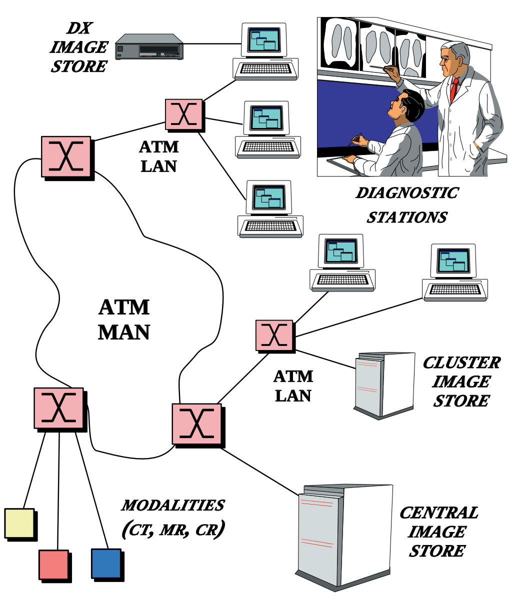
Design Patterns for Developing and Using Real-time CORBA Object Request Brokers

Douglas C. Schmidt
schmidt@cs.wustl.edu

Washington University, St. Louis
www.cs.wustl.edu/~schmidt/TAO4.ps.gz

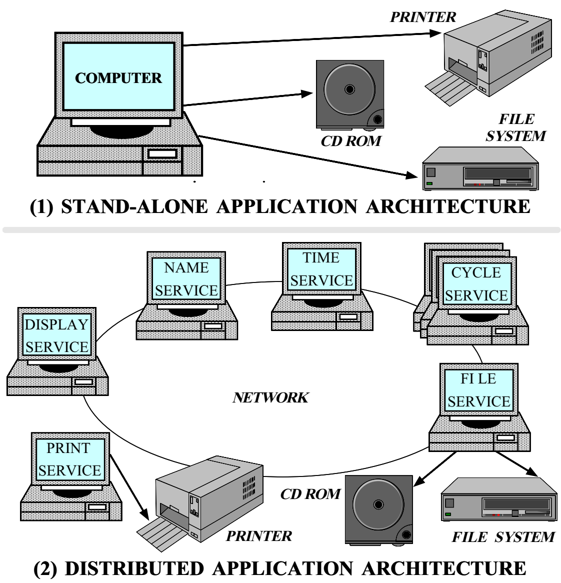
Sponsors
Bellcore, Boeing, CDI, DARPA, Kodak,
Lucent, Motorola, NSF, OTI, SAIC,
Siemens SCR, Siemens MED, Siemens ZT, and Sprint

Motivation: the Distributed Software Crisis



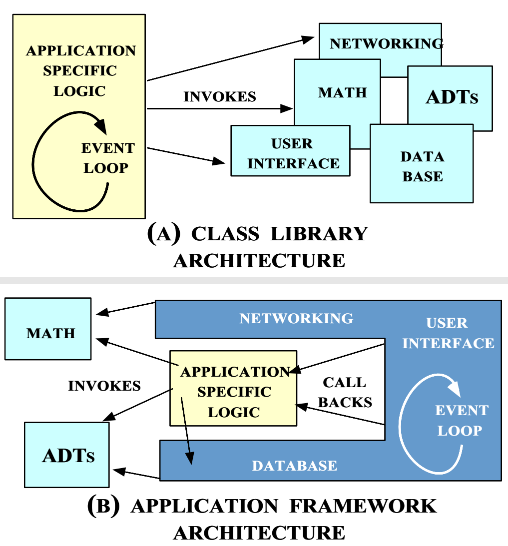
- **Symptoms**
  - Hardware gets smaller, faster, cheaper
  - Software gets larger, slower, more expensive
- **Culprits**
  - *Accidental* and *inherent* complexity
- **Solutions**
  - Middleware, frameworks, components, and patterns

Sources of Complexity for Distributed Applications



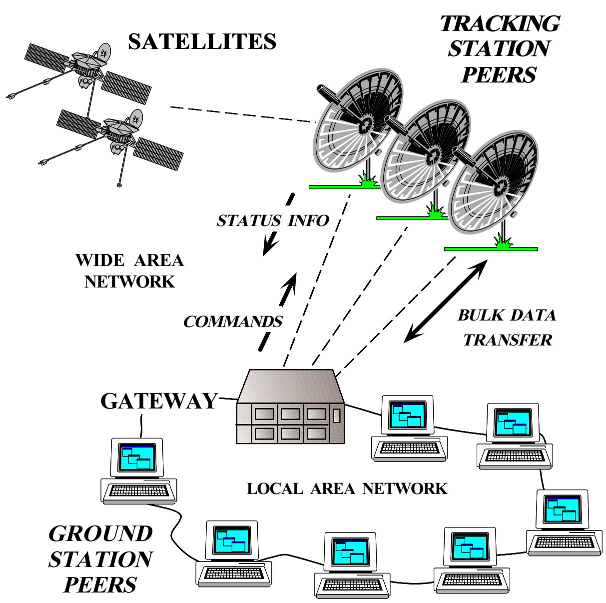
- **Inherent complexity**
  - Latency
  - Reliability
  - Partitioning
  - Ordering
- **Accidental Complexity**
  - Low-level APIs
  - Poor debugging tools
  - Algorithmic decomposition
  - Continuous re-invention

Techniques for Improving Software Quality and Productivity



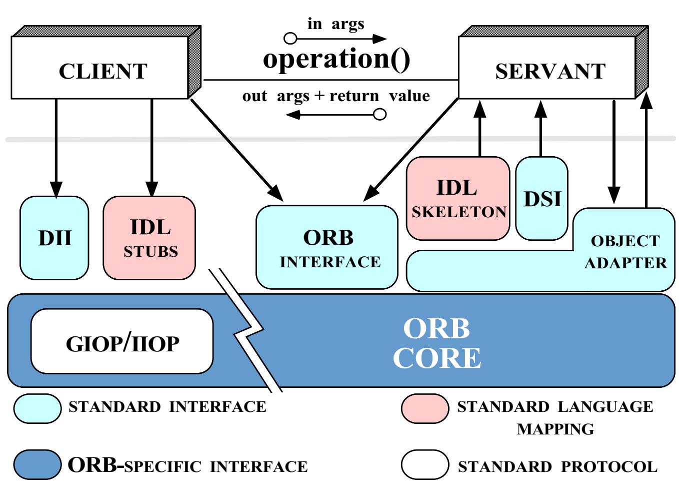
- **Proven solutions**
  - *Components*
    - ∗ Self-contained, “pluggable” ADTs
  - *Frameworks*
    - ∗ Reusable, “semi-complete” applications
  - *Patterns*
    - ∗ Problem/solution pairs in a context
  - *Architecture*
    - ∗ Families of related patterns and components

Motivation for Real-time Middleware



- Many applications require QoS guarantees
  - *e.g.*, telecom, avionics, WWW
- Existing middleware doesn't support QoS effectively
  - *e.g.*, CORBA, DCOM, DCE
- Solutions must be *integrated*
  - *Vertically* and *horizontally*

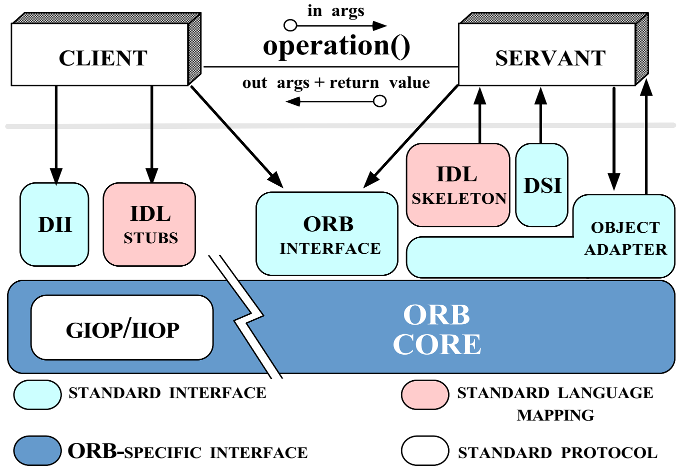
Candidate Solution: CORBA



www.cs.wustl.edu/~schmidt/corba.html

- **Goals of CORBA**
  - Simplify distribution by automating
    - Object location and activation
    - Parameter marshaling
    - Demultiplexing
    - Error handling
  - Provide foundation for higher-level services

