Jensen (MITRE) as Specification Lead
- At the time of this writing (April 2000), the Expert Group has met three times
- The Expert Group began with the approach proposed in JSR-50, and may modify it somewhat
- The technical approach is very similar to that of the proposed specification for Dynamic Scheduling Real-Time CORBA

The Distributed Real-Time Specification for Java: Summary

- Work has begun on the Distributed Real-Time Specification for Java (DRTSJ), in Sun's Java Community Process
- "Distributed real-time" means acceptable predictability of multi-node application behaviors' collective timeliness (given whatever OS and network infrastructure), regardless of the programming model (control flow, mobile code, etc.)
- A multi-node application behavior's timeliness properties must be explicitly employed for resource management consistently on each node involved in that application multi-node behavior
- In Java, using RMI, these properties must be acquired, propagated, and deposited when RMI's and any associated returns occur
- With control flow programming models, that enhancement supports predictability of end-to-end timeliness

JSR-50:
the Expert Group member organizations

- Ada Core
- aJile
- Boeing
- CMU
- IBM
- LaCross Consulting
- Lockheed Martin
- MITRE
- Nokia
- Nortel
- NSIcom
- Omron
- Sun
- TimeSys
- USAF-RL
- Wellings (York U)
- Wells (The Open Group)
- Yamatake

A distributed system has application entities that exhibit multi-node behaviors

- For the purpose of this presentation, the term ***distributed system*** informally refers to a computing system whose programming model is based on there being application entities that exhibit multi-node behaviors
- Each of these multi-node behaviors has multi-node properties – these properties may include (but are not limited to)
  - a unique identifier
  - timeliness
  - security
  - resource ownership
  - transactional context

Distributed systems can be categorized in various ways for various purposes

- Here we categorize them in a very simple way

  according to their programming model for the multi-node interaction aspect of application behaviors

  - *networked* (asynchronous message passing among objects)
  - *control flow* (method invocation between objects)
  - *data flow* (e.g., publish/subscribe among objects)
  - *blackboards/spaces* (e.g., Linda, JavaSpaces*)*
  - ***mobile objects, autonomous agents, autonomous decentralized systems***

- The first three of these categories have long histories of successful use in real-time as well as non-real-time application domains

A distributed system usually has one primary application programming model

- A distributed system usually has one programming model as the first class abstraction, and sometimes others are implemented in terms of it (perhaps at lower performance)
- For example, OMG's CORBA standard specifies a first class control flow programming model, but an optional data flow programming model is being proposed as a layered service
- Of course, a first class distributed system programming model is normally implemented on a communication facility that typically has multiple levels which are not visible to the application –

  e.g., a blackboard abstraction may be implemented using RPC that is implemented using asynchronous message passing

A real-time distributed system has acceptable timeliness of multi-node application behaviors

- The defining characteristic of any real-time distributed computing system, whatever its programming model, is that
  - the timeliness (optimality and predictability of optimality) of each multi-node application behavior
    - on each individual node it involves
    - collectively on all nodes it involves
  - is acceptable to that application
  - under the current circumstances
- The "current circumstances" include the latency characteristics of the underlying infrastructure (OS's, network)

A multi-node behavior's timeliness properties must be used coherently on all involved nodes

- **In most cases, the fundamental requirement for achieving acceptable multi-node timeliness is that**

  a multi-node application behavior's timeliness properties

  - **time constraints**
  - **expected execution time**
  - **execution time received thus far**
  - **etc.**

  be explicitly employed for resource management (scheduling, etc.)

  coherently on each node involved in that application multi-node behavior

Multi-node application behavior timeliness properties must be propagated among nodes

- Thus, in dynamic real-time distributed systems, these properties must be propagated among corresponding computing node resource managers in
  - operating systems
  - Java virtual machines (JVM's)
  - middleware
  - etc.
- In static real-time distributed systems, these properties can be instantiated á priori;

  but the Distributed Real-Time Specification for Java is concerned primarily with dynamic systems

Real-time distributed Java systems can use RMI to propagate timeliness properties

- In real-time distributed Java systems that use RMI,

  a multi-node application behavior's end-to-end timeliness (and other) properties must be

  - acquired
  - propagated
  - and deposited

  when RMI's and any associated returns occur
- This should be transparent to the application programmer
- This enhancement is an appropriate mechanism, regardless of what programming model semantics are manifest with RMI's –

  e.g., whether performing a basic RPC-like method invocation, or passing an object by copy or reference

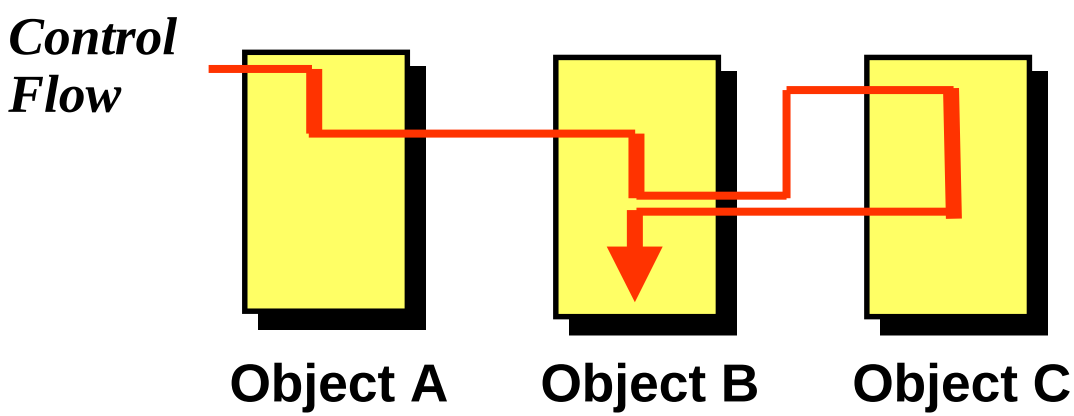
There are several ways to use timeliness properties for scheduling coherently on each node

