Real-time Middleware for Distributed and Embedded Systems

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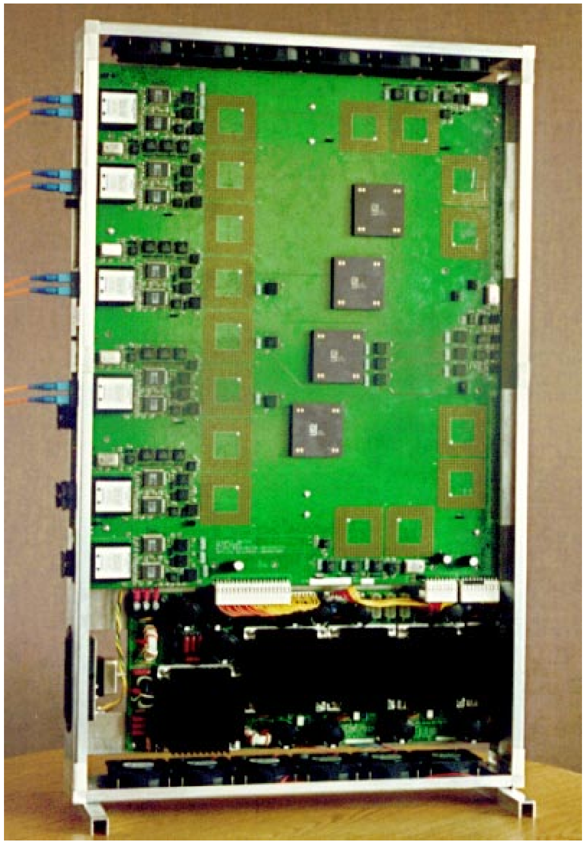
November 1999

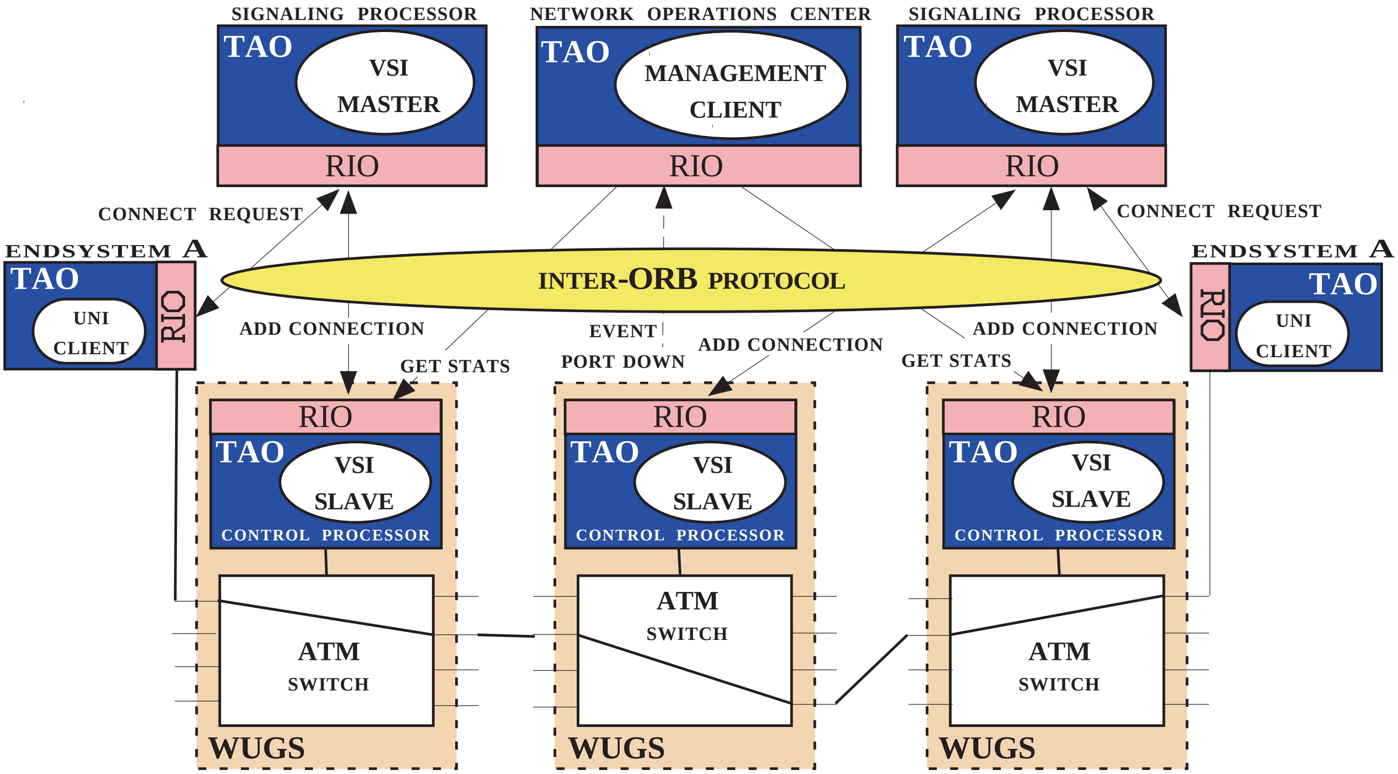
Motivation: the Telecom Software Crisis



www.arl.wustl.edu/arl/

- **Symptoms**
  - Network element ***hardware*** gets smaller, faster, cheaper
  - Communication ***software*** gets larger, slower, more expensive
- **Culprits**
  - ***Inherent*** and ***accidental*** complexity
- **Solution Approach**
  - Manage & control network elements via ***QoS-enabled middleware***

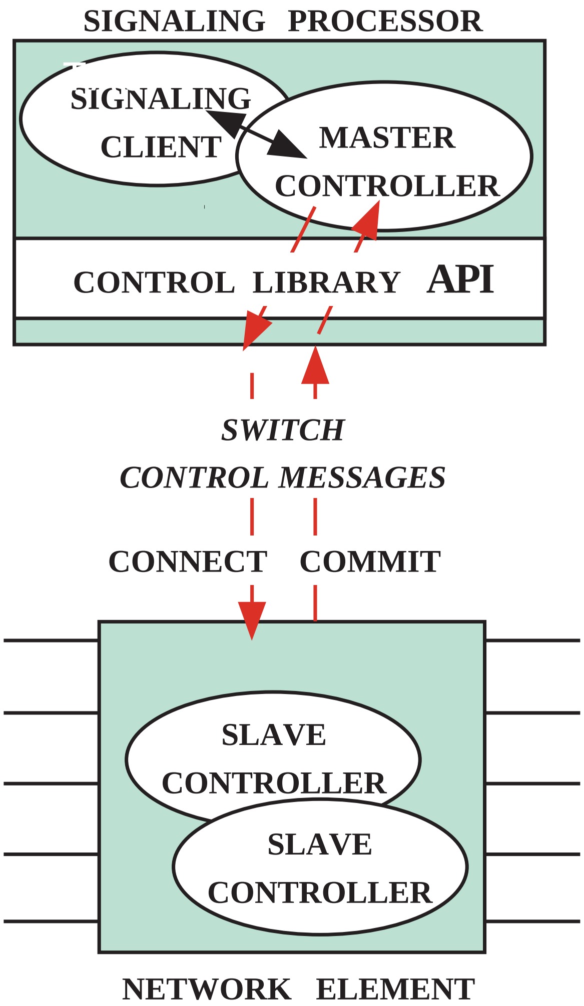
Goal: Apply Embedded Middleware to Network Element Mgmt & Control



Domain Challenges

- High-speed (20 Gbps) ATM switches w/embedded controllers
- Low-latency and statistical real-time deadlines
- COTS infrastructure, standards-based open systems, and small footprint

Problem: Low-level Switch Control & Management (*e.g.*, GSMP & VSI)



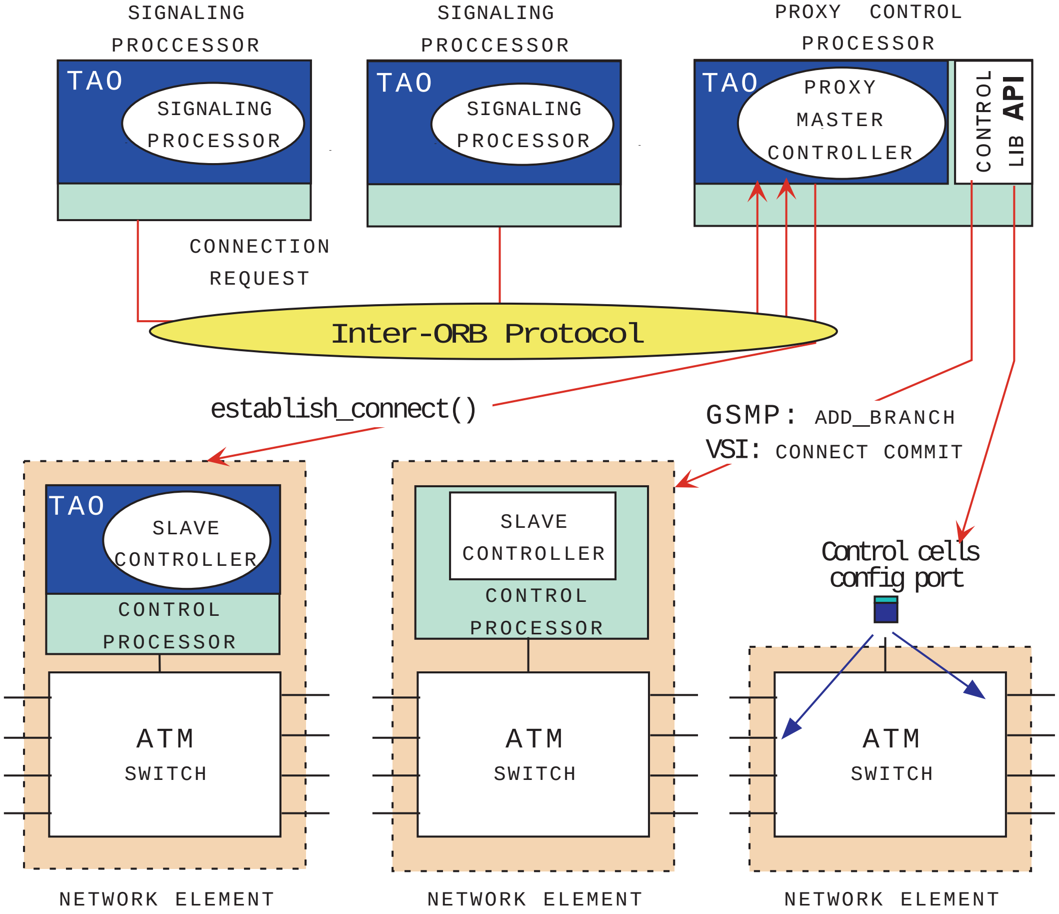
Features

- Setup & release connections
- Add & delete point-to-multipoint leaves
- Manage ATM switch ports
- Request configuration information & statistics

Drawbacks

- Non-portable, tedious, and error-prone programming APIs

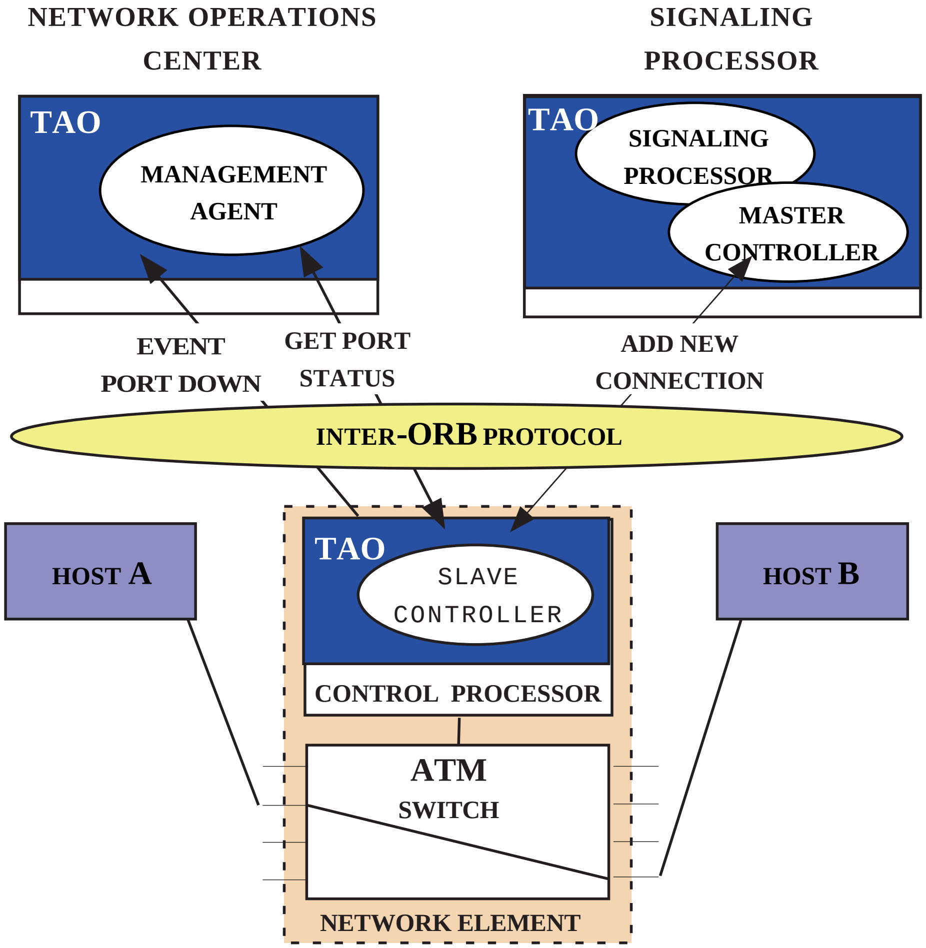
Proxy Server Configuration



Features

- Supports standard CORBA programming API
- Can use standard ORB
- Transparent to existing GSMP & VSI servers
- Scales to distributed configuration
  - *i.e.*, one CP can control multiple switches