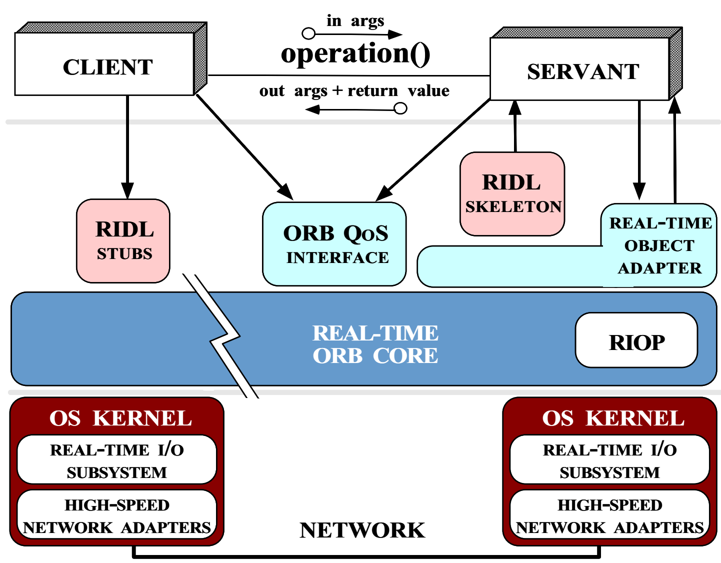
Limitations of CORBA for Real-time Systems



www.cs.wustl.edu/~schmidt/ORB-endsystem.ps.gz

- **Limitations**
  - Lack of QoS specifications
  - Lack of QoS enforcement
  - Lack of real-time programming features
  - Lack of performance optimizations

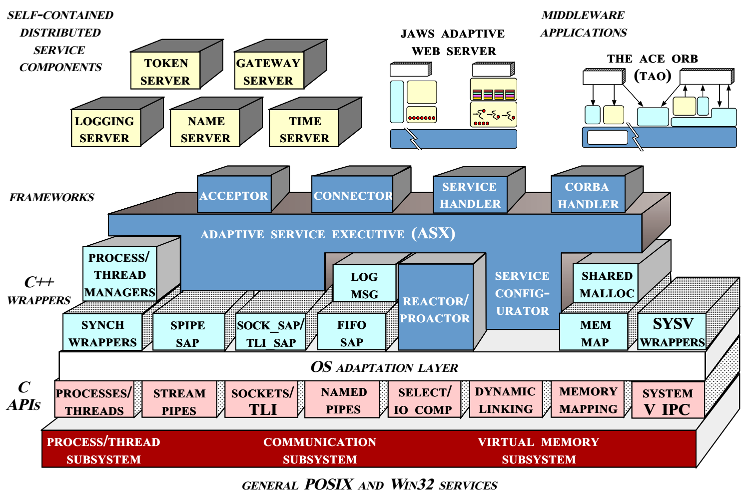
The ACE ORB (TAO)



www.cs.wustl.edu/~schmidt/TAO.html

- **TAO Overview**
  - A high-performance, real-time ORB
    - Telecom and avionics focus
  - Leverages the ACE framework
    - Runs on RTOSs, POSIX, and Win32
- **Related work**
  - QuO at BBN
  - ARMADA at U. Mich.

The ADAPTIVE Communication Environment (ACE)



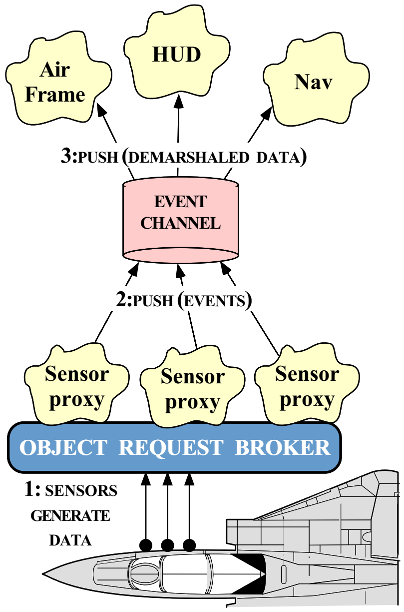
www.cs.wustl.edu/~schmidt/ACE.html

- **ACE Overview**
  - Concurrent OO networking framework
  - Ported to C++ and Java
  - Runs on RTOSs, POSIX, and Win32
- **Related work**
  - x-Kernel
  - SysV STREAMS

ACE Statistics

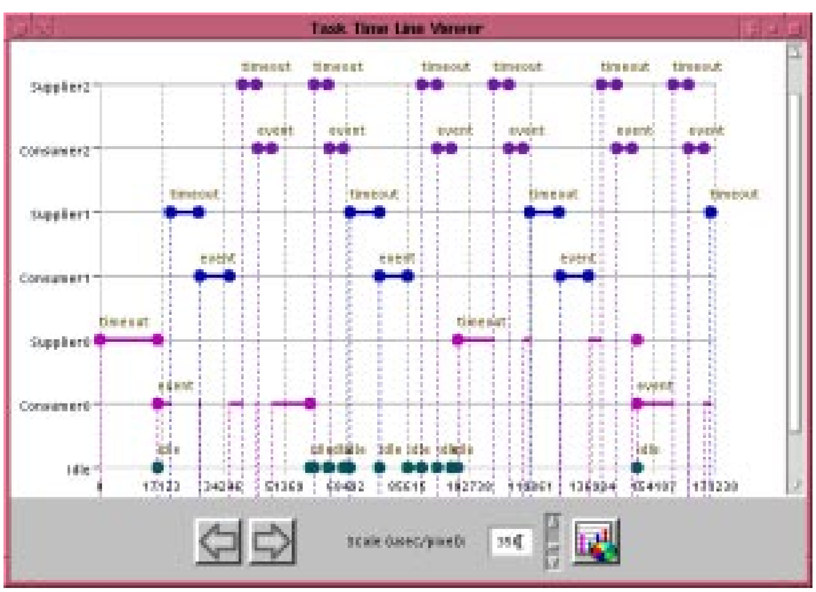
- ACE contain $>$ 125,000 lines of C++
  - Over 10 person-years of effort
- Ported to UNIX, Win32, MVS, and embedded platforms
  - *e.g.*, VxWorks, Chorus, LynxOS, pSoS
- Large user community
  - www.cs.wustl.edu/~schmidt/ACE-users.html
- Currently used by dozens of companies
  - Bellcore, Boeing, Ericsson, Kodak, Lucent, Motorola, SAIC, Siemens, StorTek, etc.
- Supported commercially
  - www.riverace.com

Applying ORBs to Real-time Avionics

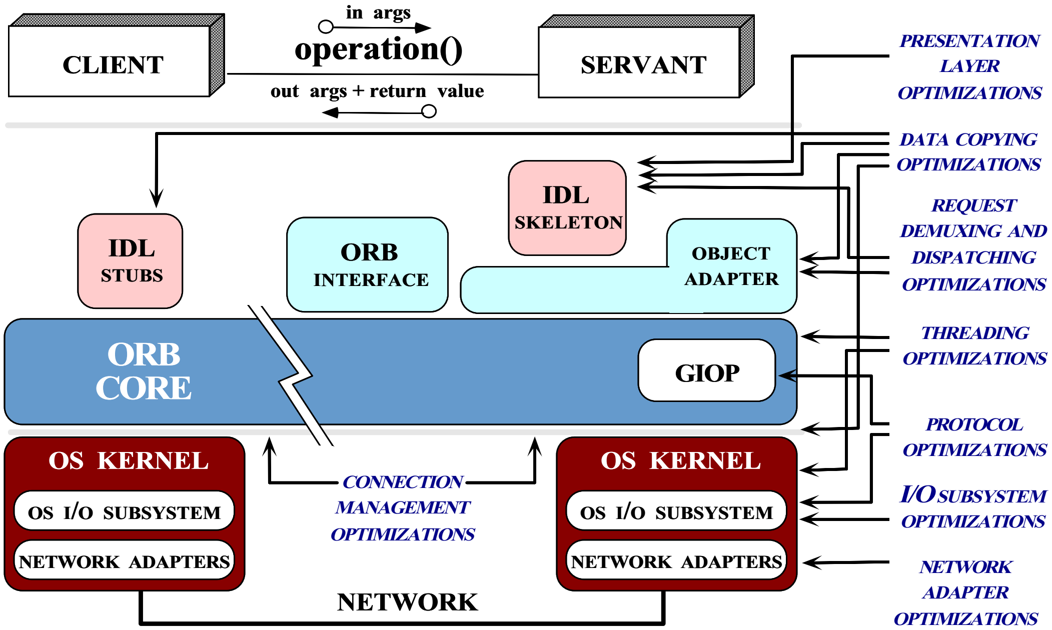


- **Domain Challenges**
  - Periodic deterministic real-time deadlines
  - COTS infrastructure
  - Open systems