- Timeliness properties can be propagated, and used consistently by node resource managers
  - e.g., every node schedules using the same policy
  - this can provide some approximate global optimality
- Timeliness properties can be propagated, and used by a logically singular global scheduler that is instantiated on every node
  - the schedulers interact to schedule all the nodes
  - global optimality is formally impossible in general, but may be better approximated in many cases
- One or more levels of “meta” resource managers above the node resource managers function according to either of the above two cases
- This RMI enhancement can be used for any of these cases

JSR-50's initial emphasis is on control flow programming models

- Control flow models are familiar and accepted in distributed real-time practice
- A distributed control flow program's components may be spread across multiple computing nodes
- Execution flows as one or more sequences of constituent operations occurring on multiple nodes,

  each via a sequence of method invocations/returns



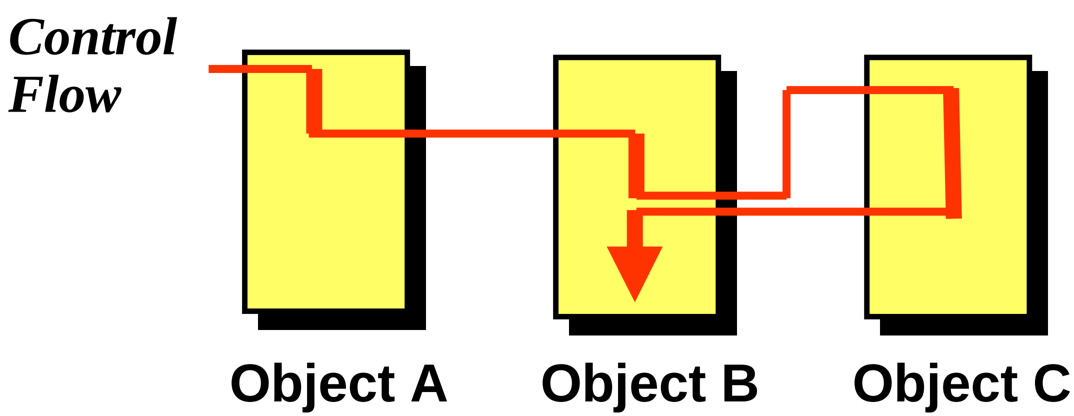
Control flow has compelling advantages as a native model for distributed real-time software

- Many distributed real-time computer systems and applications involve a mixture of control flow and data flow
- Distributed control flow is a natural, well-understood, incremental extension to local control flow (procedure calls)
- Familiarity is an especially important factor in attaining adoption in real-time application domains, such as industrial automation, defense, and telecommunications
- All distributed systems have inherent complications due to network latencies, partial failures, synchronization and concurrency control, etc. –

  many of these are more easily managed in control flow programming models than in other (e.g., data flow, autonomous agent) programming models

Timeliness in distributed real-time control flow programming models is end-to-end

- **The defining characteristic of any real-time distributed computing system having a control flow programming model is that**
  - **the timeliness (optimality and predictability of optimality) of each trans-node application control flow**
  - **is acceptable to that application**
  - **under the current circumstances**