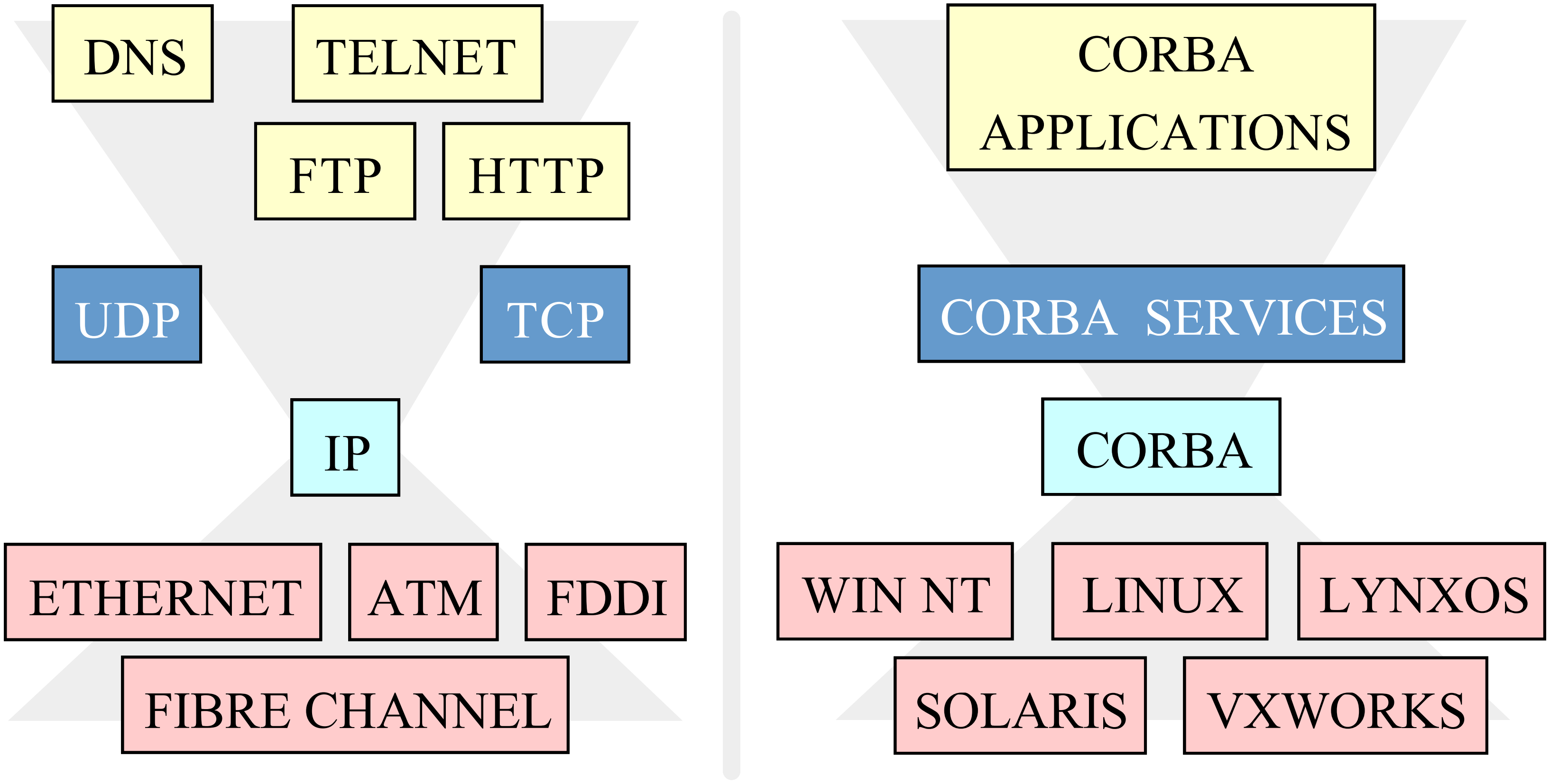
Embedded ORB Configuration



Features

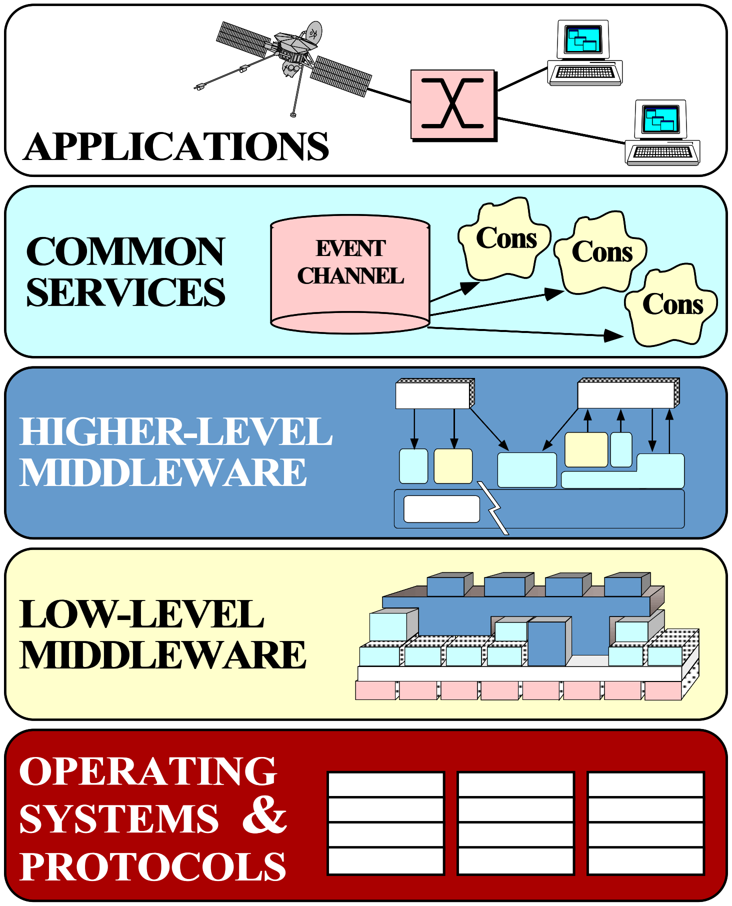
- Leverages middleware flexibility and standardization
- Multiple protocols can be supported
  - GSMP & VSI in-line bridging, GIOP/IIOP, etc.
- Minimal footprint

Context: Levels of Abstraction in Internetworking and Middleware



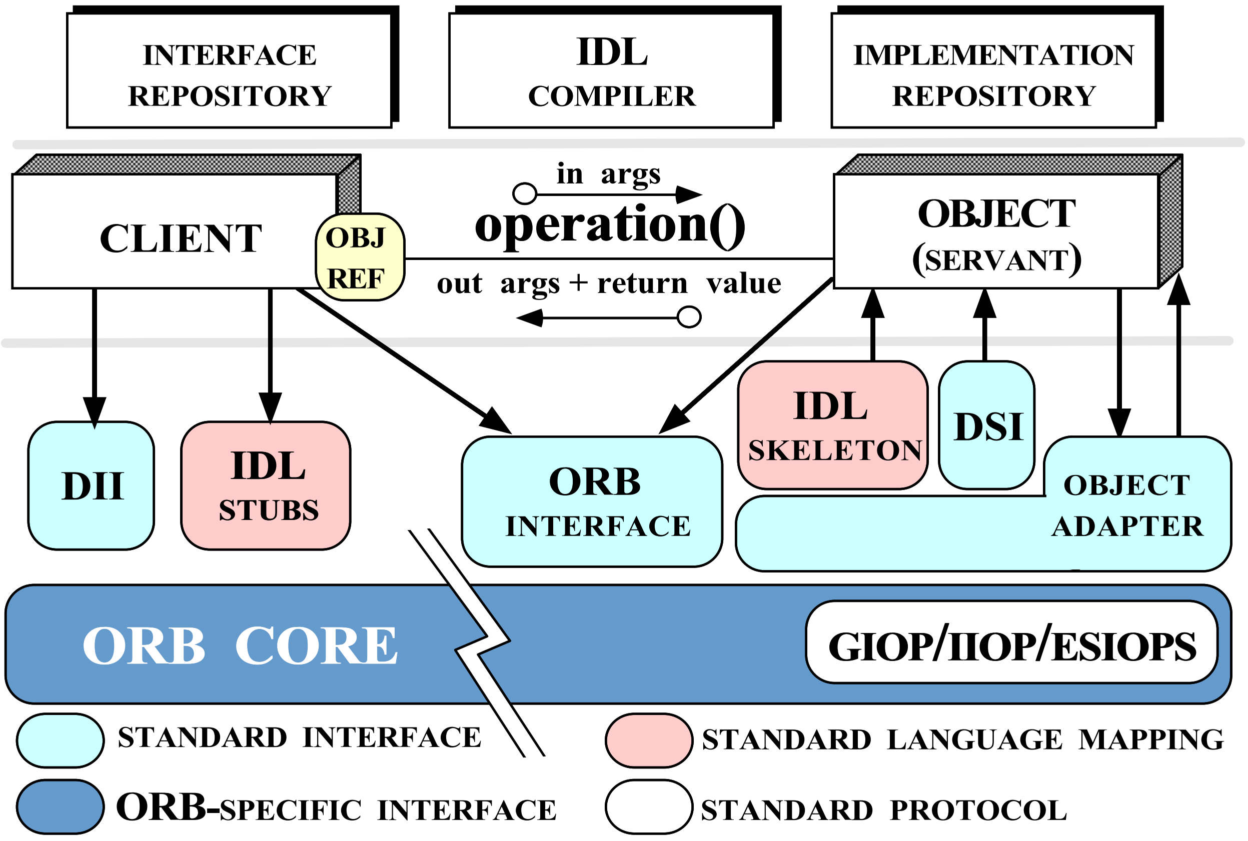
INTERNETWORKING ARCH ***MIDDLEWARE ARCH***

Problem: Lack of QoS-enabled Middleware



- Many telecom applications require QoS guarantees
  - *e.g.*, call-processing, network/switch management, wireless systems
- Building these applications manually is hard
- Existing middleware doesn't support QoS effectively
  - *e.g.*, CORBA, DCOM, DCE, Java
- Solutions must be integrated horizontally & vertically

Candidate Solution: CORBA



INTERFACE REPOSITORY

IDL COMPILER

IMPLEMENTATION REPOSITORY

CLIENT

OBJ REF

in args

operation()

out args + return value

OBJECT (SERVANT)

DII

IDL STUBS

ORB INTERFACE

IDL SKELETON

DSI

OBJECT ADAPTER

ORB CORE

GIOP/IIOP/ESIOPS

STANDARD INTERFACE

STANDARD LANGUAGE MAPPING

ORB-SPECIFIC INTERFACE

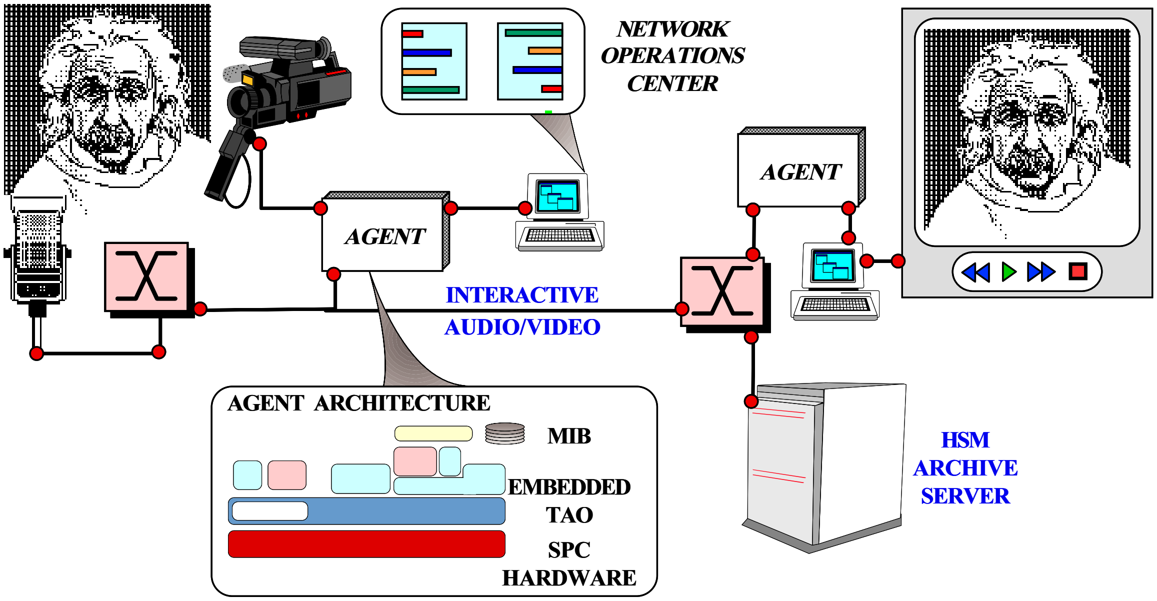
STANDARD PROTOCOL

www.cs.wustl.edu/∼schmidt/corba.html

Goals of CORBA

- Simplify distribution by automating
  - Object location & activation
  - Parameter marshaling
  - Demultiplexing
  - Error handling
- Provide foundation for higher-level services

Caveat: Requirements/Limitations of CORBA for Telecom



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

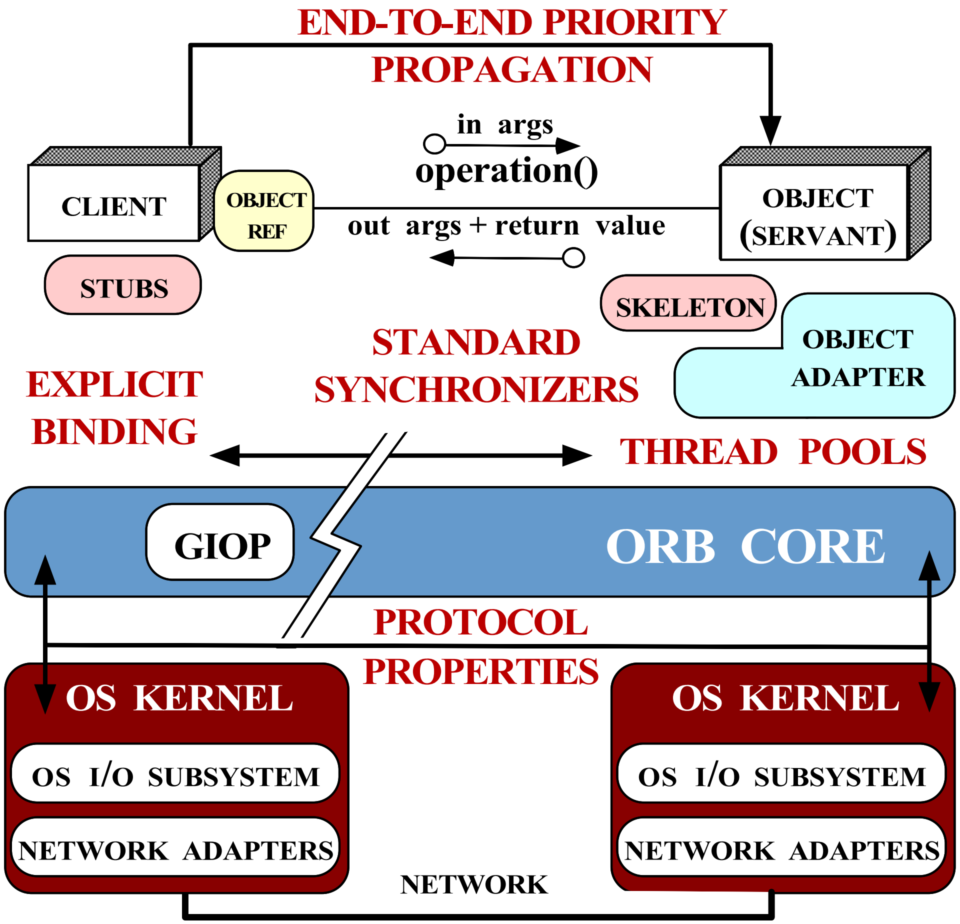
Requirements

- Location transparency
- Performance transparency
- Predictability transparency
- Reliability tranparency