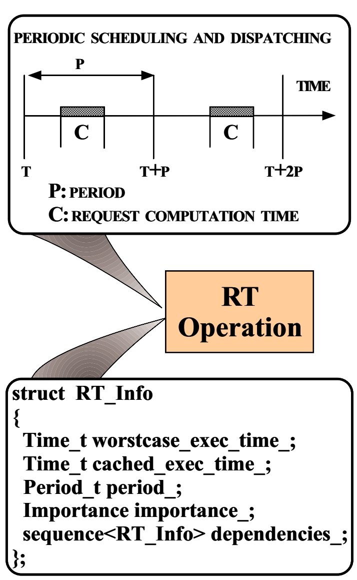
Visualizing Periods for Avionics Operations



Real-time Features and Optimizations in TAO

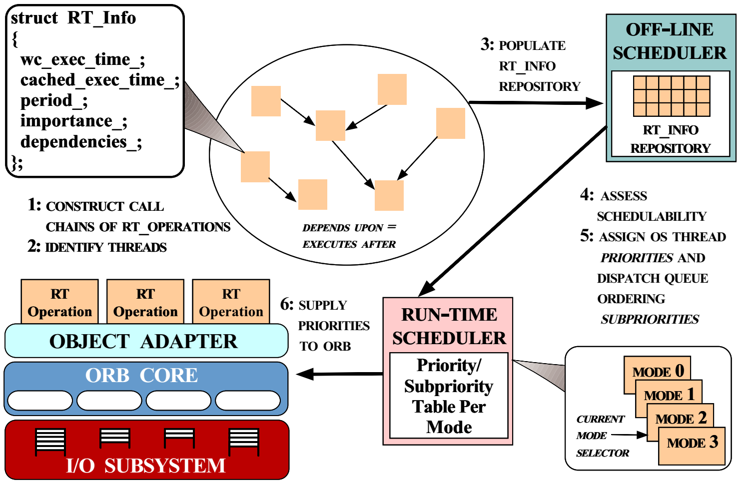


Providing QoS to CORBA Operations



- **Design Challenges**
  - Specifying/enforcing QoS requirements
  - Focus on *Operations* upon *Objects*
    - Rather than on communication channels or threads/synchronization
- **Initial focus**
  - Determinisitic deadlines
  - Static scheduling
- **Solution approach**
  - Servants publish resource (*e.g.*, CPU) requirements and (periodic) deadlines
  - Most clients are also servants

TAO's Real-time Scheduling Service

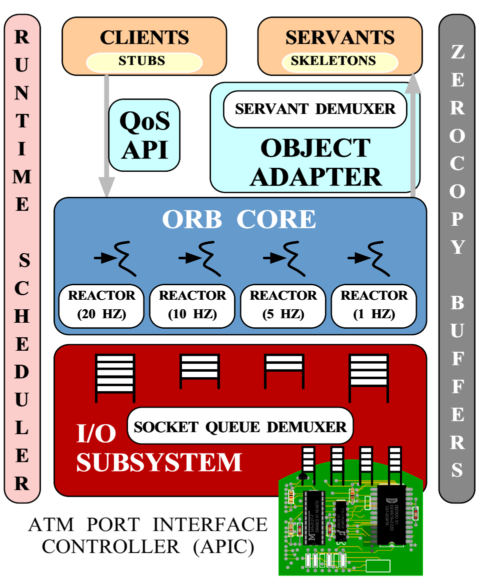


www.cs.wustl.edu/~schmidt/TAO.ps.gz

- **Components**
  - Offline
    - Assess schedule feasibility
    - Assign thread and queue priorities
  - Online
    - Supply priorities to ORB endsystem dispatcher via $O(1)$ table lookup

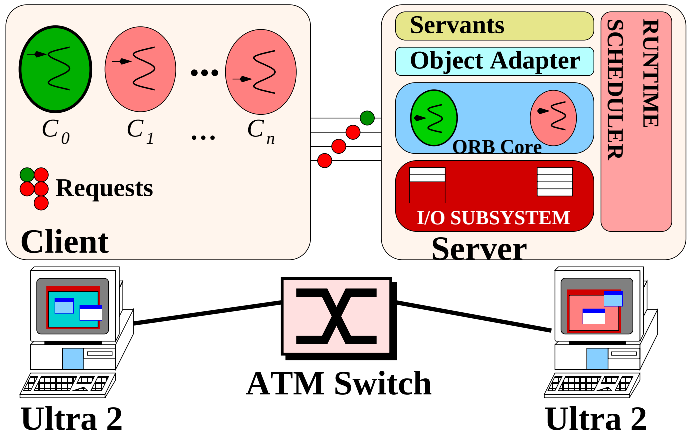
Douglas C. Schmidt High-performance, Real-time ORBs

TAO's Real-time ORB Endsystem Architecture



- **Solution Approach**
  - Integrate RT dispatcher into ORB endsystem
  - Support multiple request scheduling strategies
    - *e.g.*, RMS, RMS with Deferred Preemption, and EDF
  - Requests ordered across thread priorities by OS dispatcher
  - Requests ordered within priorities based on *data dependencies* and *importance*

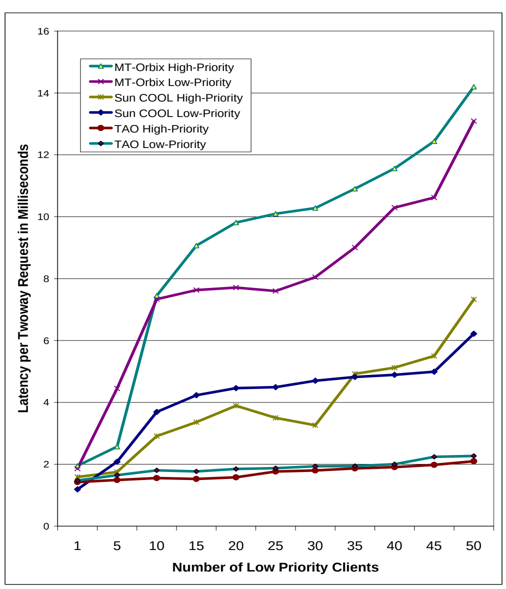
Priority Inversion Experiments



www.cs.wustl.edu/∼schmidt/RT-perf.ps.gz

- One high priority client
- *1..n* low priority clients
- Server factory implements *thread-per-rate*
  - *Highest* real-time priority for high priority client
  - *Lowest* real-time priority for low priority clients

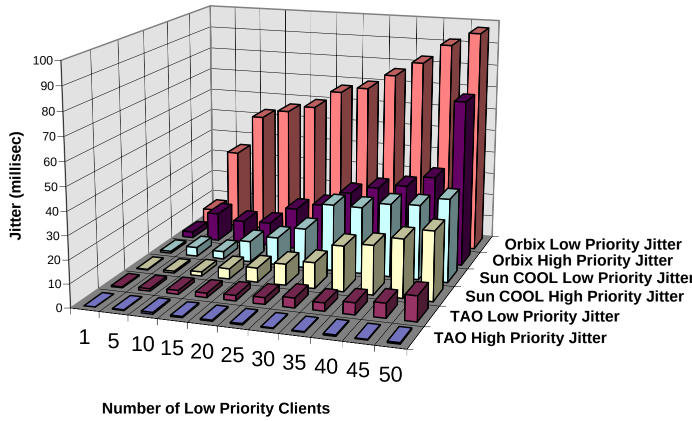
Priority Inversion Experiment Results



MT-Orbix, Chorus, and TAO Priority Inversion

- **Synopsis of results**
  - Chorus' latency is lower for small # of clients
    - ∼1.2msec vs. ∼1.4sec vs. ∼2.0sec
  - TAO's latency is *much* lower for large # of clients
    - ∼2.3msec vs. ∼7.6msec vs. ∼14.1msec
  - TAO avoids priority inversion
    - *i.e.*, high priority client always has lowest latency