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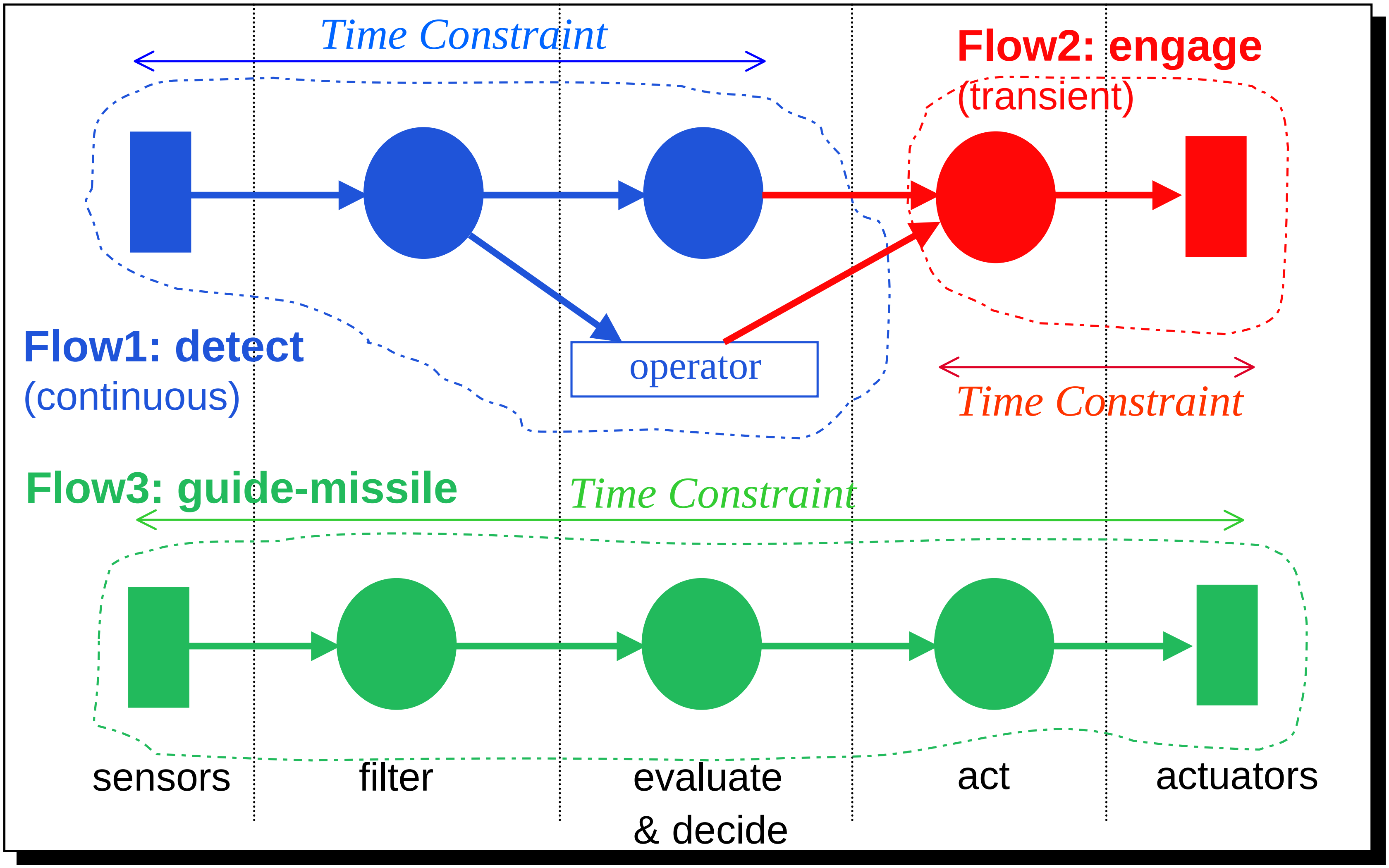
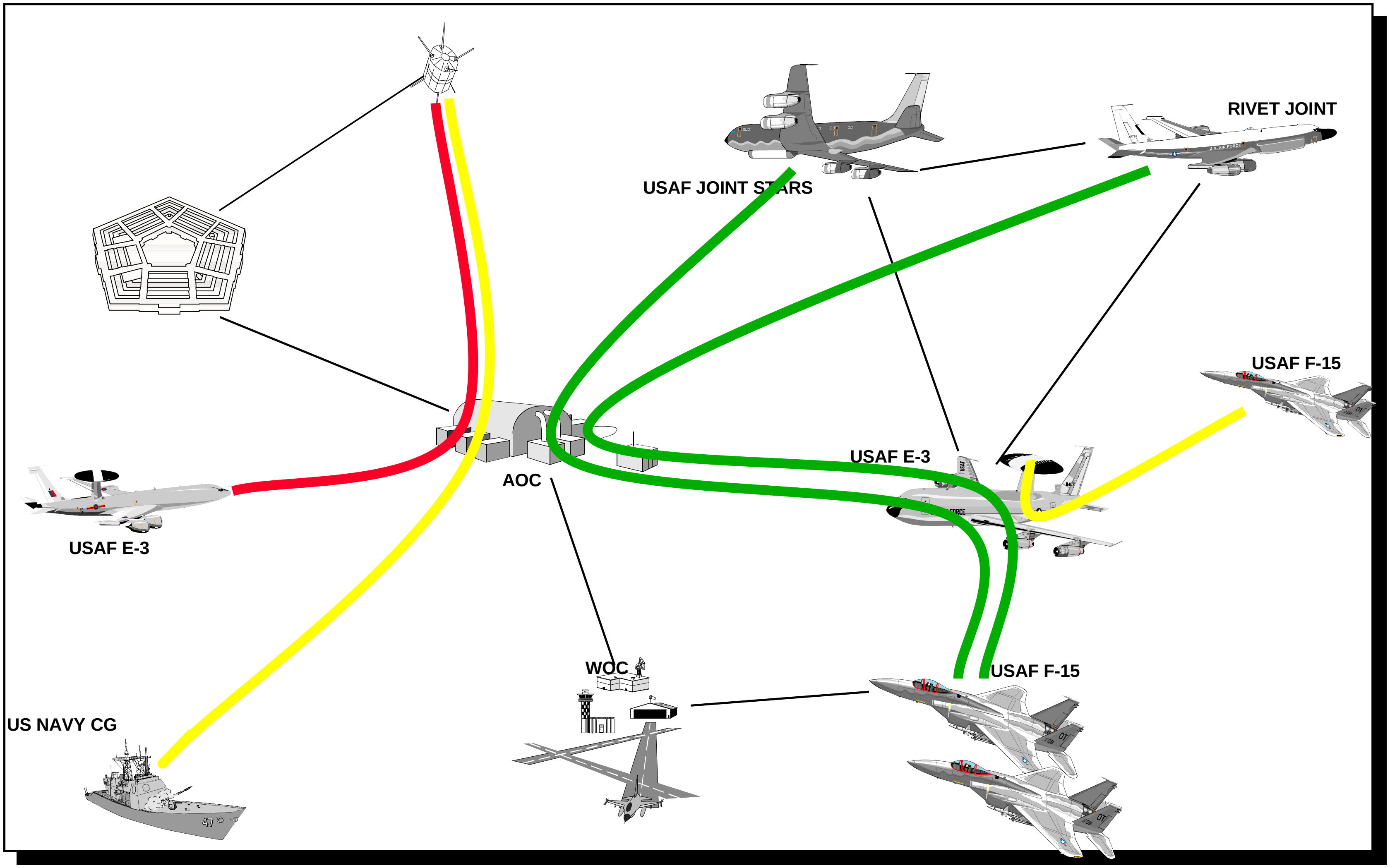
Control flow method invocations (and returns) are location-independent, and other code is not