Limitations

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

Overview of the Real-time CORBA Specification

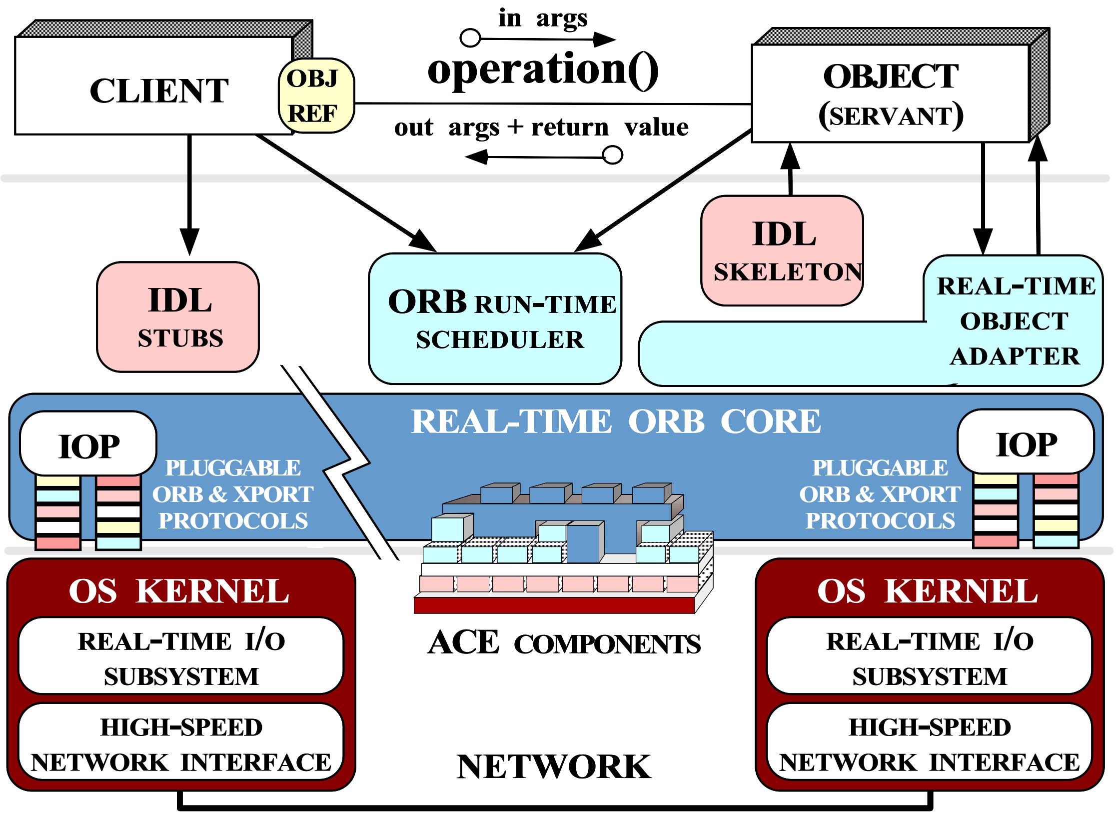


Features

1. End-to-end priority propagation
2. Protocol properties
3. Thread pools
4. Explicit binding
5. Standard synchronizers

www.cs.wustl.edu/∼schmidt/oorc.ps.gz

Our Approach: The ACE ORB (TAO)

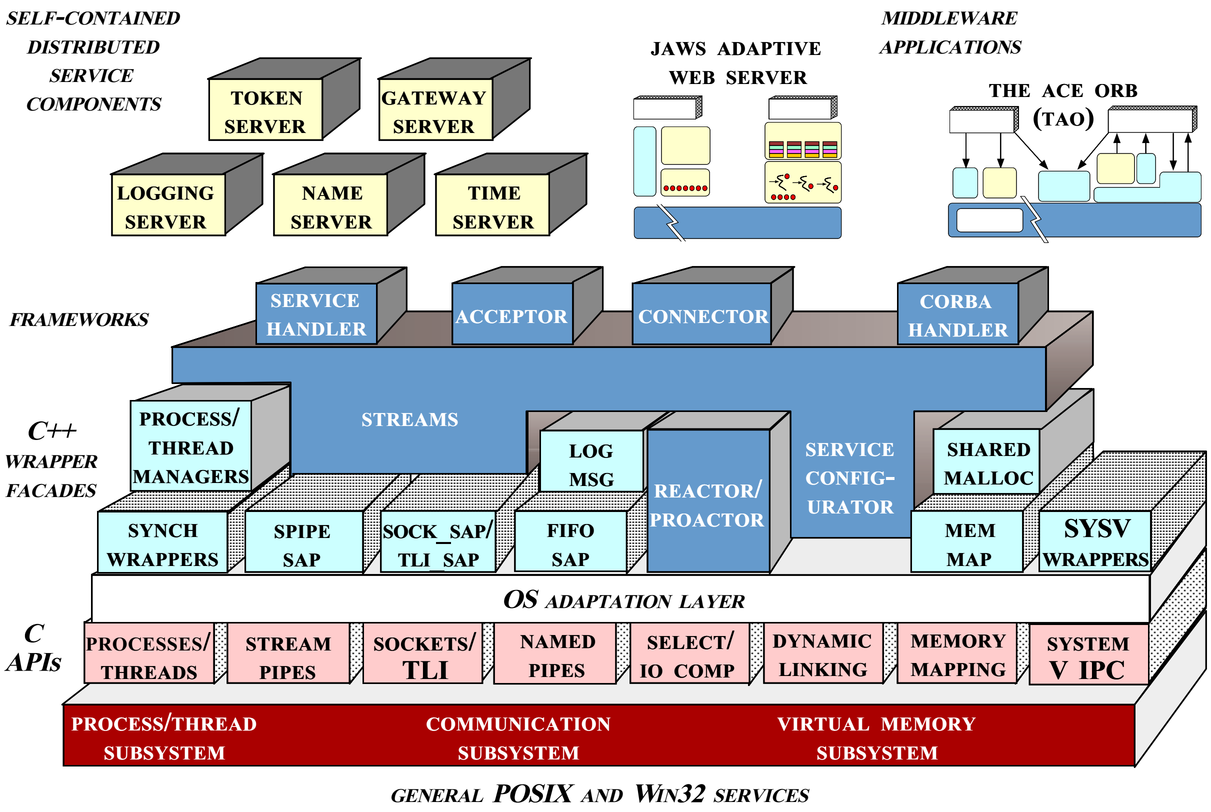


www.cs.wustl.edu/∼schmidt/TAO.html

TAO Overview →

- An open-source, standards-based, real-time, high-performance CORBA ORB
- Runs on POSIX/UNIX, Win32, & RTOS platforms
  - *e.g.*, VxWorks, Chorus, LynxOS
- Leverages ACE

The ADAPTIVE Communication Environment (ACE)



www.cs.wustl.edu/∼schmidt/ACE.html

ACE Overview →

- A concurrent OO networking framework
- Available in C++ and Java
- Ported to POSIX, Win32, and RTOSs

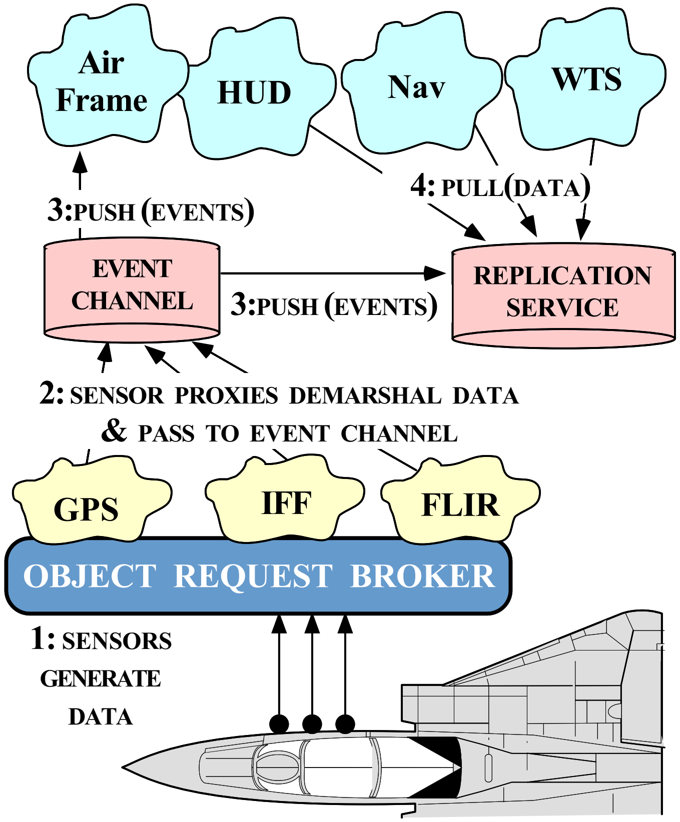
Related work →

- x-Kernel
- SysV STREAMS

ACE and TAO Statistics

- Over 35 person-years of effort
  - ACE $>$ 200,000 LOC
  - TAO $>$ 125,000 LOC
  - TAO IDL compiler $>$ 100,000 LOC
  - TAO CORBA Object Services $>$ 150,000 LOC
- Ported to UNIX, Win32, MVS, and RTOS platforms
- Large user community
  - www.cs.wustl.edu/~schmidt/ACE-users.html
- Currently used by dozens of companies
  - Bellcore, Boeing, Ericsson, Kodak, Lockheed, Lucent, Motorola, Nokia, Nortel, Raytheon, SAIC, Siemens, etc.
- Supported commercially
  - ACE → www.riverace.com
  - TAO → www.ociweb.com

Applying TAO to Avionics Mission Computing



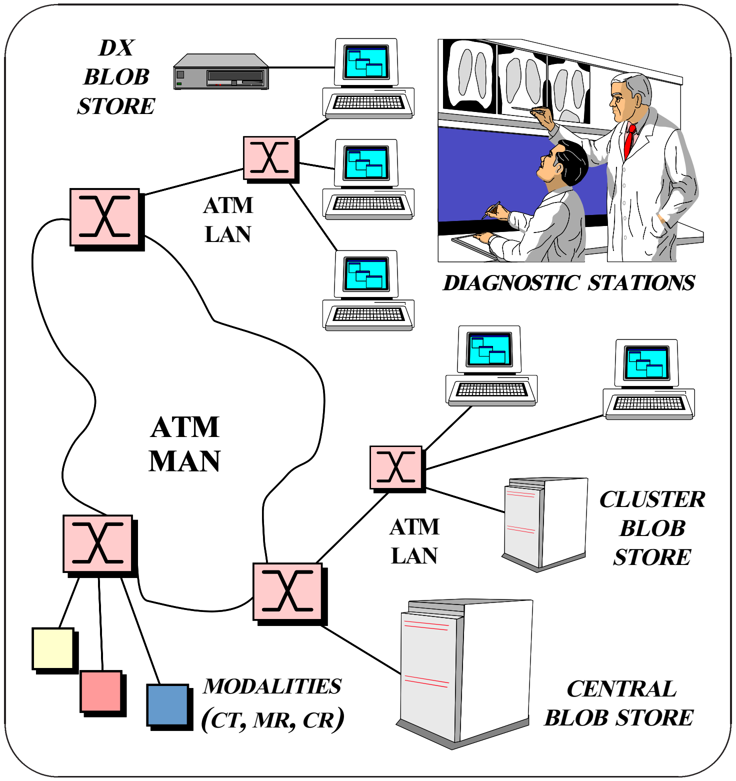
www.cs.wustl.edu/∼schmidt/JSAC-98.ps.gz

Domain Challenges

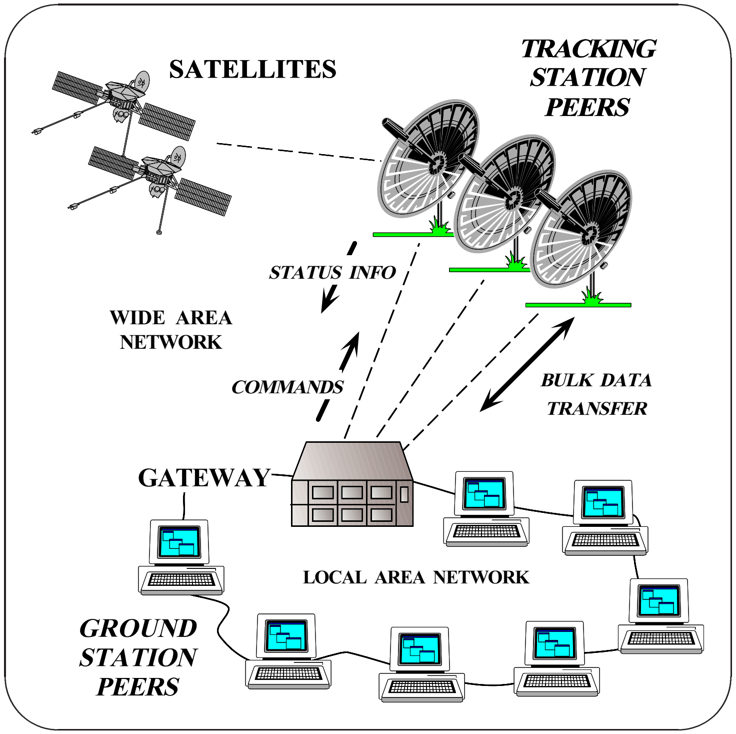
- Deterministic & statistical real-time deadlines
- Periodic & aperiodic processing
- COTS and open systems
- Reusable components
- Support platform upgrades