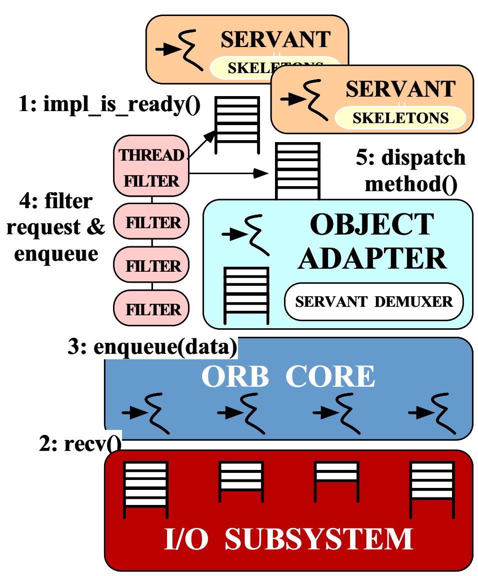
Jitter Experiment Results



MT-Orbix, Chorus, and TAO Jitter

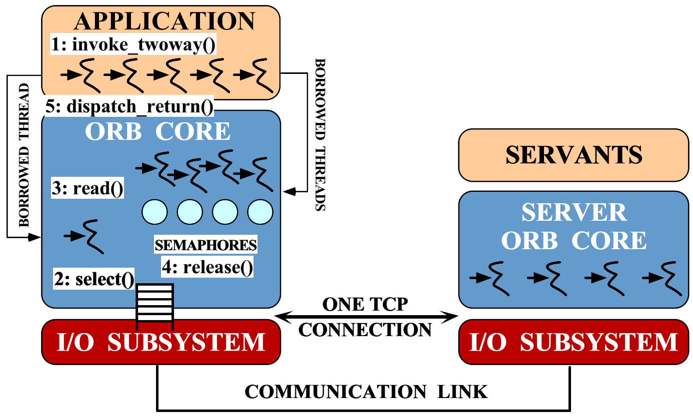
- **Definition**
  - Jitter is the variance from the average latency
- **Synopsis of results**
  - TAO's jitter is lowest and most consistent
  - MT-Orbix's jitter is highest and more variable

Problem: Improper ORB Concurrency Model



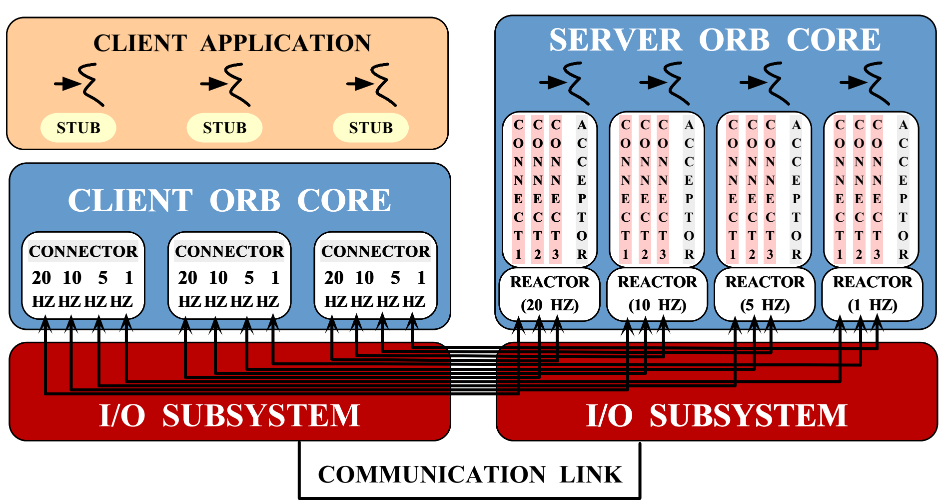
- **Common Problems**
  - High overhead
    - Context switching
    - Synchronization
  - Priority inversions
    - FIFO request queueing
    - Improper thread priorities
  - Lack of application control over concurrency model

Problem: ORB Shared Connection Model



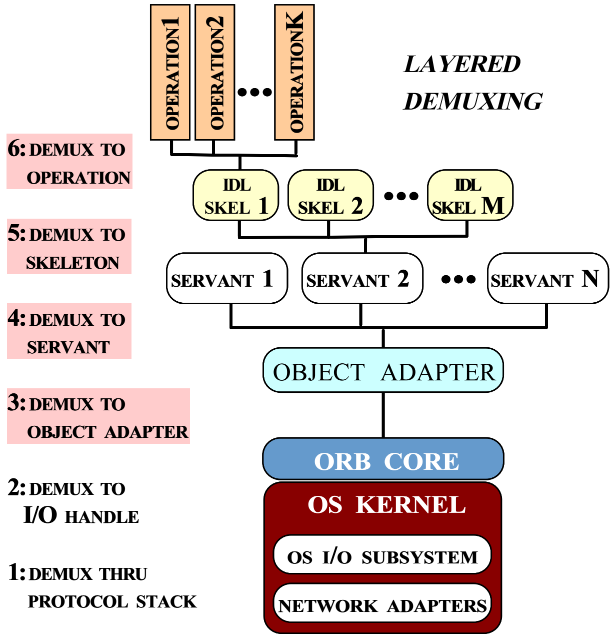
- **Common Problems**
  - Priority inversions
    - Sharing multiple priorities on a single connection
  - Complex connection multiplexing
  - Synchronization overhead

TAO's Inter-ORB Connection Topology



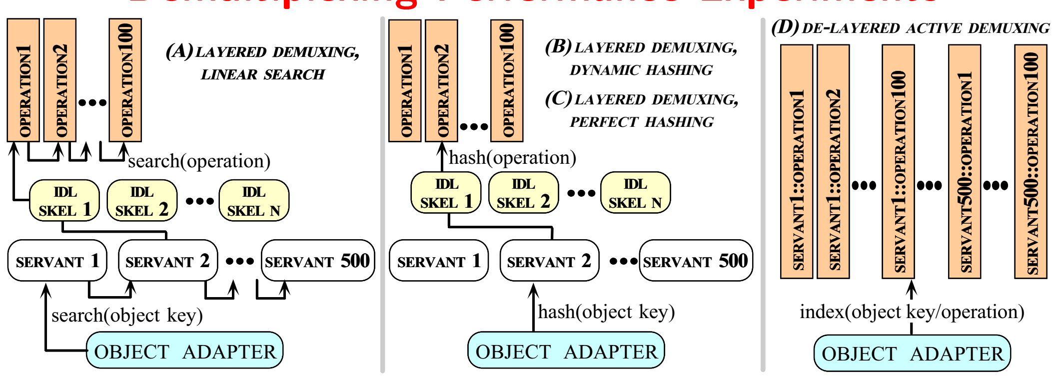
www.cs.wustl.edu/∼schmidt/RT-middleware.ps.gz

Problem: Reducing Demultiplexing Latency



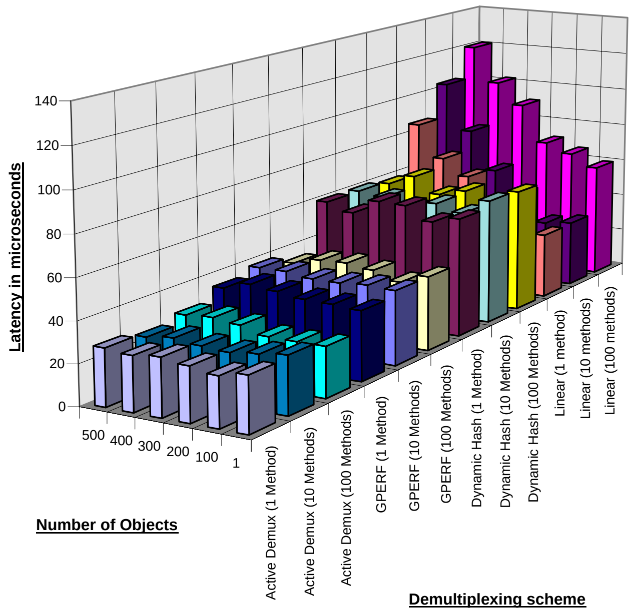
- **Design Challenges**
  - Minimize demuxing layers
  - Provide $O(1)$ operation demuxing
  - Avoid priority inversions
  - Remain CORBA-compliant

Demultiplexing Performance Experiments



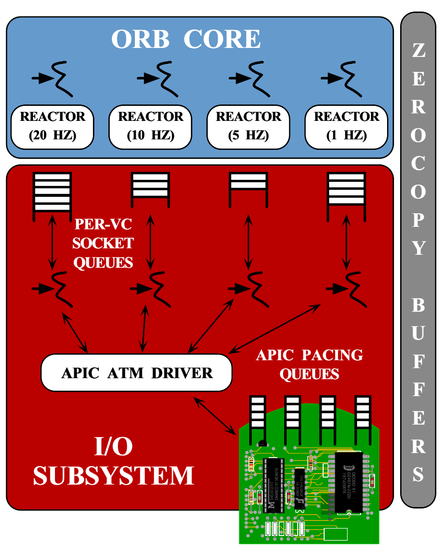
- Linear search based on `Orbix` demuxing strategy
- Perfect hashing based on GNU `gperf`
  - `www.cs.wustl.edu/~schmidt/gperf.ps.gz`
- Results at `www.cs.wustl.edu/~schmidt/GLOBECOM-97.ps.gz`