- All the code in a control flow model program is not usually expected to be location-independent
- That would be very difficult, due to
  - network latencies
  - partial failures
  - synchronization
  - concurrency control
  - etc.
- The primary benefits of control flow can be obtained by a programming model having
  - location-independent invocations and returns
  - location-dependent (node-local) code otherwise

Example control flows in a notional anti-air warfare system



Example of control flows in a notional C^2 system of systems



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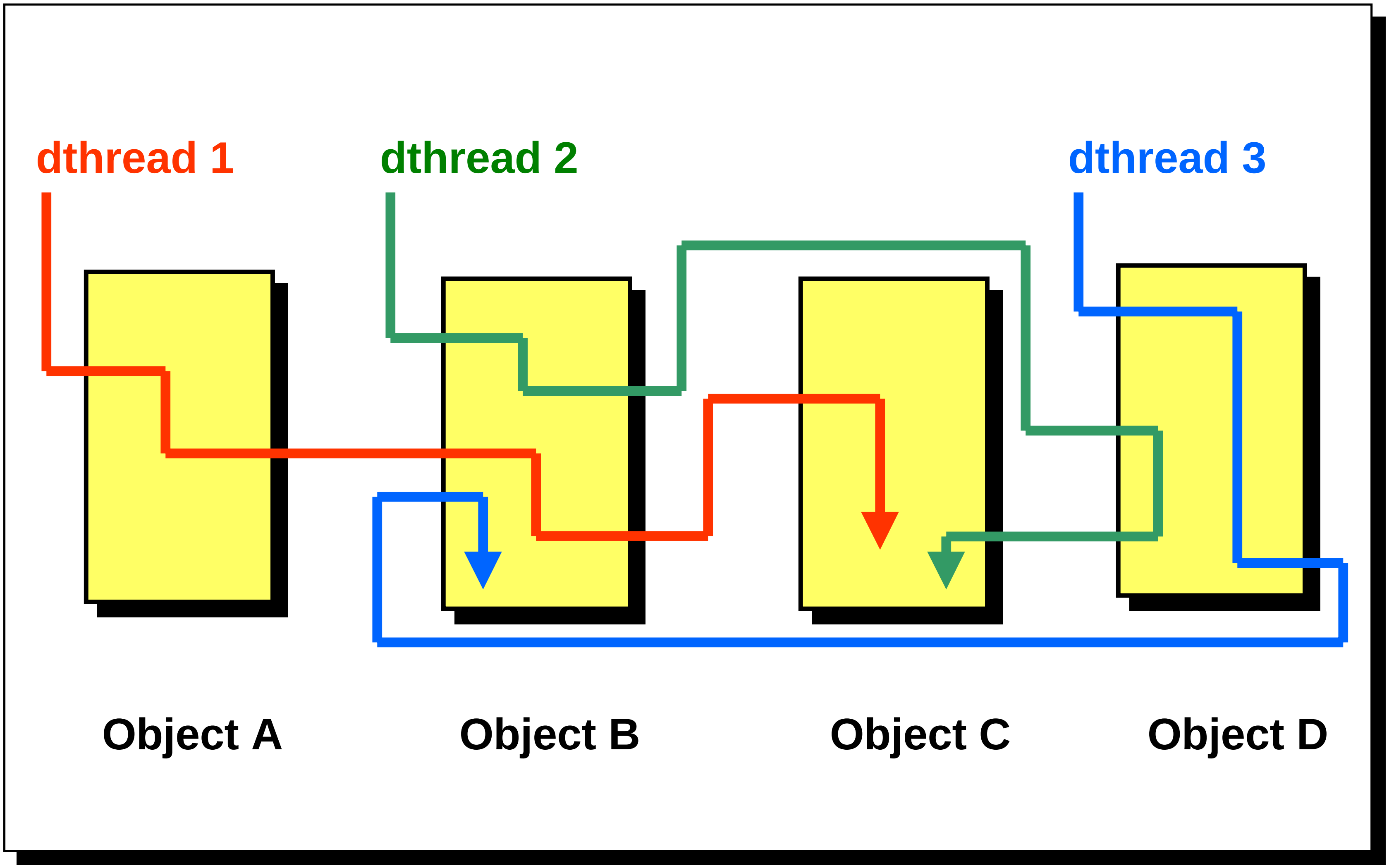
A *distributable thread* is an end-to-end control flow abstraction