www.cs.wustl.edu/∼schmidt/TAO-boeing.html

Applying TAO to Other Performance-Sensitive Applications

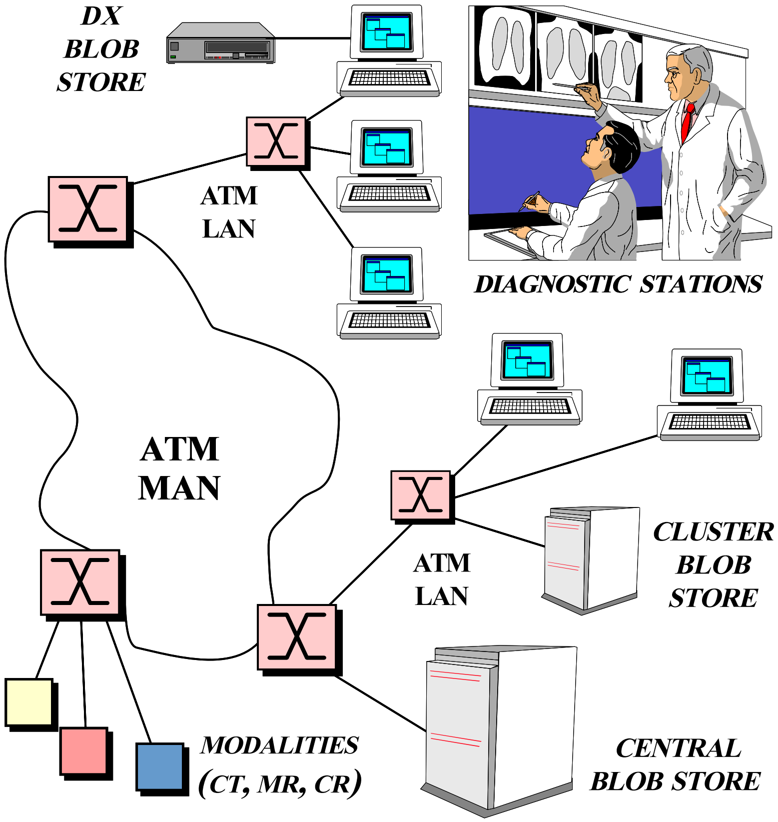


Medical Imaging



Satellite Surveillance

Problem: Optimizing Complex Software



www.cs.wustl.edu/∼schmidt/
JSAC-99.ps.gz

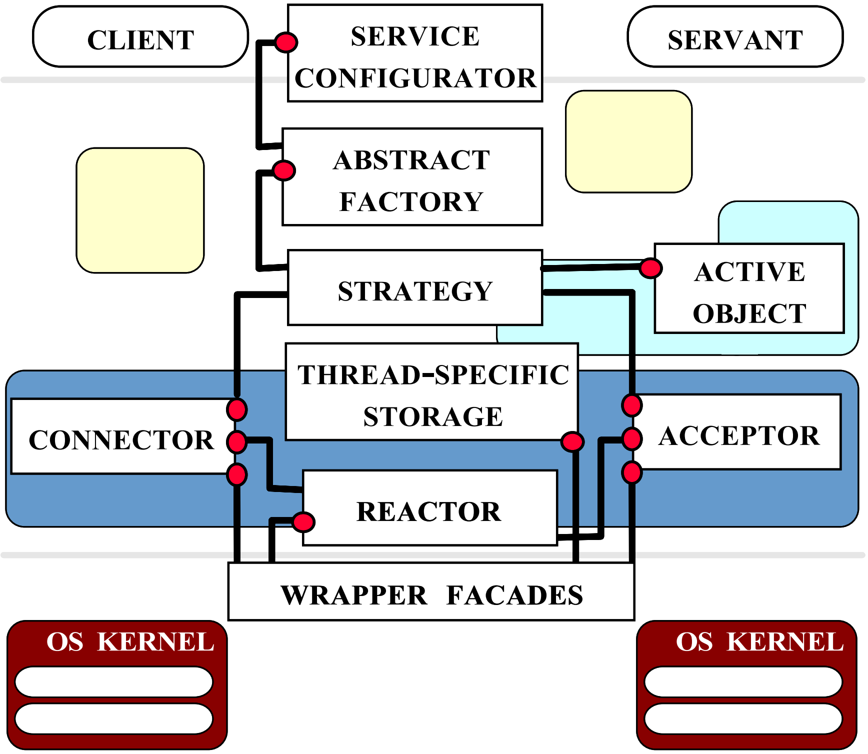
Common Problems →

- Optimizing complex software is hard
- Small “mistakes” can be costly

Solution Approach (Iterative) →

- Pinpoint overhead via *white-box* metrics
  - *e.g.*, `Quantify` and `VMEtro`
- Apply patterns and framework components
- Revalidate via white-box and black-box metrics

Solution 1: Patterns and Framework Components



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

Definitions

- *Pattern*
  - A solution to a problem in a context
- *Framework*
  - A “semi-complete” application built with components
- *Components*
  - Self-contained, “pluggable” ADTs

Solution 2: ORB Optimization Principle Patterns

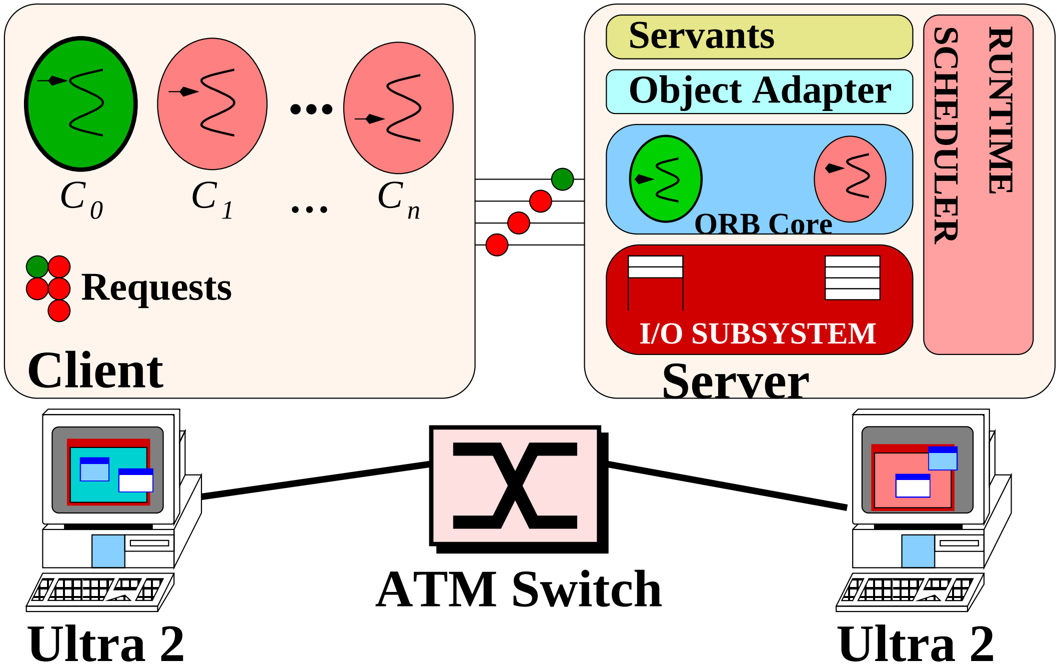
Definition

- ***Optimization principle patterns*** document rules for avoiding common design and implementation problems that can degrade the performance, scalability, and predictability of complex systems

Key Principle Patterns Used in TAO

#	**Principle Pattern**
1	Optimize for the common case
2	Remove gratuitous waste
3	Replace inefficient general-purpose functions with efficient special-purpose ones
4	Shift computation in time, *e.g.*, precompute
5	Store redundant state to speed-up expensive operations
6	Pass hints between layers and components
7	Don't be tied to reference implementations/models
8	Use efficient/predictable data structures

ORB Latency and Priority Inversion Experiments

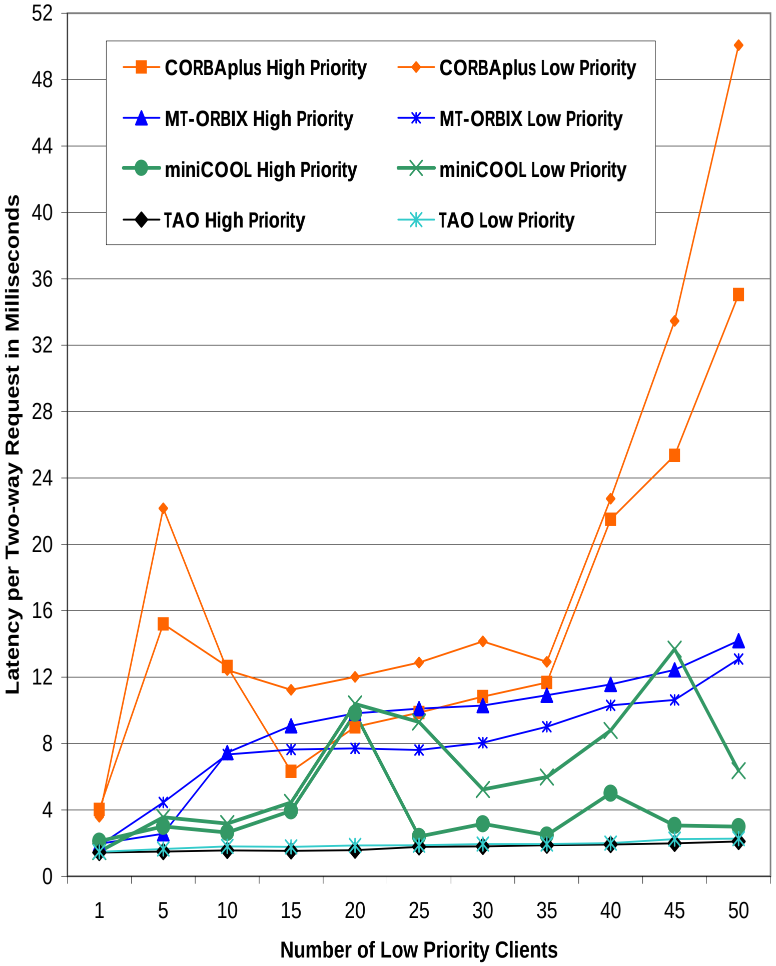


www.cs.wustl.edu/∼schmidt/RT-perf.ps.gz

Method

- Vary ORBs, hold OS constant
- Solaris real-time threads
- High priority client C_0 connects to servant S_0 with matching priorities
- Clients $C_1 \ldots C_n$ have same lower priority
- Clients $C_1 \ldots C_n$ connect to servant S_1
- Clients invoke two-way CORBA calls that cube a number on the servant and returns result

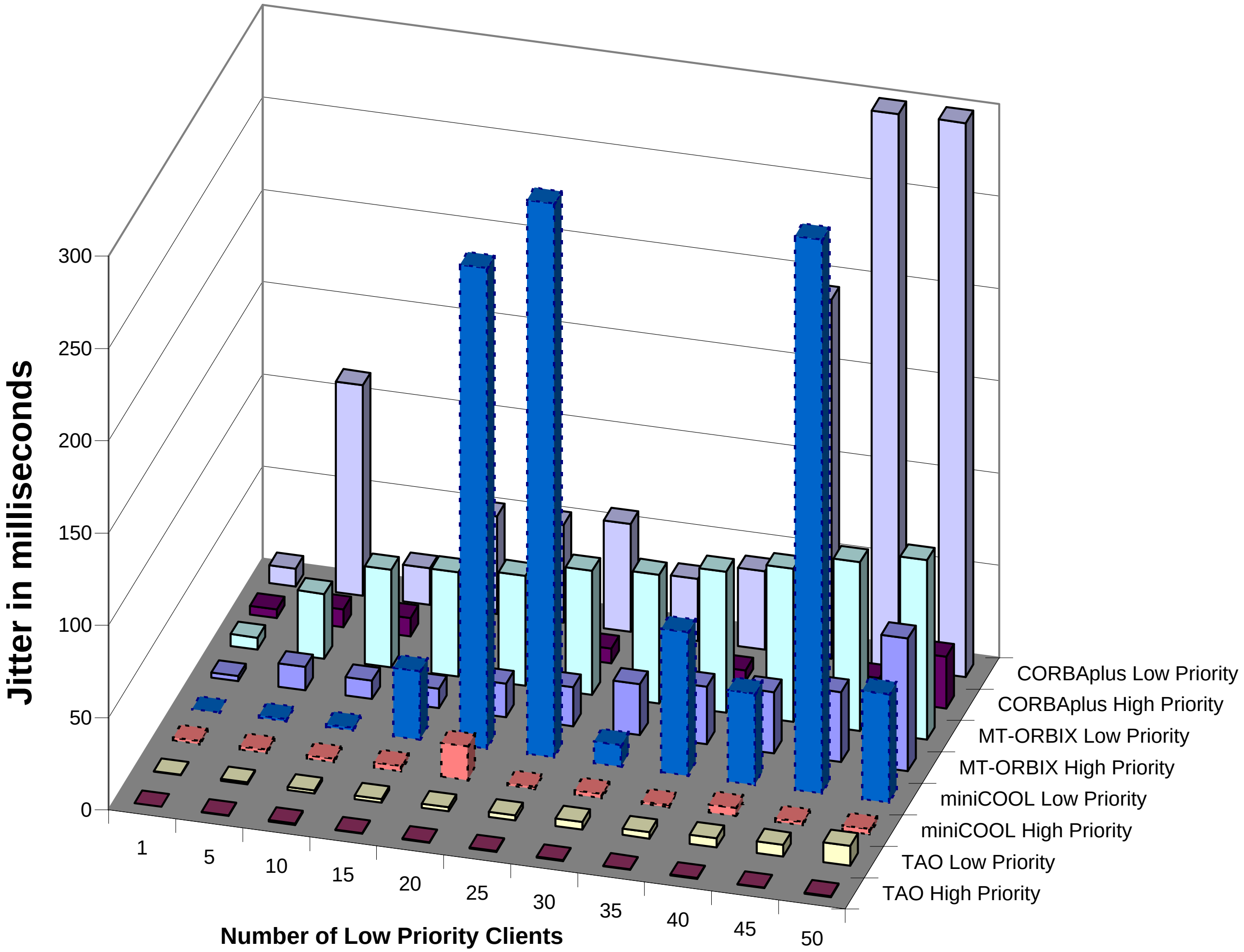
ORB Latency and Priority Inversion Results



Synopsis of Results

- TAO's latency is lowest for large # of clients
- TAO avoids priority inversion
  - *i.e.*, high priority client always has lowest latency
- Primary overhead stems from *concurrency* and *connection* architecture
  - *e.g.*, synchronization and context switching