Demultiplexing Performance Results



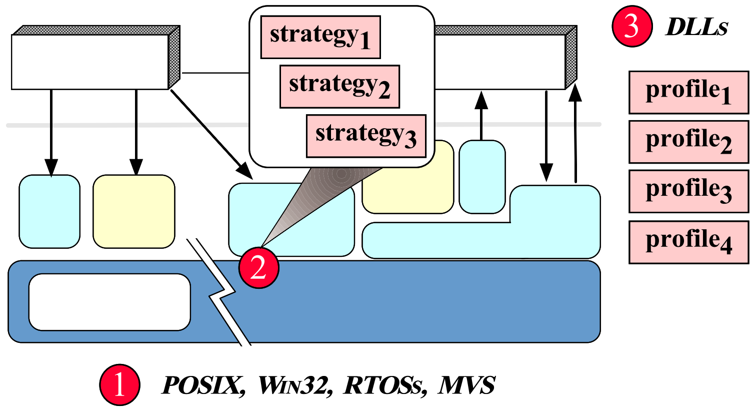
- **Synopsis**
  - Linear search is far too costly
  - Dynamic hashing is too erratic
  - `gperf` solution is 100% compatible, but static
  - Active demuxing may not be 100% compatible, but is dynamic

Integrating TAO with RT I/O Subsystem and ATM



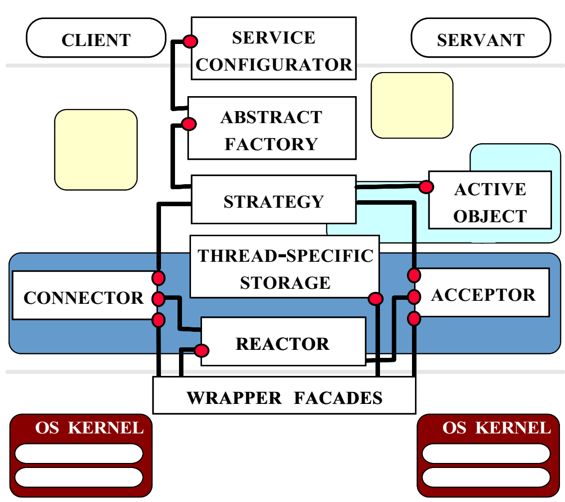
- **Key Features**
  - Vertical integration of QoS through ORB, OS, and ATM network
  - Provides rate-based QoS end-to-end
  - Leverages APIC features for cell pacing

Dimensions of ORB Extensibility



- *Extensible to retarget on new platforms*
- *Extensible via custom implementation strategies*
- *Extensible via dynamic configuration of custom strategies*

Applying Patterns to Develop Extensible ORBs



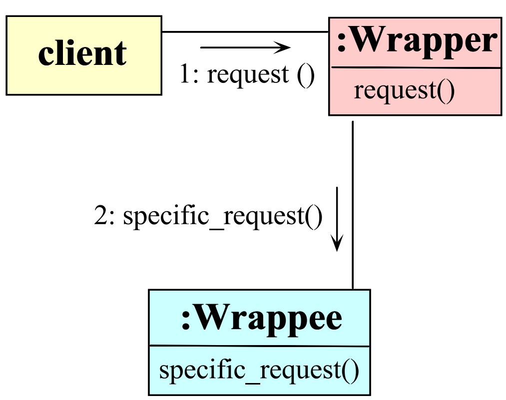
www.cs.wustl.edu/∼schmidt/ORB-patterns.ps.gz

- **Definition**
  - "A recurring solution to a design problem in a particular context"
- **Benefits of Patterns**
  - Facilitate design reuse
  - Preserve crucial design information
  - Guide design choices
  - Document common traps and pitfalls

Addressing ORB Portability and Typesafety Challenges

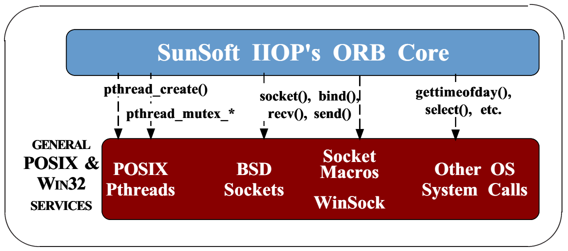
- Problem
  - Building an ORB using low-level system APIs is hard
- Forces
  - Low-level APIs are tedious to program
  - Low-level APIs are error-prone
  - Low-level APIs are non-portable
- Solution
  - Apply the *Wrapper Facade* pattern to encapsulate low-level OS programming details

Enhancing Portability and Typesafety with the Wrapper Facade Pattern

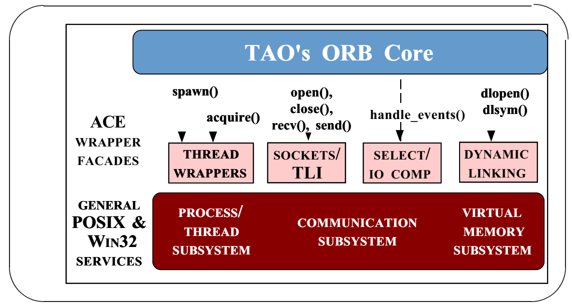


- **Intent**
  - *Encapsulates low-level, stand-alone system mechanisms within type-safe, modular, and portable class interfaces*
- **Forces Resolved**
  - Avoid tedious, error-prone, and non-portable system APIs
  - Create cohesive abstractions

Using the Wrapper Facade Pattern in TAO



SunSoft IIOP



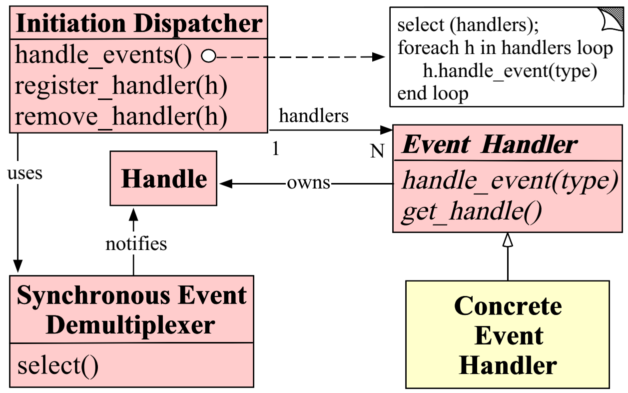
TAO

- TAO's wrapper facades are based on ACE
- The Wrapper Facade pattern substantially increased portability and reduced the amount of *ad hoc* code

Addressing ORB Demuxing and Dispatching Challenges

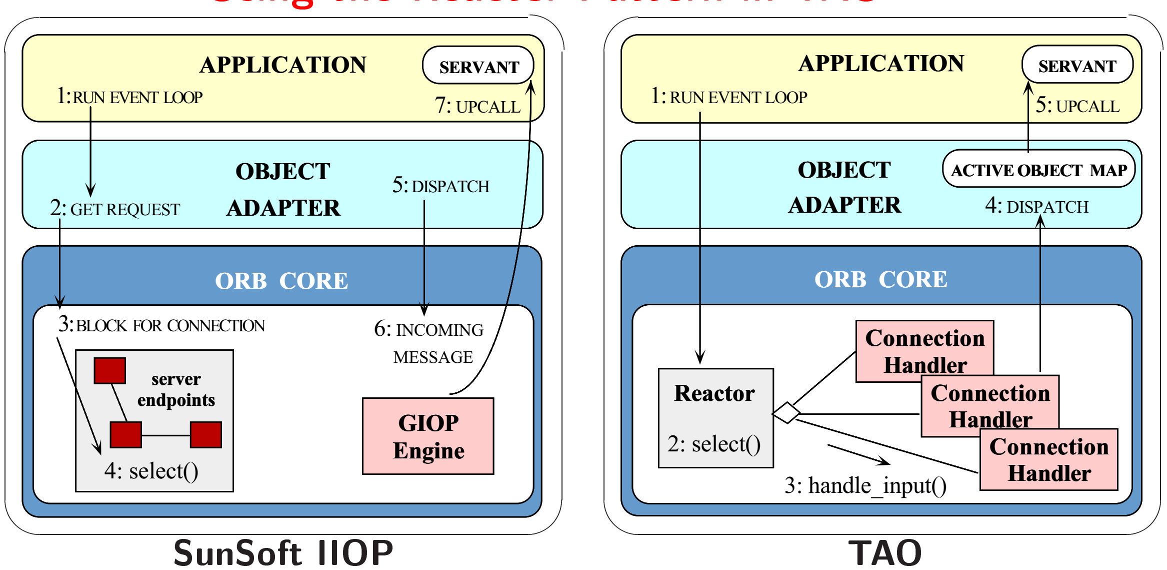
- Problem
  - ORBs must process many different types of events simultaneously
- Forces
  - Multi-threading is not always available
  - Multi-threading is not always efficient
  - Tightly coupling general event processing with ORB-specific logic is inflexible
- Solution
  - Use the *Reactor* pattern to decouple generic event processing from ORB-specific processing