- **A control flow distributed object program can be thought of in terms of an end-to-end abstraction we'll call a *distributable thread***
- **A distributable thread is a logically distinct and identifiable locus of control flow movement, within and among objects (and thus nodes)**
- **A distributable thread executes a remote method, like a local one, directly itself –
by extending and retracting itself between objects and (transparently) nodes**
- **The distributable thread (not a local thread) is the schedulable entity**
- **A program may consist of multiple concurrent distributable threads**

A *distributable thread* is an end-to-end control flow abstraction



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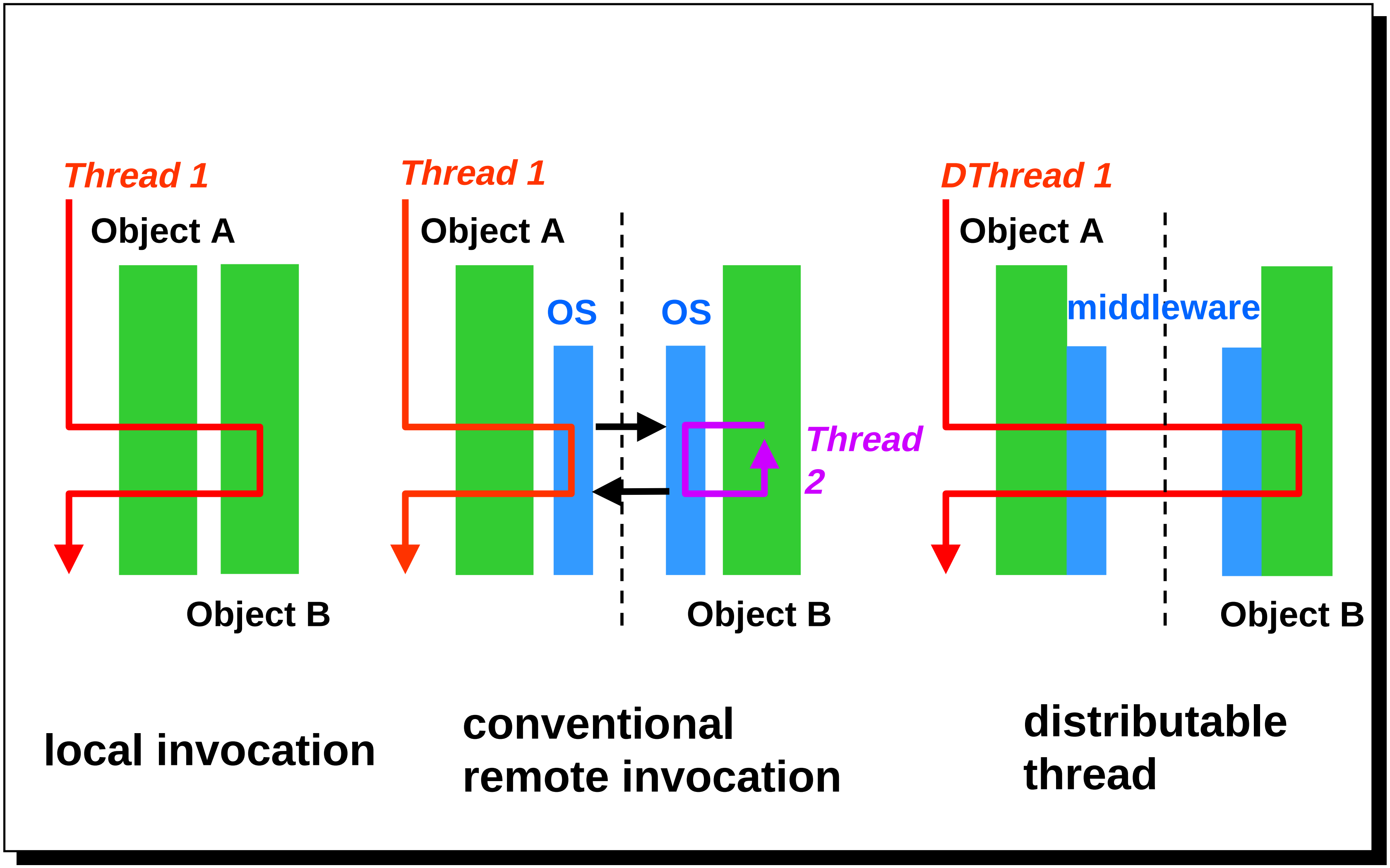
Concurrency is at the distributable thread level

- **A distributable thread always has exactly one execution point (*head*) in the whole system**
  - **control flow can be forked by creating or awakening other distributable threads**
- **Multiple distributable threads execute concurrently and asynchronously, by default**
- **Distributable threads synchronize through method execution**
  - **object writers control distributable thread concurrency – e.g.,**
    - **monitor (no concurrency)**
    - **re-entrant**
    - **recursive**

Conventional distributed object models don't retain local semantics on remote invocations