ORB Jitter Results



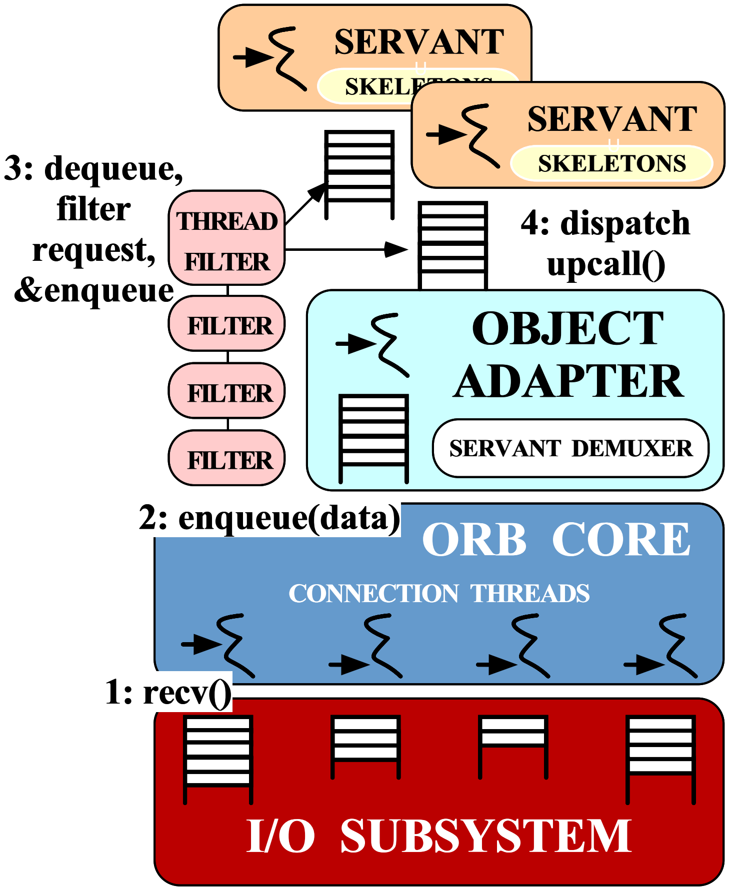
Definition

- Jitter → standard deviation from average latency

Synopsis of Results

- TAO's jitter is lowest and most consistent
- CORBAplus' jitter is highest and most variable

Problem: Improper ORB Concurrency Models

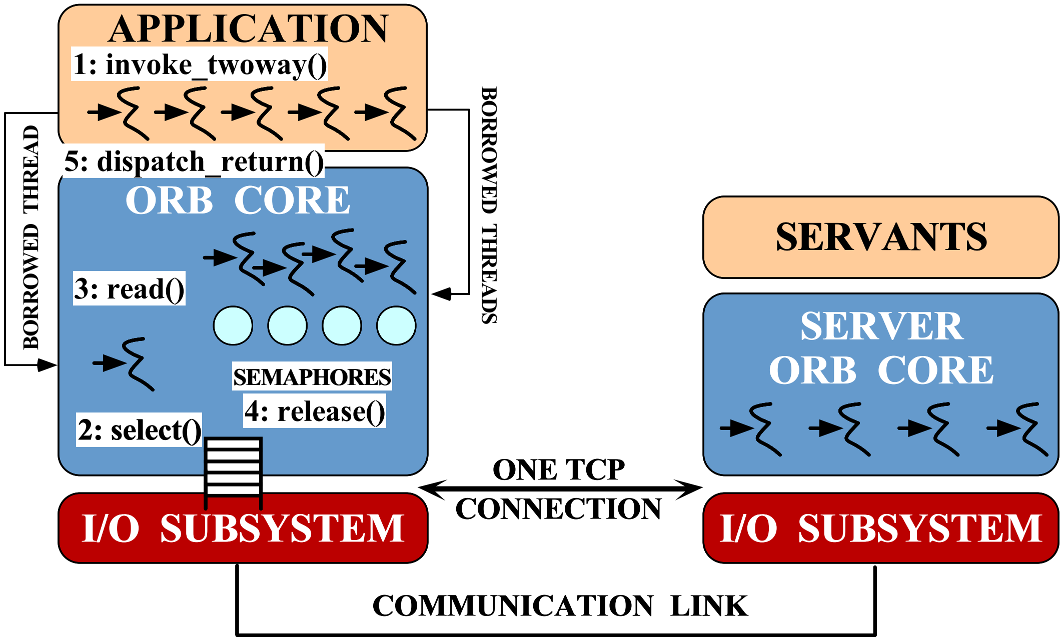


Common Problems

- High context switching and synchronization overhead
- Thread-level and packet-level priority inversions
- Lack of application control over concurrency model

www.cs.wustl.edu/∼schmidt/CACM-arch.ps.gz

Problem: ORB Shared Connection Models



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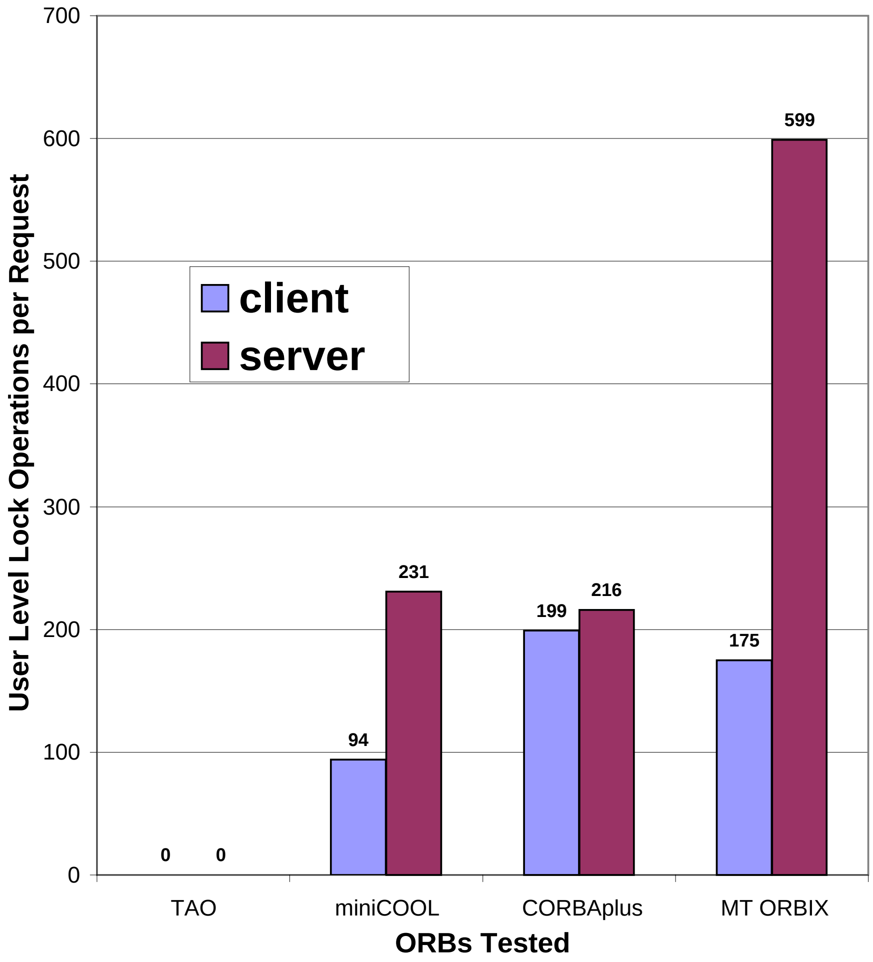
RTAS-98.ps.gz

Common Problems

- Request-level priority inversions
  - Sharing multiple priorities on a single connection
- Complex connection multiplexing
- Synchronization overhead

Problem: High Locking Overhead



Common Problems

- Locking overhead affects latency and jitter significantly
- Memory management commonly involves locking

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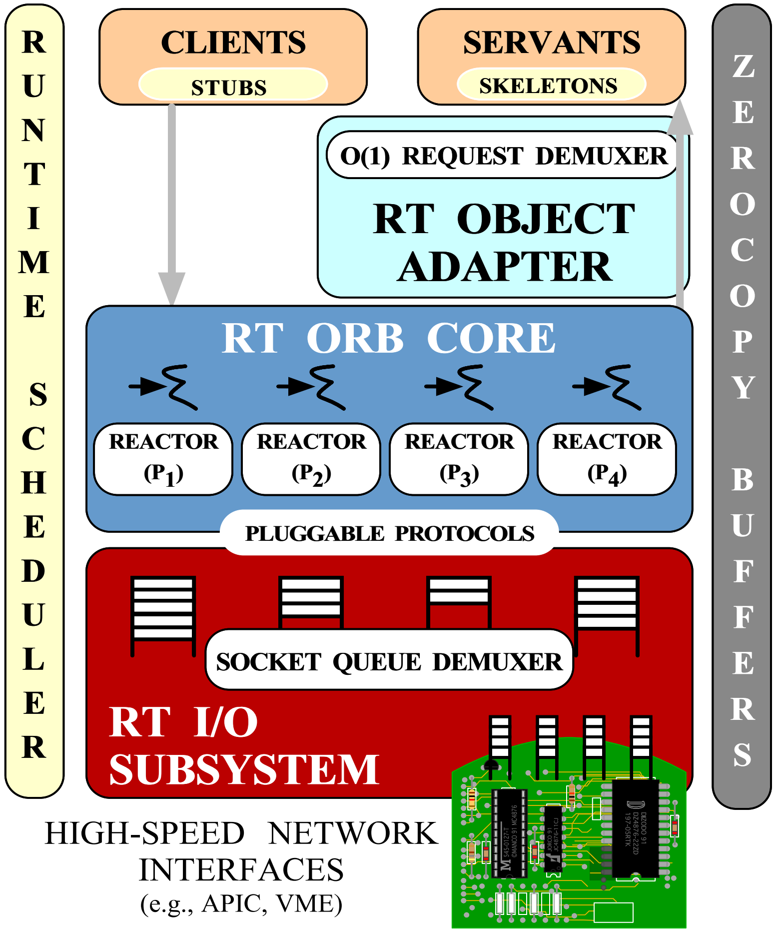
RTAS-98.ps.gz

Solution: TAO's ORB Endsystem Architecture



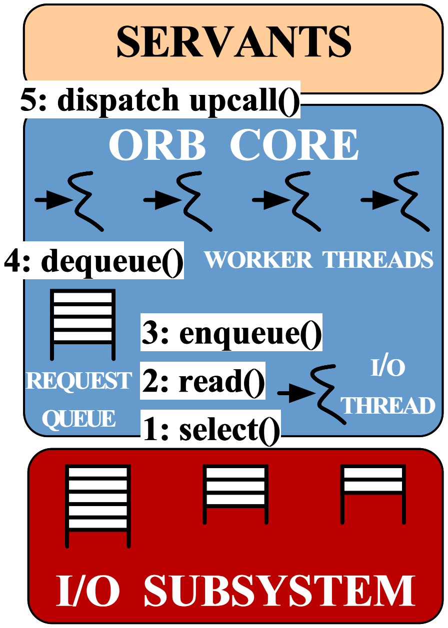
Solution Approach →

- Integrate scheduler into ORB endsystem
- Co-schedule threads
- Leader/followers thread pool

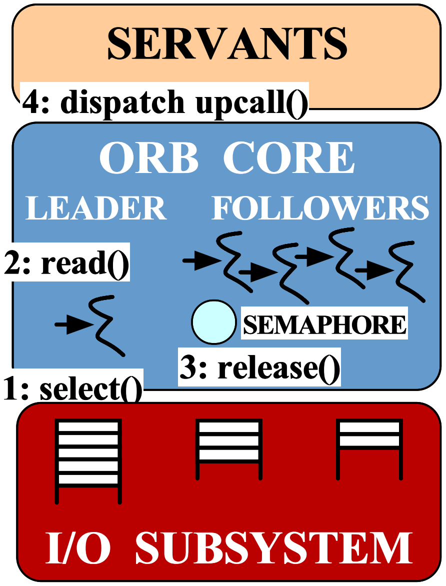
Principle Patterns →

- Pass hints, precompute, optimize common case, remove gratuitous waste, store state, don't be tied to reference implementations & models