Enhancing Demuxing with the Reactor Pattern



- **Intent**
  - *Decouples synchronous event demuxing/dispatching from event handling*
- **Forces Resolved**
  - Demuxing events efficiently within one thread
  - Extending applications without changing demux infrastructure

Using the Reactor Pattern in TAO

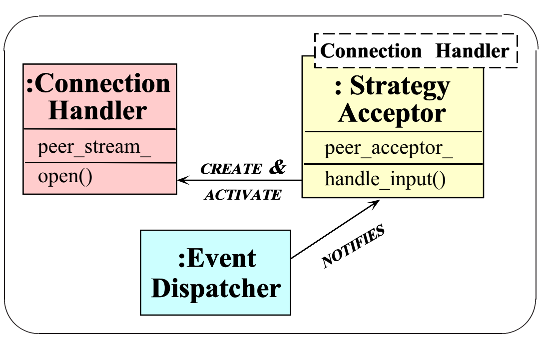


- The ACE Reactor pattern is widely used by industry

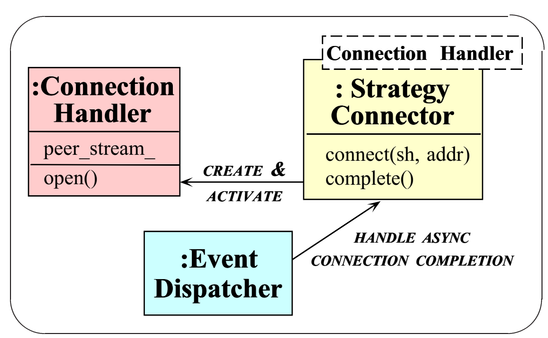
Addressing ORB Endpoint Initialization Challenges

- Problem
  - The *communication protocol* used between ORBs is often orthogonal to its *connection establishment* and *service handler initialization protocol*
- Forces
  - Low-level connection APIs are error-prone and non-portable
  - Separating *initialization* from subsequent *processing* increases software reuse for many types of communication software
- Solution
  - Use the *Acceptor-Connector* pattern to decouple passive/active connection establishment and GIOP connection handler initialization from the subsequent ORB interoperability protocol (*e.g.*, IIOP)

Enhancing Endpoint Initialization with the Acceptor-Connector Pattern



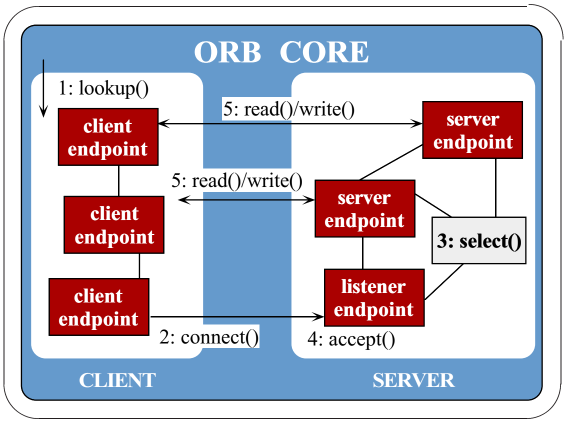
Acceptor Structure



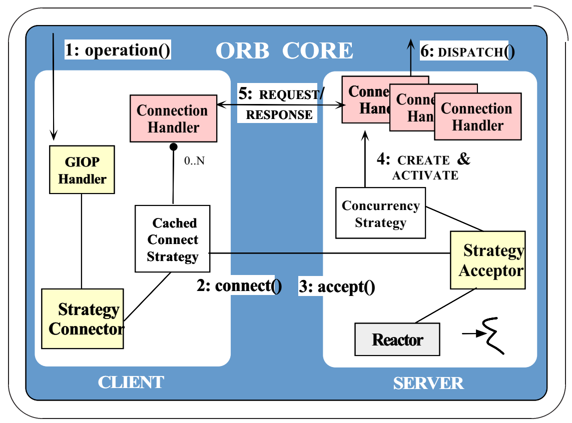
Connector Structure

- **Intent**
  - *Decouple connection establishment and service handler initialization from subsequent service processing*

Using the Acceptor-Connector Pattern in TAO



SunSoft IIOP



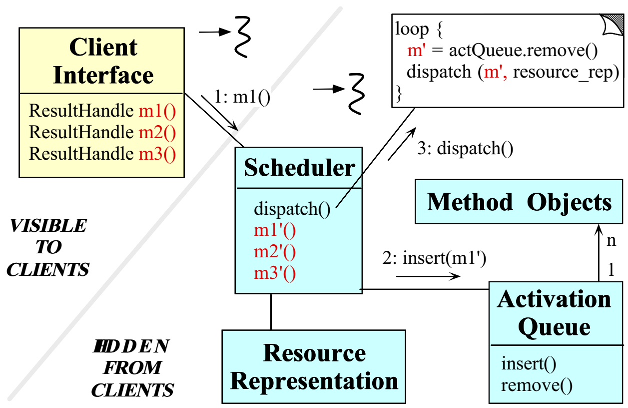
TAO

- **Forces Resolved**
  - (1) Improve portability and reuse and (2) avoid common mistakes

Addressing ORB Concurrency Challenges

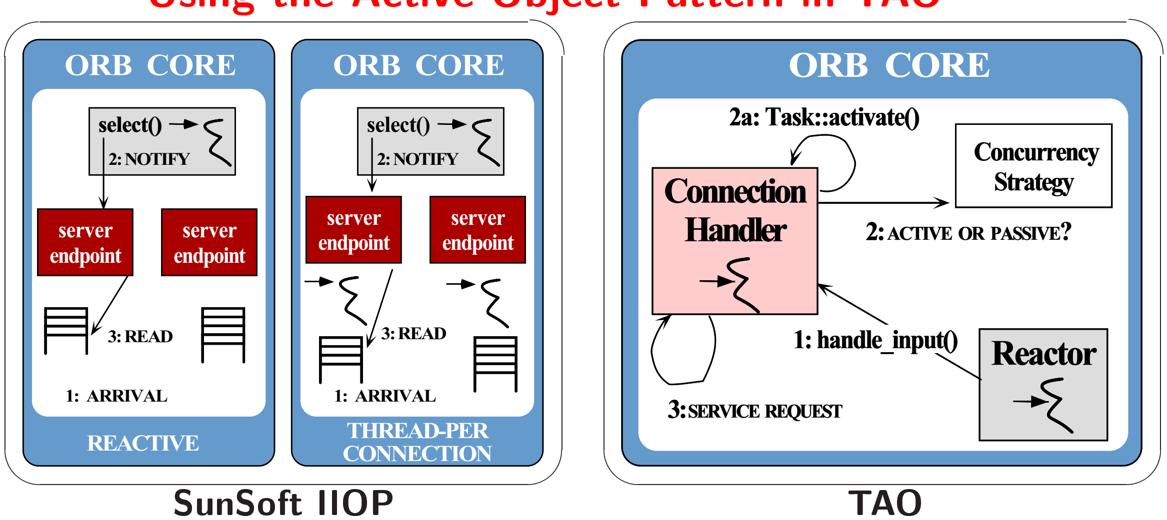
- Problem
  - Multi-threaded ORBs are needed since Reactive ORBs are often inefficient, non-scalable, and non-robust
- Forces
  - Multi-threading can be very hard to program
  - No single multi-threading model is always optimal
- Solution
  - Use the *Active Object* pattern to allow multiple concurrent server operations using an OO programming style

Enhancing ORB Concurrency with the Active Object Pattern



- **Intent**
  - *Decouples the thread of request execution from the thread of request reception*
- **Forces Resolved**
  - Allow blocking operations
  - Permit flexible concurrency strategies

Using the Active Object Pattern in TAO

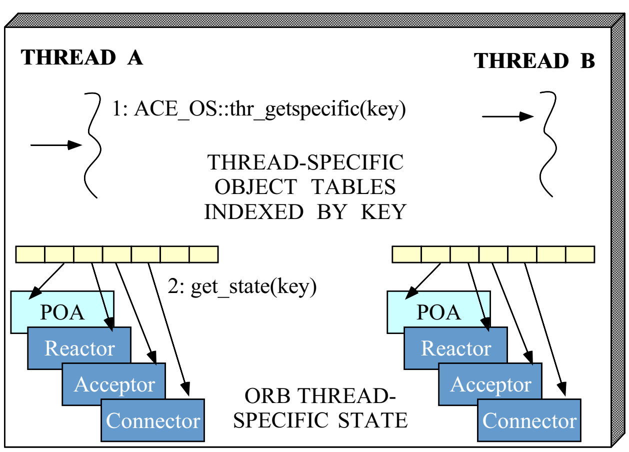


- TAO supports several variants of Active Objects (*e.g.*, Thread-per-Connection, Thread-per-Request, Thread Pool, Thread-per-Rate, etc.)