- For a local invocation in most distributed object systems
  - there is only one thread
  - it retains its identity and properties (e.g., timeliness) whichever method it executes
- Conventional remote method invocation (and RPC) involve
  - separate schedulable entities on each node (client, servant)
  - which communicate with each other
- That
  - doesn't accurately reflect the programmer's intention of control flow spanning objects, and thus physical nodes, in a location-independent way
  - impedes maintaining end-to-end properties

A distributable thread has location-independent method invocations



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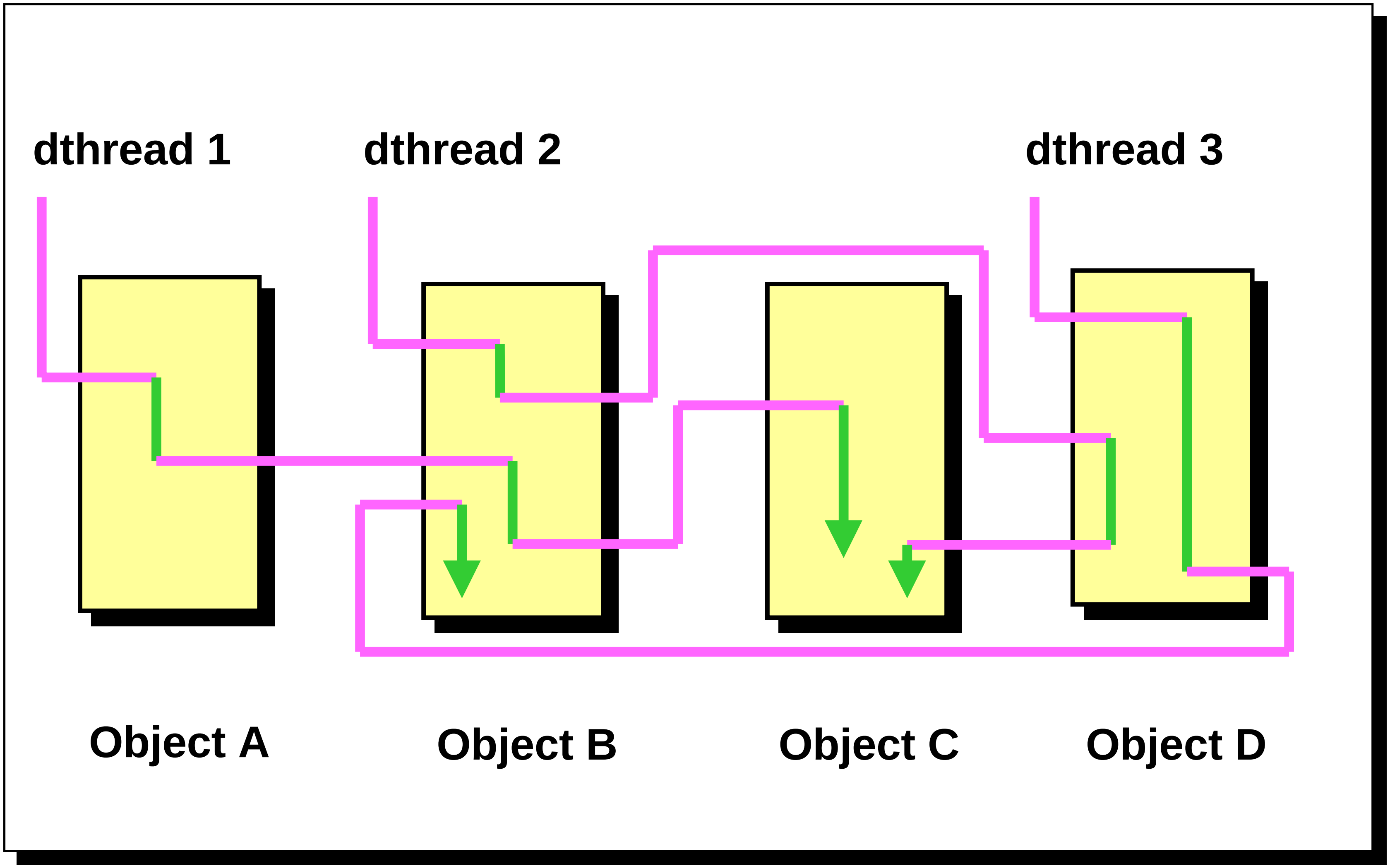
A distributable thread is sequential rather than synchronous

- The synchrony of a conventional method invocation (or RPC) is often cited as a concurrency limitation
- But a DT is a sequential model like a local thread
- A DT is always executing somewhere, while it is the most eligible there
  - it is not doing "send/wait's" as with conventional method invocations (or RPC's)
- Remote invocations and returns are scheduling events at both source and destination nodes
  - each node's processor is always executing the most eligible DT there
  - the other DT's there wait as they should
- Local method invocations/returns benefit from not requiring context switches like threads normally do

A distributable thread is built using local (e.g., RTOS) threads and method invocations

- The distributable thread abstraction is implemented using local (RTOS or JVM) threads, as part of
  - middleware
  - local operating systems
  - JVM's
- In Java, a distributable thread would be implemented by the concatenation of local (per node) threads sequentially performing RMI's when they transit nodes

A distributable thread is built using local (e.g., RTOS) threads and method invocations



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Multi-node application entities have end-to-end properties