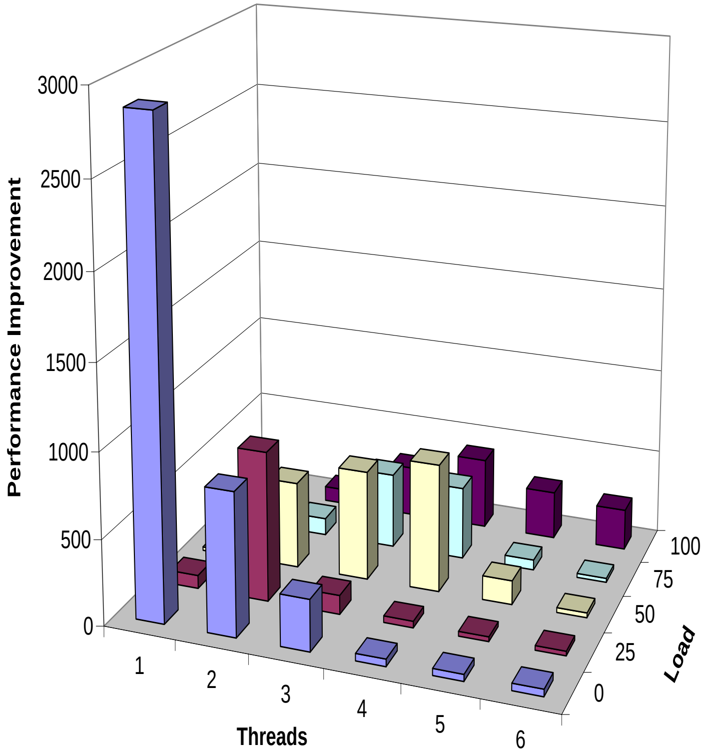
Thread Pool Comparison Results



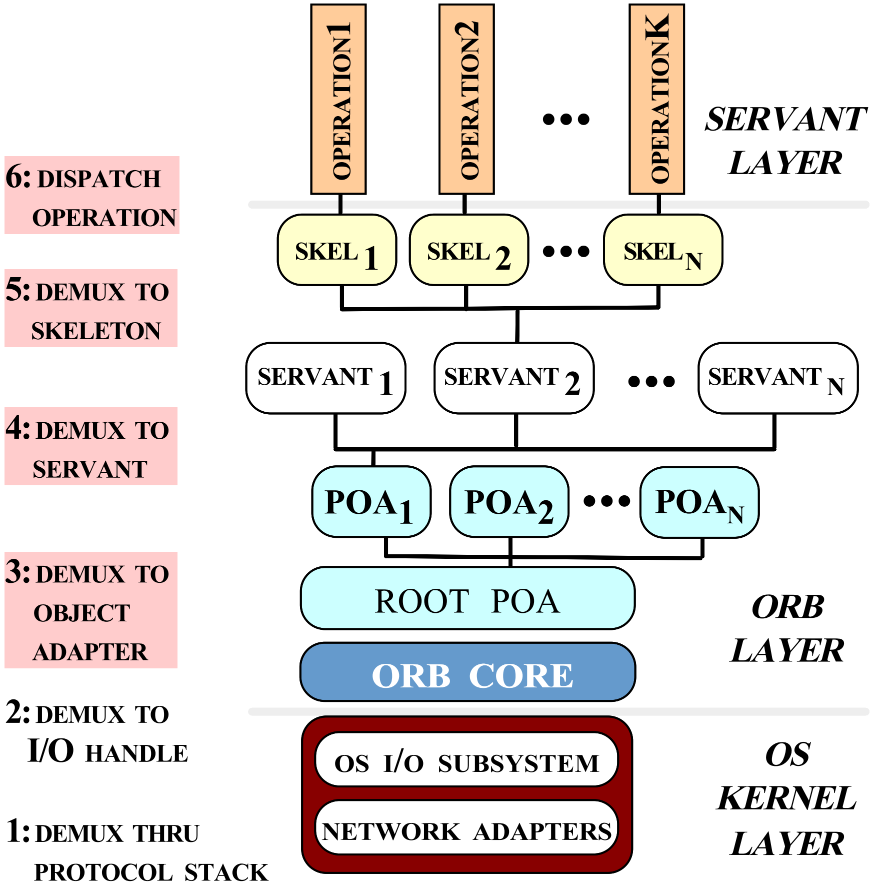
Worker Thread Pool



Leader/Follower Thread Pool



Problem: Reducing Demultiplexing Latency

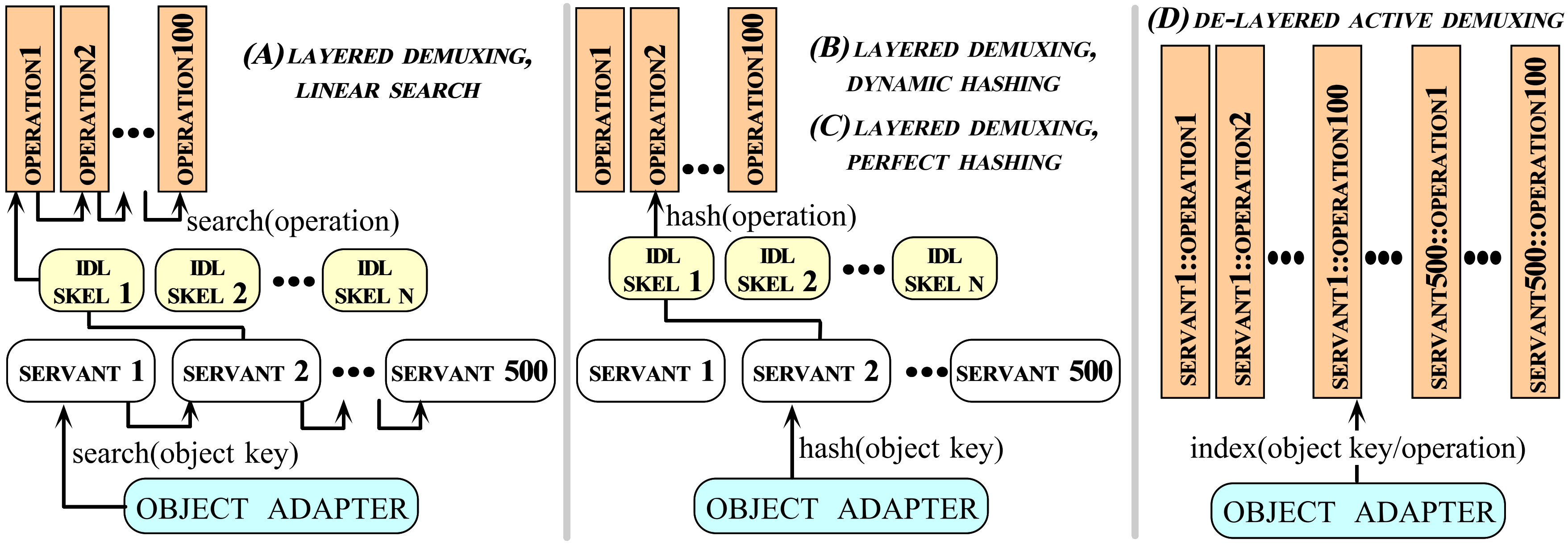


Design Challenges

- Minimize demuxing layers
- Provide $O(1)$ operation demuxing through all layers
- Avoid priority inversions
- Remain CORBA-compliant

www.cs.wustl.edu/∼schmidt/POA.ps.gz

Solution: TAO's Request Demultiplexing Optimizations



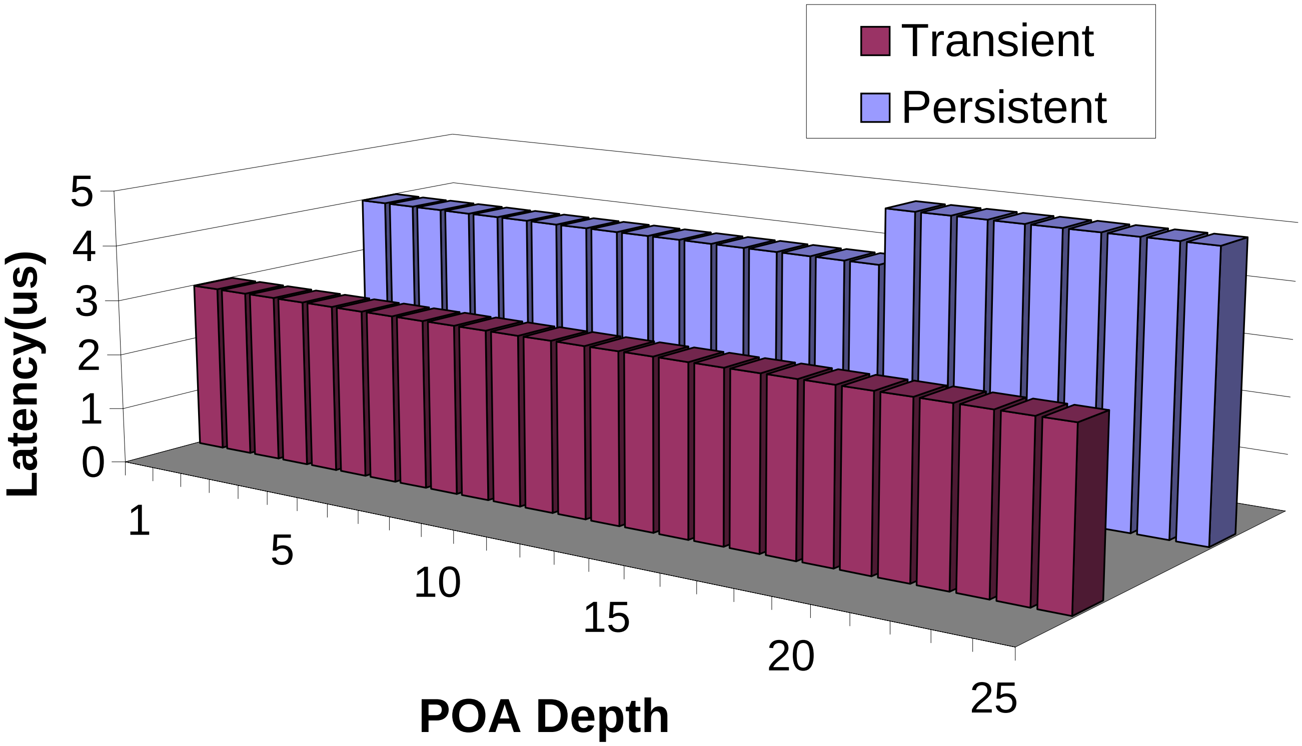
Demuxing

- www.cs.wustl.edu/∼schmidt/{ieee_tc-97,COOTS-99}.ps.gz

Perfect hashing

- www.cs.wustl.edu/∼schmidt/gperf.ps.gz

POA Demultiplexing Results



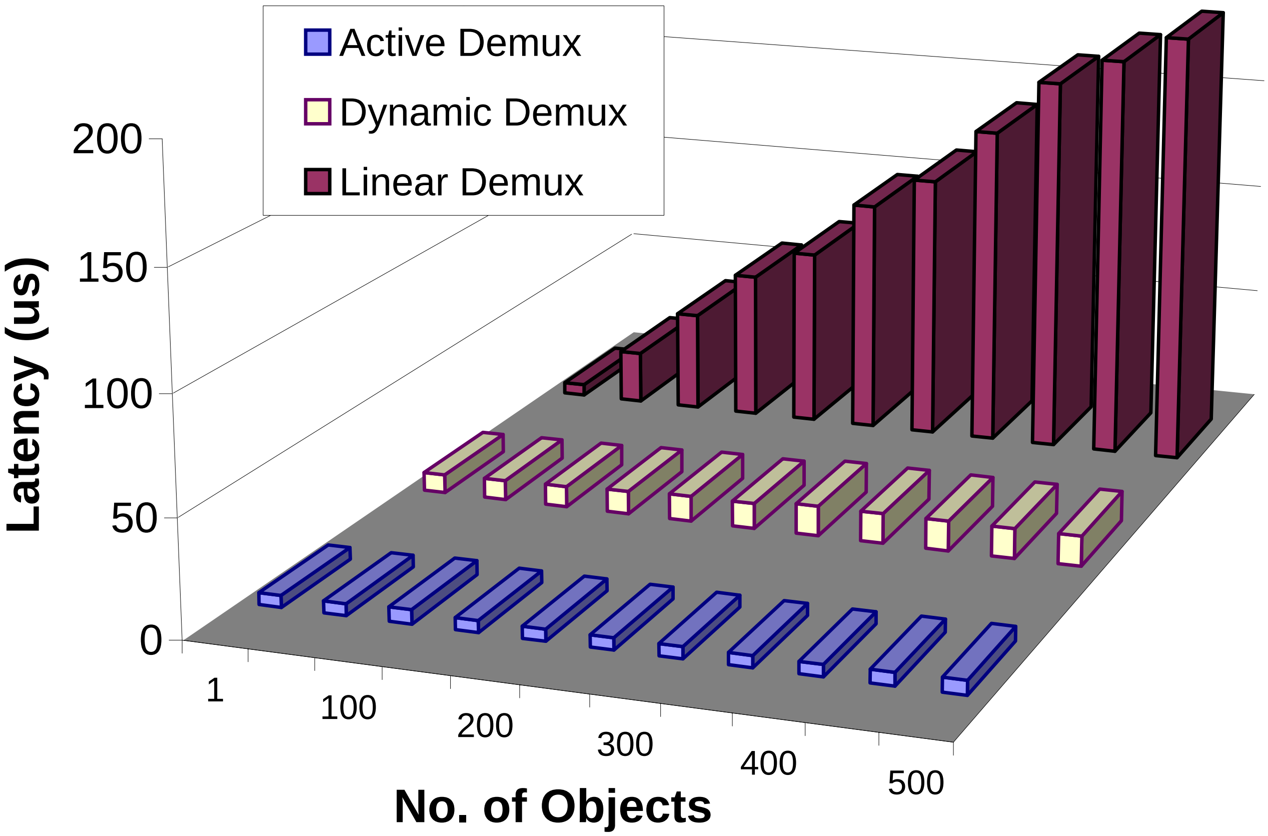
Synopsis of Results

- Active demux is efficient & predictable for both transient and persistent object references.