Reducing Lock Contention and Priority Inversions with the Thread-Specific Storage Pattern

- Problem
  - It is important to minimize the amount of locking required to serialize access to resources shared by an ORB
- Forces
  - Locks increase *performance overhead*
  - Locks increase potential for *priority inversion*
  - Different concurrency schemes yield different locking costs
- Solution
  - Use the *Thread-Specific Storage* pattern to maximize threading-model flexibility and minimize lock contention and priority inversion

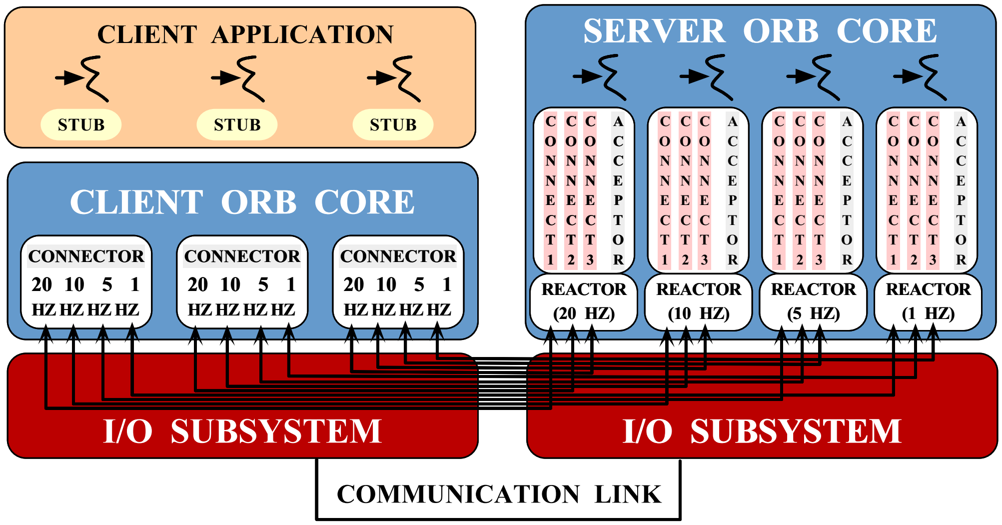
Minimizing ORB Locking with the Thread-Specific Storage Pattern



- **Forces Resolved**
  - Minimizes overhead and priority inversion

- **Intent**
  - *Allows multiple threads to use one logically global access point to retrieve ORB thread-specific data without incurring locking overhead for each access*

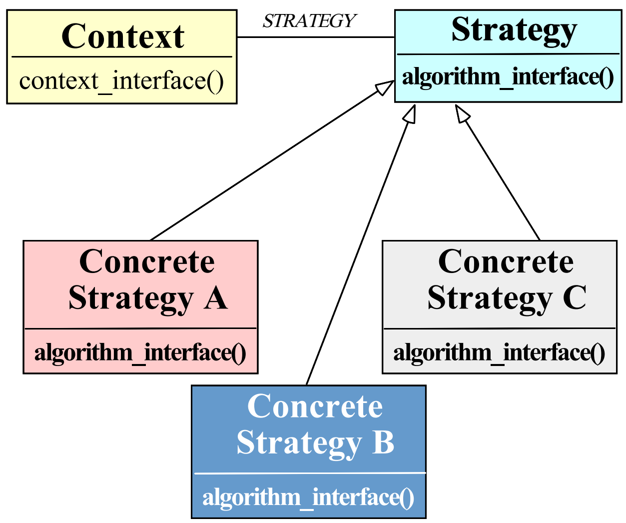
Using Thread-Specific Storage in TAO



Addressing ORB Flexibility Challenges

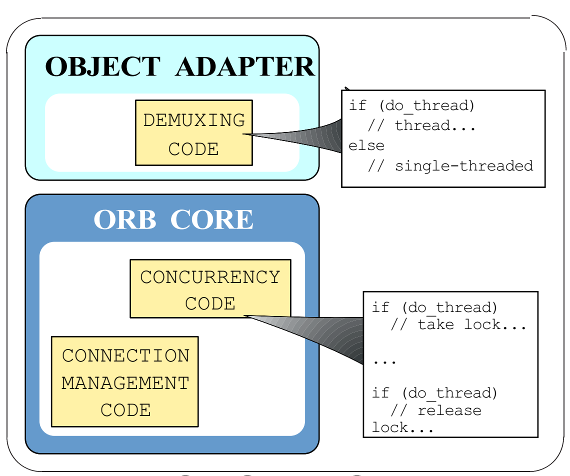
- Problem
  - Real-world ORBs must be flexible to satisfy the requirements of many different types of end-users and applications
- Forces
  - *Ad hoc* schemes for ORB flexibility are too static and non-extensible
  - Flexibility often has many (related) dimensions
- Solution
  - Use the *Strategy* pattern to support multiple transparently "pluggable" ORB strategies

Enhancing ORB Flexibility with the Strategy Pattern

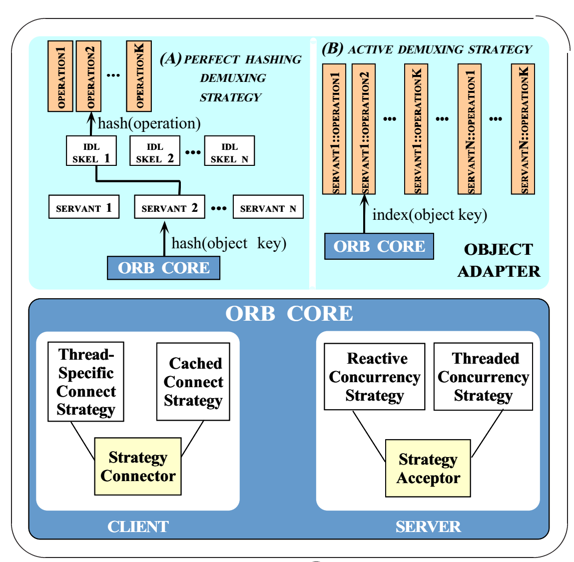


- **Intent**
  - *Factor out similarity among algorithmic alternatives*
- **Forces Resolved**
  - Orthogonally replace behavioral subsets transparently
  - Associating state with an algorithm

Using the Strategy Pattern in TAO



SunSoft IIOP

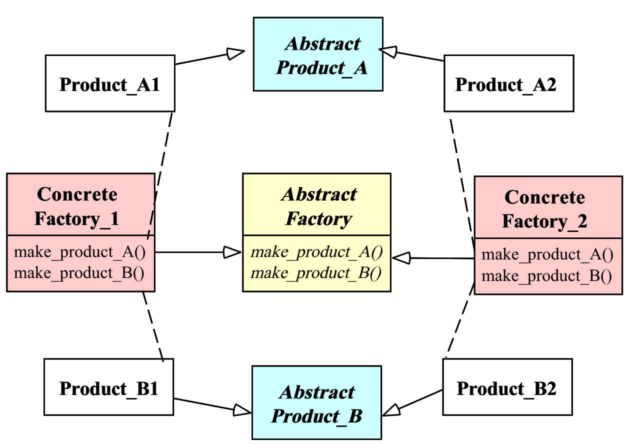


TAO

Addressing ORB Configurability Challenges

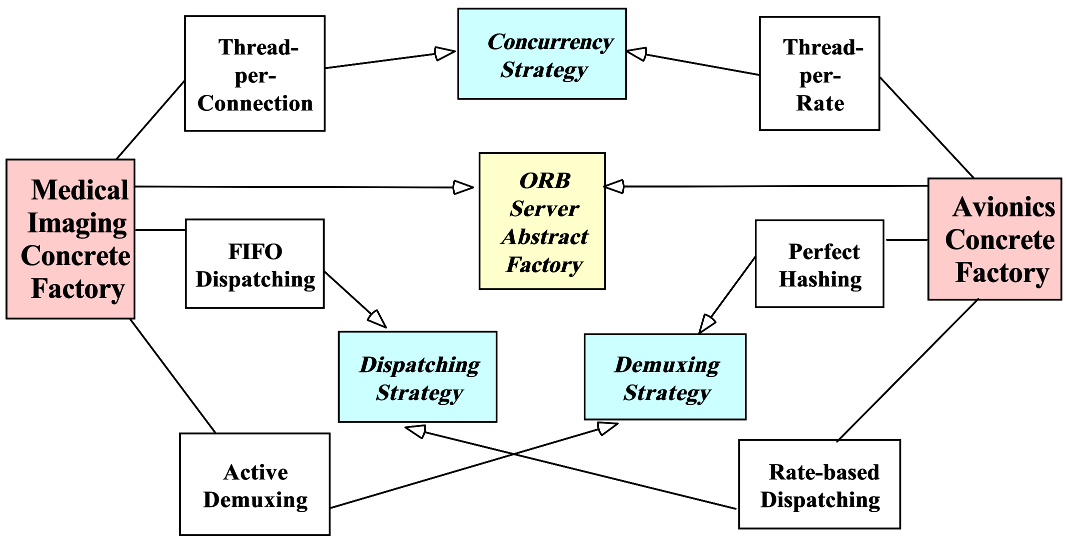
- Problem
  - Agressive use of the Strategy pattern can create a configuration nightmare
- Forces
  - It's hard to manage large numbers of individually configured strategies
  - It's hard to ensure that groups of semantically compatible strategies are configured
- Solution
  - Use the *Abstract Factory* pattern to consolidate multiple ORB strategies into semantically compatible configurations