- ❑ Distributed systems have requirements for end-to-end properties of their collective multi-mode behaviors – e.g.,
  - timeliness
  - reliability/availability
  - security
  - transactional context
  - resource ownership
  - dependencies
  - etc.
- ❑ For control flow programming models, these are end-to-end properties

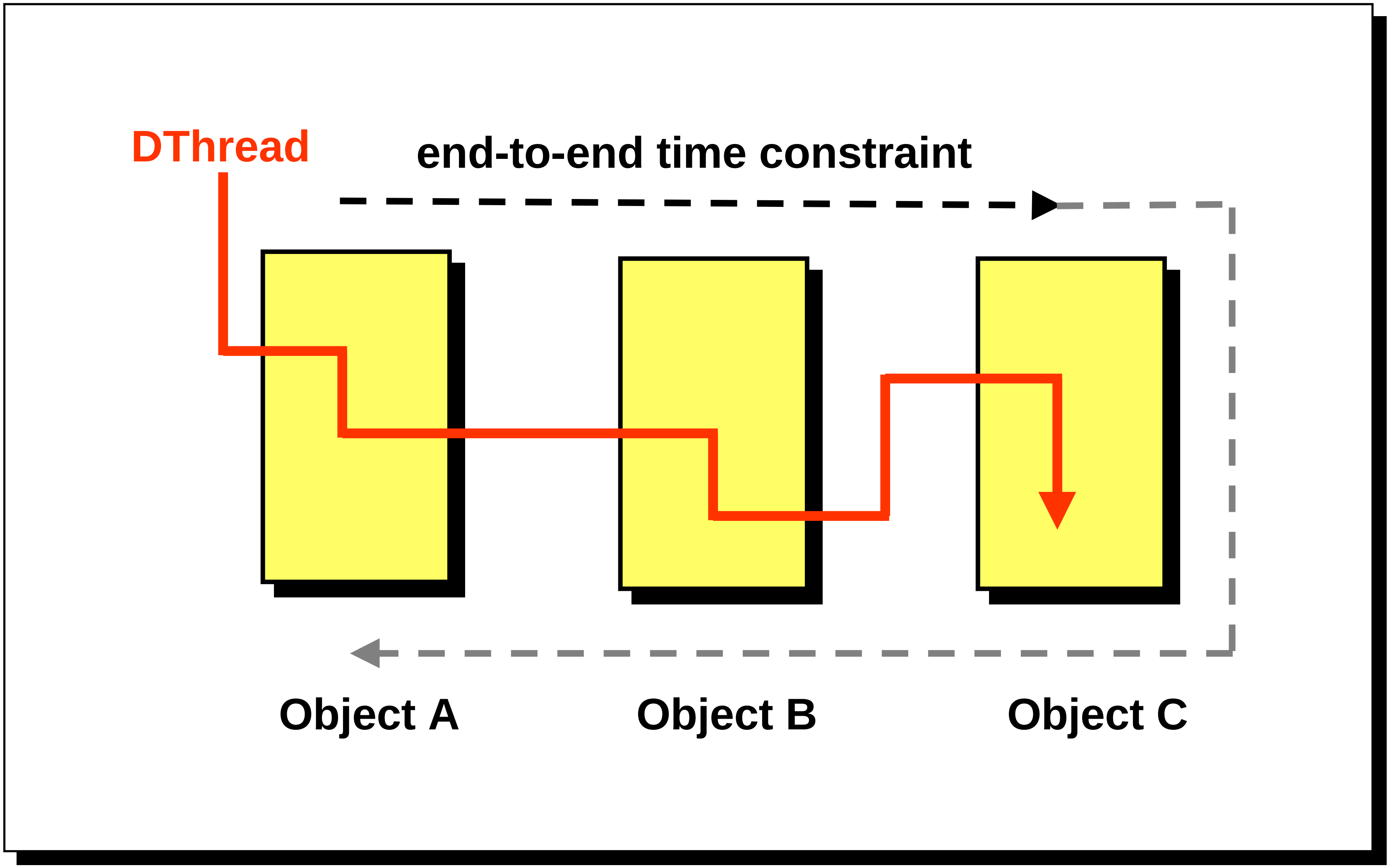
A distributable thread has end-to-end timeliness attributes

- Each distributable thread may have execution scheduling attributes – e.g., time constraints, etc.
- These specify the end-to-end timeliness for it completing the sequential execution of methods in object instances that may reside on multiple physical nodes
- Execution of the distributable thread is governed by those scheduling parameters, according to the scheduling policy, regardless of the distributable thread's execution point transiting nodes
- Any of the three distributed scheduling approaches can be used
- The goal is to provide acceptable (as defined by the application) end-to-end timeliness of collective distributable thread execution

The distributable thread abstraction propagates computational context end-to-end

- **When a distributable thread transits a node boundary, its timeliness parameters are propagated to the remote scheduling policy instance**
  - **in the OS, JVM, or middleware**
- **When/if it returns, updated timeliness parameters are propagated back to the invoker's scheduling policy instance**
- **(Other end-to-end properties may also be propagated – e.g., ID, resource ownership, dependencies, rights, security, transactional context)**
- **This should be transparent to the application programmer**

A distributable thread supports end-to-end properties such as timeliness



The distributable thread model applies to the whole predictability/time-frame space of real-time systems