Principle Patterns

- Precompute, pass hints, use special-purpose & predictable data structures

Servant Demultiplexing Results



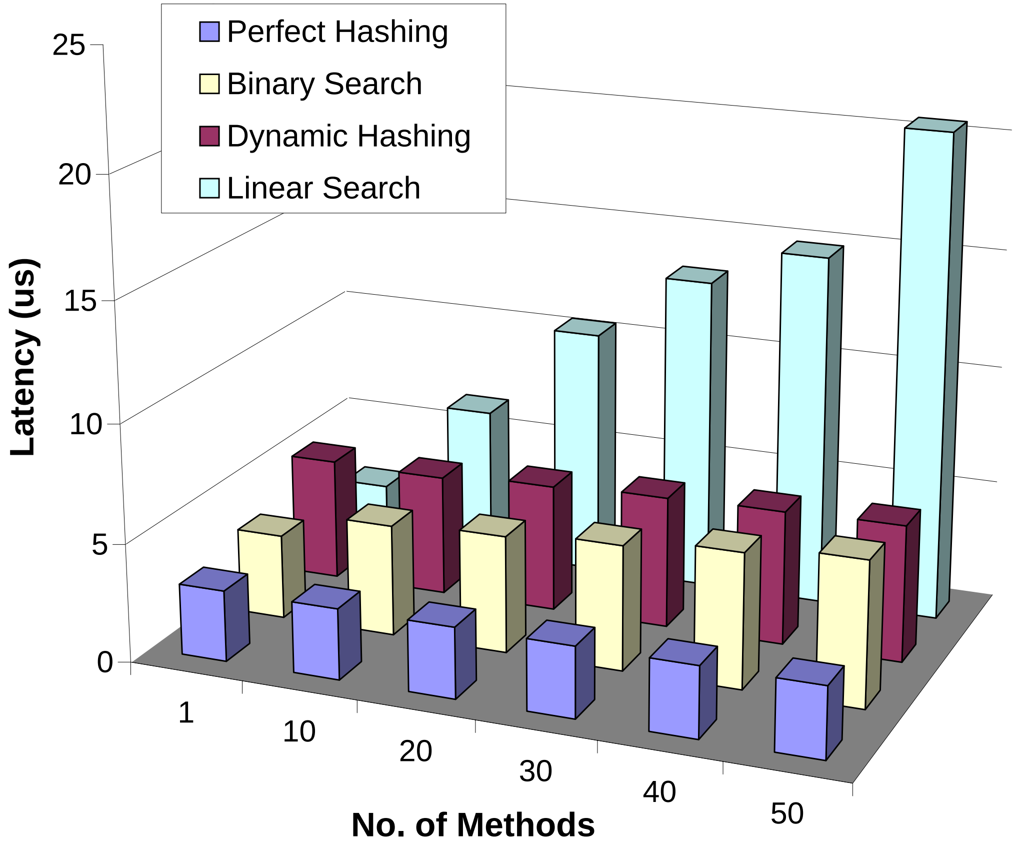
Synopsis of Results

- Linear demux is costly
- Active demux is most efficient & predictable

Principle Patterns

- Precompute, pass hints, use special-purpose & predictable data structures

Operation Demultiplexing Results



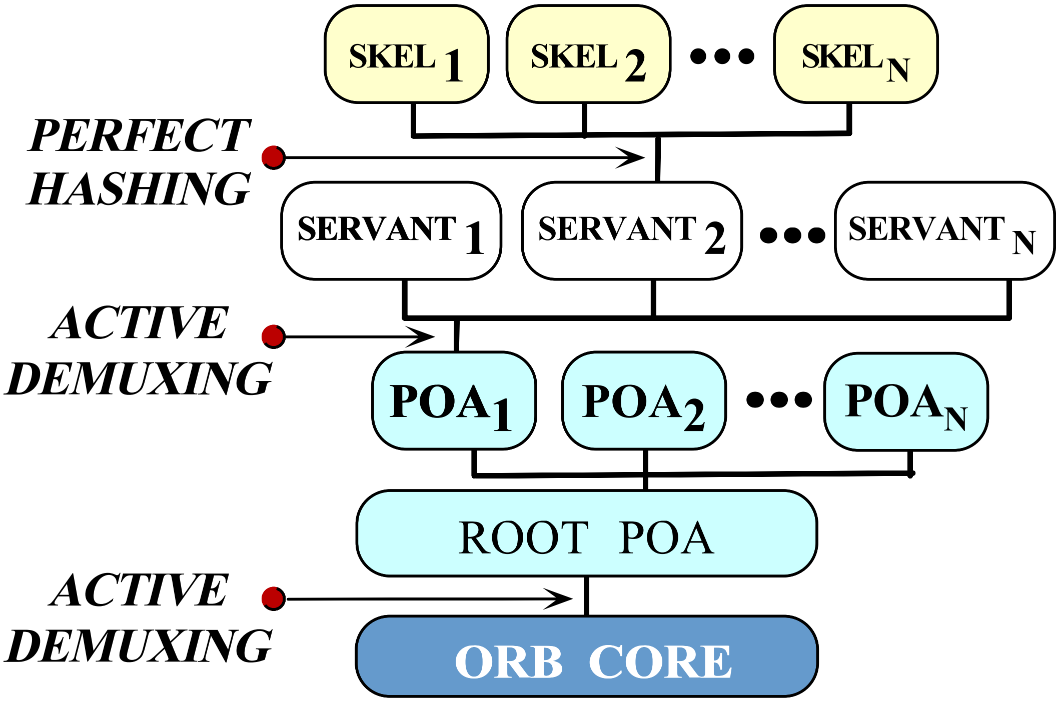
Synopsis of Results →

- Perfect Hashing
  - Highly predictable
  - Low-latency
- Others strategies slower

Principle Patterns →

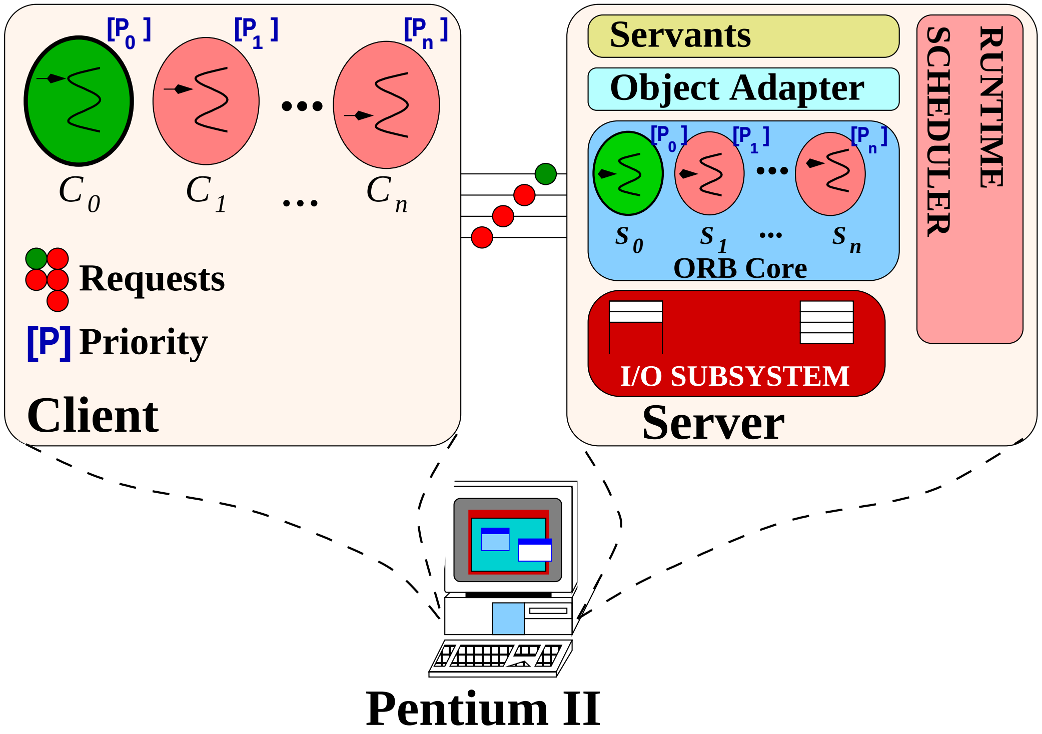
- Precompute, use predictable data structures, remove gratuitous waste

TAO Request Demultiplexing Summary



Demultiplexing Stage	Absolute Time (μs)
1. Request parsing	2
2. POA demux	2
3. Servant demux	3
4. Operation demux	2
5. Parameter demarshaling	operation dependent
6. User upcall	servant dependent
7. Results marshaling	operation dependent

Real-time ORB/OS Performance Experiments

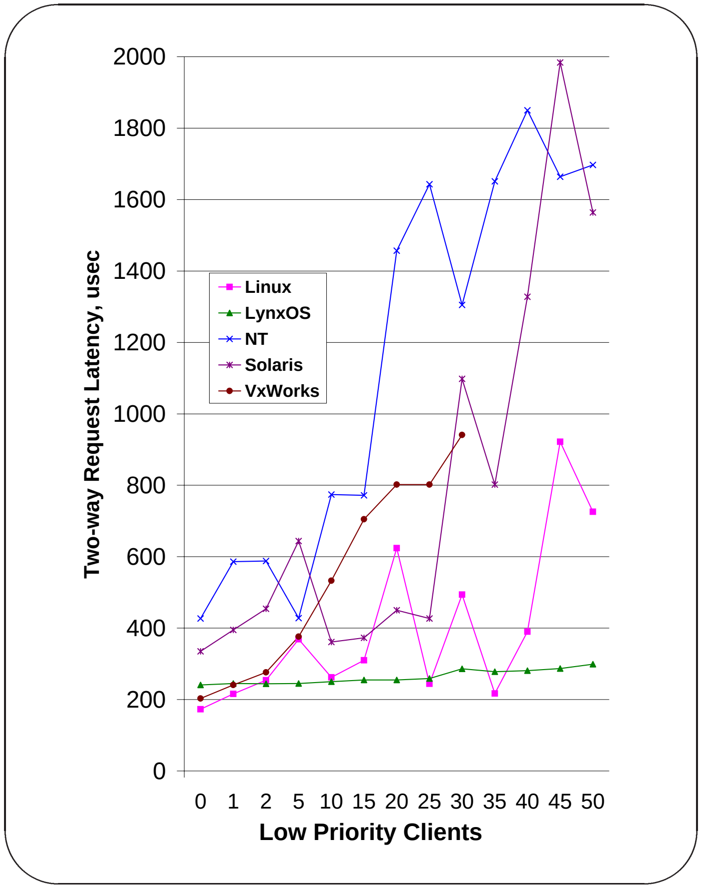


www.cs.wustl.edu/∼schmidt/RT-OS.ps.gz

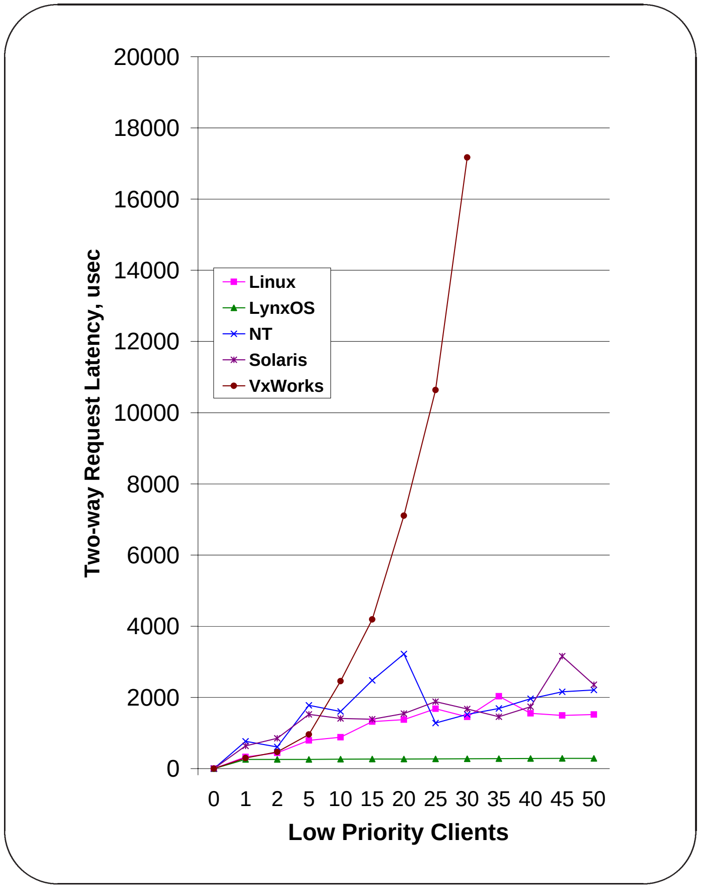
Method

- Vary OS, hold ORBs constant
- Single-processor Intel Pentium II 450 Mhz, 256 Mbytes of RAM
- Client and servant run on the same machine
- Client C_i connects to servant S_i with priority P_i
  - i ranges from $1 \ldots 50$
- Clients invoke two-way CORBA calls that cube a number on the servant and returns result