Centralizing ORB Configurability with the Abstract Factory Pattern



- **Intent**
  - *Integrate all strategies used to configure an ORB*
- **Forces Resolved**
  - Consolidates customization of many strategies
  - Ensures semantic compatibility of strategies

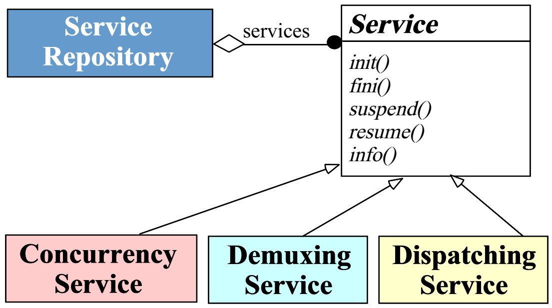
Using the Abstract Factory Pattern in TAO



Addressing ORB Dynamic Configurability Challenges

- Problem
  - Prematurely committing ourselves to a particular ORB configuration is inflexible and inefficient
- Forces
  - Certain ORB configuration decisions can't be made efficiently until run-time
  - Forcing users to pay for components they don't use is undesirable
- Solution
  - Use the *Service Configurator* pattern to assemble the desired ORB components dynamically

Enhancing Dynamic ORB Extensibility with the Service Configurator Pattern

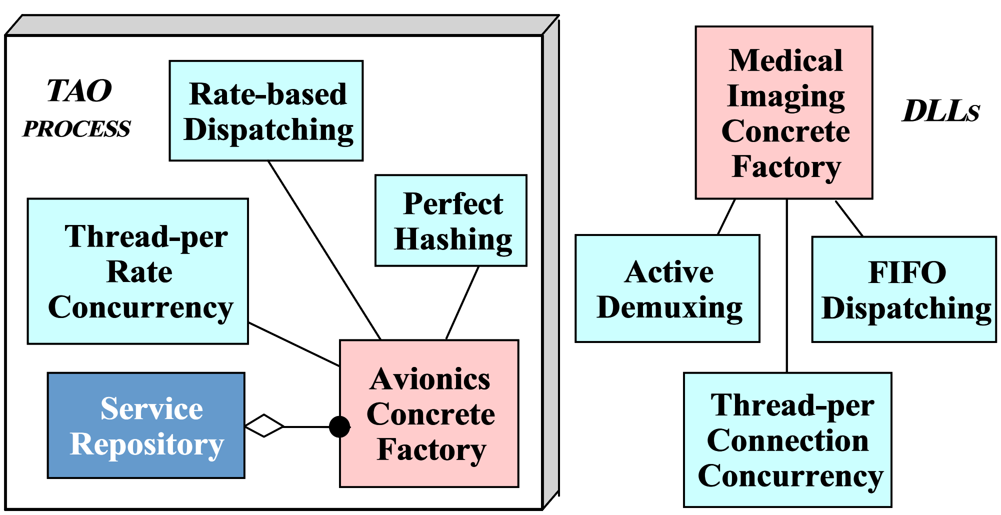



```
CORBA::ORB_init (int &argc, char *argv[])
{
  // Configure the ORB.
  Service_Config tao (argc, argv);

  // Perform initialization...
}
```

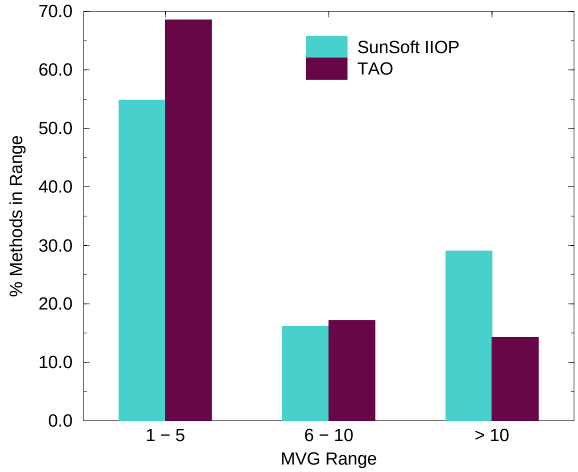
- **Intent**
  - *Decouples ORB strategies from time when they are configured*
- **Forces Resolved**
  - Reduce resource utilization
  - Support dynamic (re)configuration

Using the Service Configurator Pattern in TAO



Run-time Configuration

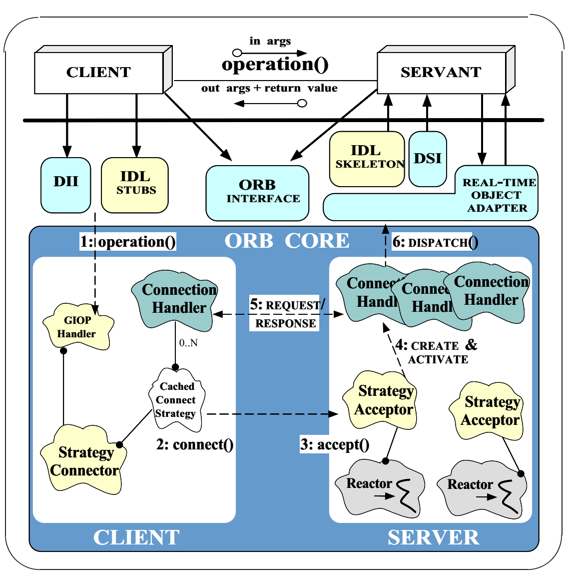
Quantifying the Benefits of Patterns

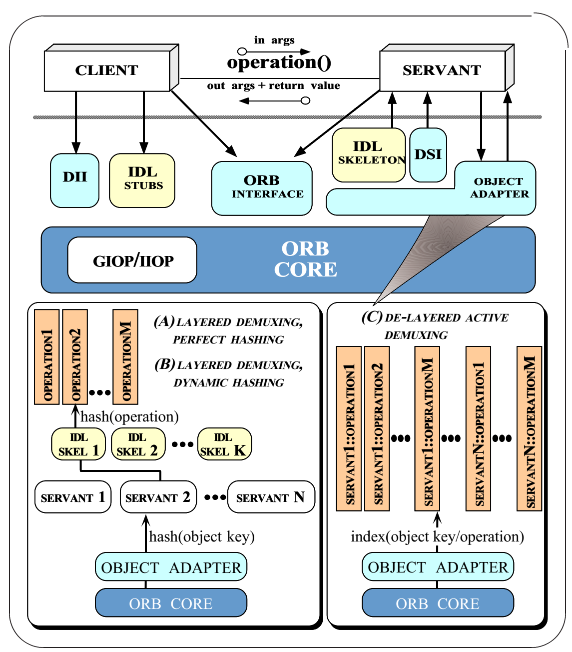


Macabe Complexity Metric Scores for TAO and SunSoft IIOP

- **Statistics**
  - Patterns greatly reduce code complexity
    - *e.g.*, Most TAO components have $v(G) < 10$
  - TAO components are substantially smaller than SunSoft IIOP
    - *e.g.*, connection management reduced by a factor of 5

Current Status of TAO





TAO Project Summary

- Current Focus: High-performance, Real-time ORBs
  - Reducing latency via *de-layered active demuxing*
  - Applying optimization principles to TypeCode interpreter
  - Enforcing periodic deadlines via Real-time ORB endystem
    - *i.e.*, support static scheduling for CORBA requests
  - Applying optimization principles to presentation layer
- Future Work
  - Pinpoint non-determinism and priority inversions in ORBs
  - Dynamic scheduling of requests
  - Distributed QoS and integration with RT I/O Subsystem
  - IDL compiler and optimized stub generation
  - TypeCode compiler optimizations

Concluding Remarks

- Developers of distributed applications confront recurring challenges that are largely application-independent
  - *e.g.*, service initialization and distribution, error handling, flow control, event demultiplexing, concurrency control, persistence, fault tolerance
- Successful developers resolve these challenges by applying appropriate *design patterns* to create communication *frameworks* and `components`
- ORBs are an effective way to achieve reuse of distributed software components
- The next-generation of ORBs will provide much better QoS support