- The distributable thread approach to control-flow style distributed programming model is applicable to real-time systems which are
  - hard
  - or anywhere else on the predictability continuum
- That continuum is orthogonal to application time-frame magnitudes, which range in practice from microseconds to megaseconds
- The distributable thread abstraction supports application timeliness requirements everywhere in that two-dimensional predictability/time-frame space of distributed real-time Java systems

The distributable thread abstraction also has implementation advantages

- The distributable thread abstraction automatically supports implementation needs, such as
  - resource limit and consumption tracking
  - server thread management
- Each object no longer has the burden of managing its own pool of threads and related resources (stacks, etc.)
- This minimizes the tendency to do pessimistic resource management strategies
- The distributable thread abstraction has been widely adopted for microkernel-based OS's for these implementation advantages, independent of the programming model

A fully specified DT abstraction must include additional facilities – not necessarily in this DRTSJ

- A specification of a complete DT abstraction would include (but not be limited to) facilities to deal with
  - DT integrity (failure detection and recovery) despite partial node and path failures
  - DT control (like thread control) – pause, resume, abort, etc.
  - distributed event handling
    - asynchronous events of interest to a DT – i.e., changes in predicated system state, such as a time constraint expiration – are delivered to its execution point for possible handling
    - and perhaps from the execution point back up the invocation chain for (additional) handling
  - distributed concurrency control among DT's

all in a timely manner

Distributed Threads in a Java Context: Design Choices

- Build on RMI
- Build on JSR-78 RMI
- Devise a new RT-RMI facility
- Use an entirely new remote access approach

Distributed Threads: Building on RMI

- DRTSJ could propose a simple extension to RMI that supports timeliness properties among nodes
  - facilitates acceptably predictable end-to-end timeliness of distributed threads
    - this is application-specific
  - extends RMI to
    - obtain, propagate, and deposit timeliness attributes among the scheduling policy instances at each node a distributed thread visits

      transparently to the programmer
- RMI must be made predictable for the cases of interest
  - without affecting non-RT uses, syntax, specified semantics, and tools for RMI

Distributed Threads: Building on JSR-78's RMI

- **JSR-78: RMI Custom Remote References**
  - **Objective: provide a general framework in J2SE RMI for customizing remote invocation behavior**
- **JSR-78 is done for J2EE/J2SE, not J2ME**
  - **technical concerns**
    - **are the intermediate interfaces sufficient for J2ME's needs?**
    - **are the supplied customizations useful for J2ME?**
    - **are they sufficient for efficiently and effectively supporting distributed threads?**
  - **logistical concerns**
    - **approval for J2ME platform**
    - **availability of code on a J2ME platform (for use in Reference Implementation)**

Distributed Threads: Devise a New RT-RMI

- Design and build a new, flexible, predictable RMI-like facility that coexists with or subsumes RMI
- RT-RMI
  - permits modification of JSR-78 interfaces and capabilities
  - must presumably “look like” and “feel like” RMI
    - else might confuse programmer
  - should accommodate (subsume?) non-RT RMI uses
  - could still be subject to RMI constraints
    - ability to affect other portions of the “distributed thread”
    - timeliness of responses
    - types of exceptions, inheritance, required interfaces, etc.

Distributed Threads: Devise a New Remote Access Approach

- Ignore RMI (sort of; it should probably work if invoked)
- Allows maximal freedom
- Permits or requires reexamination of fundamentals
  - protocols
  - interfaces
  - naming
  - stubs, skeletons
  - references, leases, garbage collection
  - exceptions
  - communication models
- Increases hurdle to mass acceptance (or at least tolerance)

Conclusion:
the Distributed Real-Time Specification for Java

- Real-time computing is about predictability of timeliness
- Distributed real-time computing is about predictability of timeliness of multi-node (e.g., trans-node) behaviors
- Acceptable predictability of timeliness of multi-node behaviors requires suitably consistent resource management on the nodes that the behaviors transit
- Suitably consistent resource management on multiple nodes requires that they share sufficient information about the behaviors' timeliness
- Shared information in a network must be explicitly propagated among the nodes
- The DRTSJ will allow RTSJ Java systems that use RMI to propagate shared information for consistent node resource management to meet multi-node (e.g., end-to-end) timeliness predictability needs

"Real-time Java" is likely to be the first successful real-time programming language

- Ada 95 is a successful real-time language technologically but is less successful commercially
- Java is already ubiquitous
- The Java platform's WORA promise currently offers the best prospective opportunity for application portability
- Real-time Java appears to be successfully addressing the deficiencies of Java for real-time computing systems
- Several major vendors have already announced that they will sell real-time Java products
- Real-time Java is poised to be the first commercially as well as technologically successful real-time programming language
- "Distributed real-time Java" will be very important to Java's success in the real-time application domains

Resources:
RTSJ and DRTSJ

- NIST Special Publication 500-243 "Requirements for Real-time Extensions for the Java Platform"
  - http://www.nist.gov/itl/div897/ctg/real-time/rt-doc/rtj-final-draft.pdf
- Real-Time Specification for Java
  - http://www.rtj.org
- Distributed Real-Time Specification for Java
  - http://www.drtsj.org
- J Consortium
  - http://www.j-consortium.org