Real-time ORB/OS Performance Results

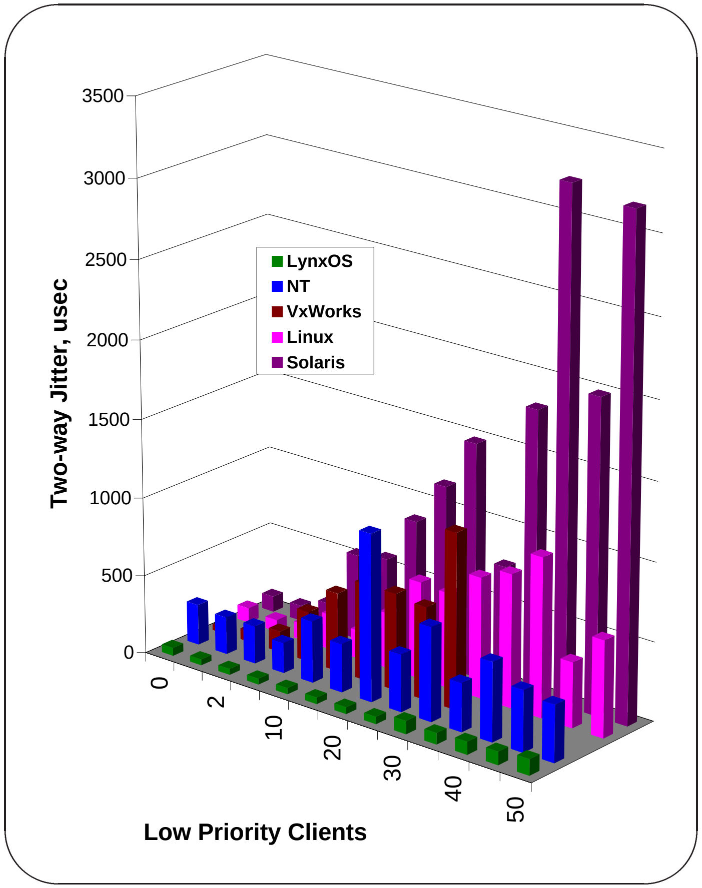


High-priority Client Latency

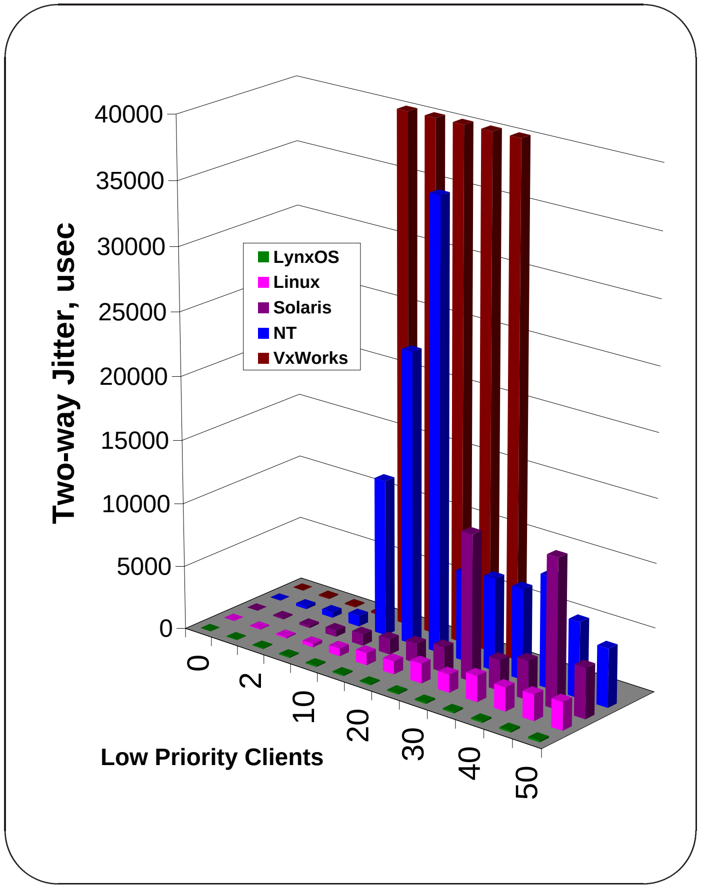


Low-priority Clients Latency

Real-time ORB/OS Jitter Results

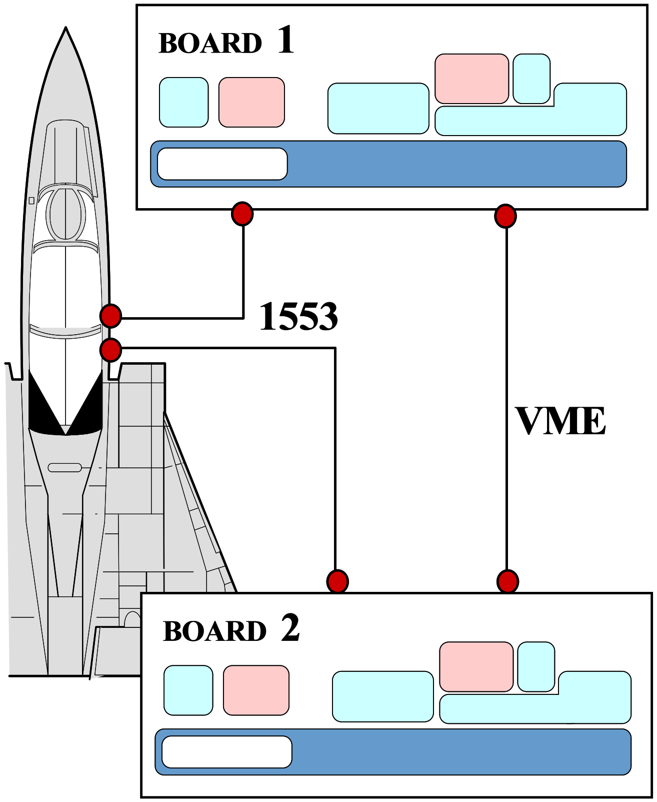


High-priority Client Jitter



Low-priority Clients Jitter

Problem: Hard-coded ORB Messaging and Transport Protocols



- GIOP/IIOP are not sufficient, *e.g.*:
  - GIOP message footprint may be too large
  - TCP lacks necessary QoS
  - Legacy commitments to existing protocols
- Many ORBs do not support "pluggable protocols"
  - This makes ORBs inflexible and inefficient

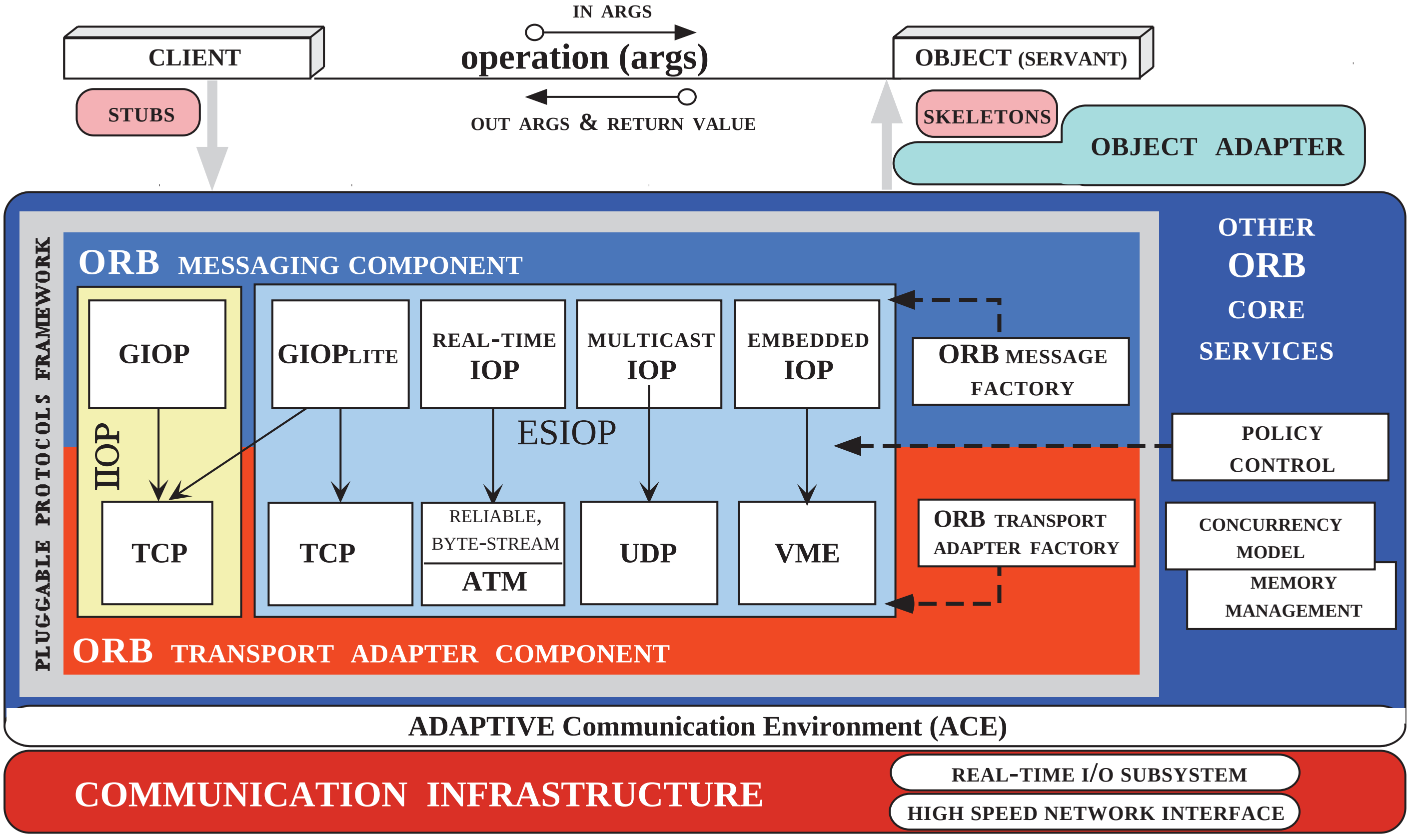
One Solution: Hacking GIOP

- GIOP requests include fields that aren’t needed in homogeneous embedded applications
  - *e.g.*, GIOP magic #, GIOP version, byte order, request principal, etc.
- These fields can be omitted without any changes to the standard CORBA programming model
- TAO’s `-ORBgioplite` option save 15 bytes per-request, yielding these calls-per-second:

	Marshaling-enabled			**Marshaling-disabled**		
	min	max	avg	min	max	avg
GIOP	2,878	2,937	2,906	2,912	2,976	2,949
GIOPlite	2,883	2,978	2,943	2,911	3,003	2,967

- The result is a measurable improvement in throughput/latency
  - However, it’s so small (2%) that hacking GIOP is of minimal gain except for low-bandwidth links

Better Solution: TAO's Pluggable Protocols Framework



IN ARGS

CLIENT

operation (args)

OBJECT (SERVANT)

STUBS

OUT ARGS & RETURN VALUE

SKELETONS

OBJECT ADAPTER

PLUGGABLE PROTOCOLS FRAMEWORK

ORB MESSAGING COMPONENT

GIOP

IIOP

TCP

GIOPLITE

TCP

REAL-TIME IOP

RELIABLE, BYTE-STREAM

ATM

MULTICAST IOP

UDP

EMBEDDED IOP

VME

ESIOP

ORB MESSAGE FACTORY

ORB TRANSPORT ADAPTER FACTORY

ORB TRANSPORT ADAPTER COMPONENT

OTHER ORB CORE SERVICES

POLICY CONTROL

CONCURRENCY MODEL

MEMORY MANAGEMENT

ADAPTIVE Communication Environment (ACE)

COMMUNICATION INFRASTRUCTURE

REAL-TIME I/O SUBSYSTEM

HIGH SPEED NETWORK INTERFACE

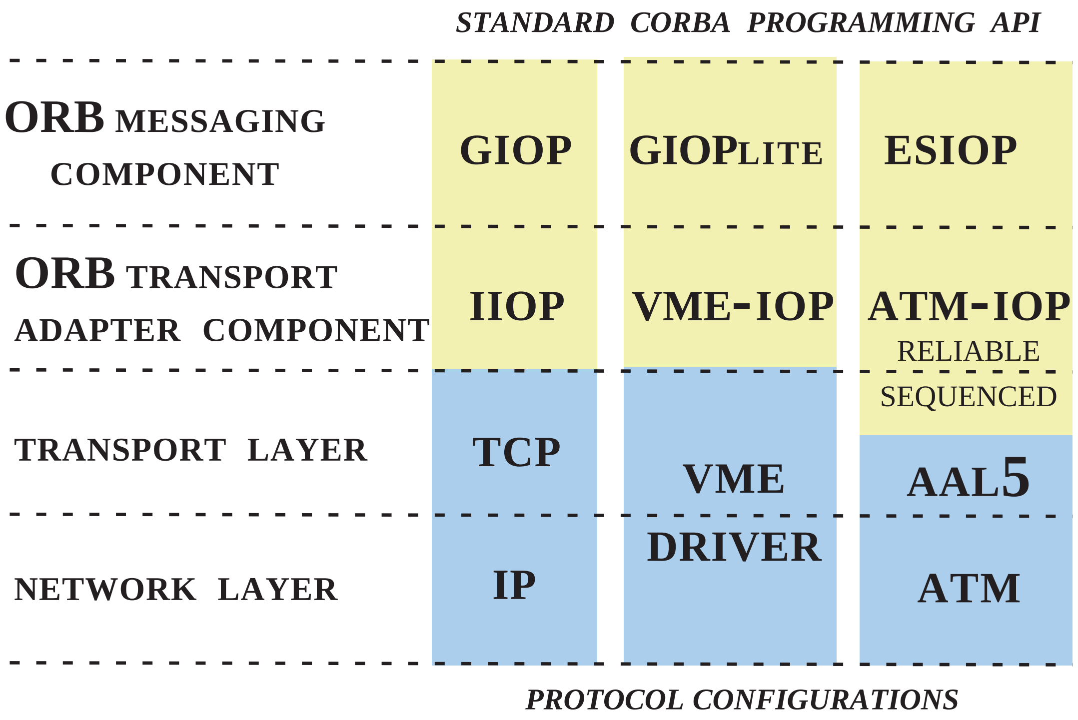
Features

- Pluggable *ORB messaging* and *transport* protocols
- Highly efficient and predictable behavior

Principle Patterns

- Replace general-purpose functions (protocols) with special-purpose ones

CORBA Protocol Interoperability Architecture

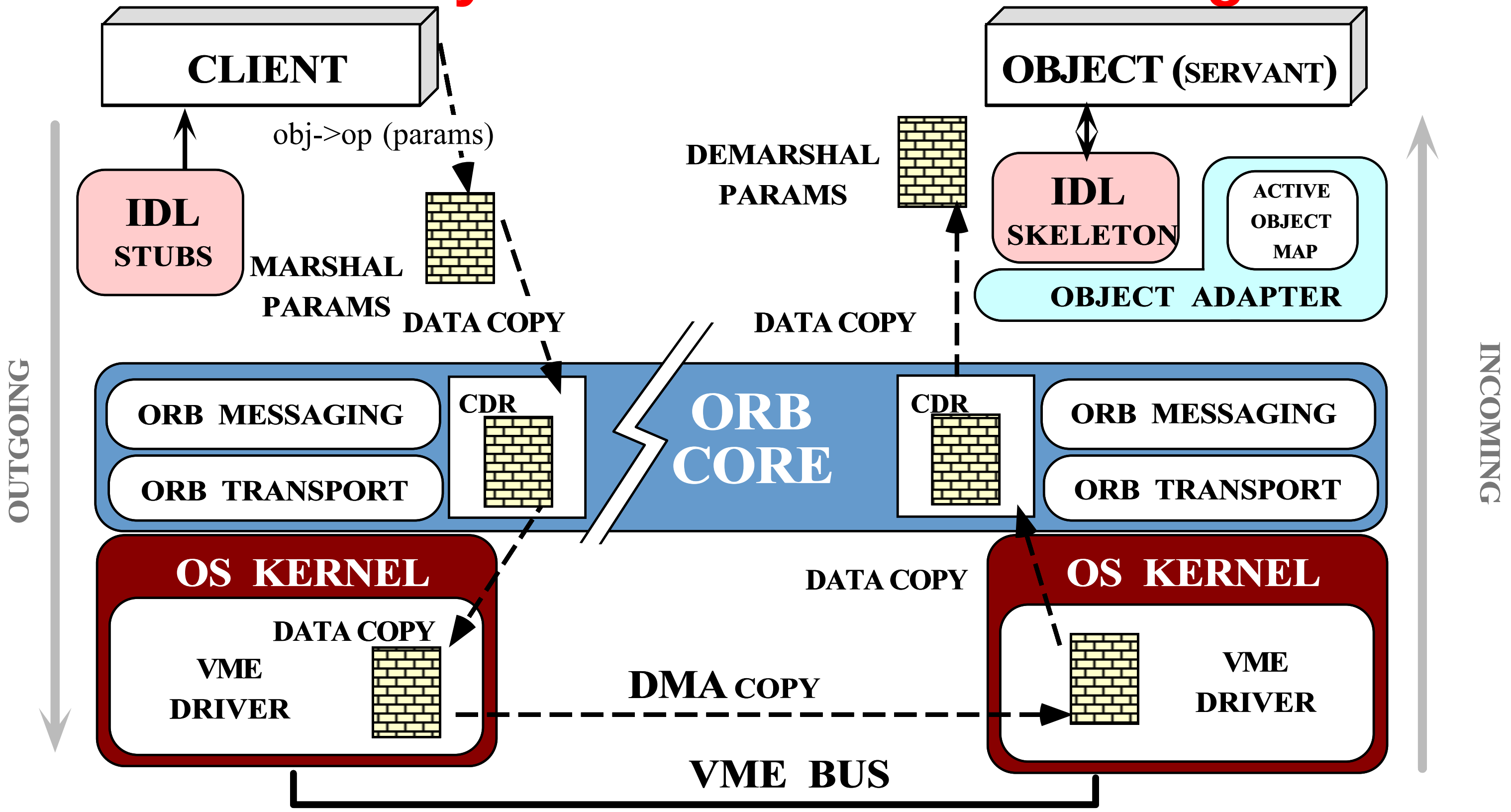


Features →

- Presentation layer
  - *e.g.*, CDR
- Message formats
  - *e.g.*, GIOP
- Transport assumptions
  - *e.g.*, TCP
- Object addressing
  - *e.g.*, IIOP IOR

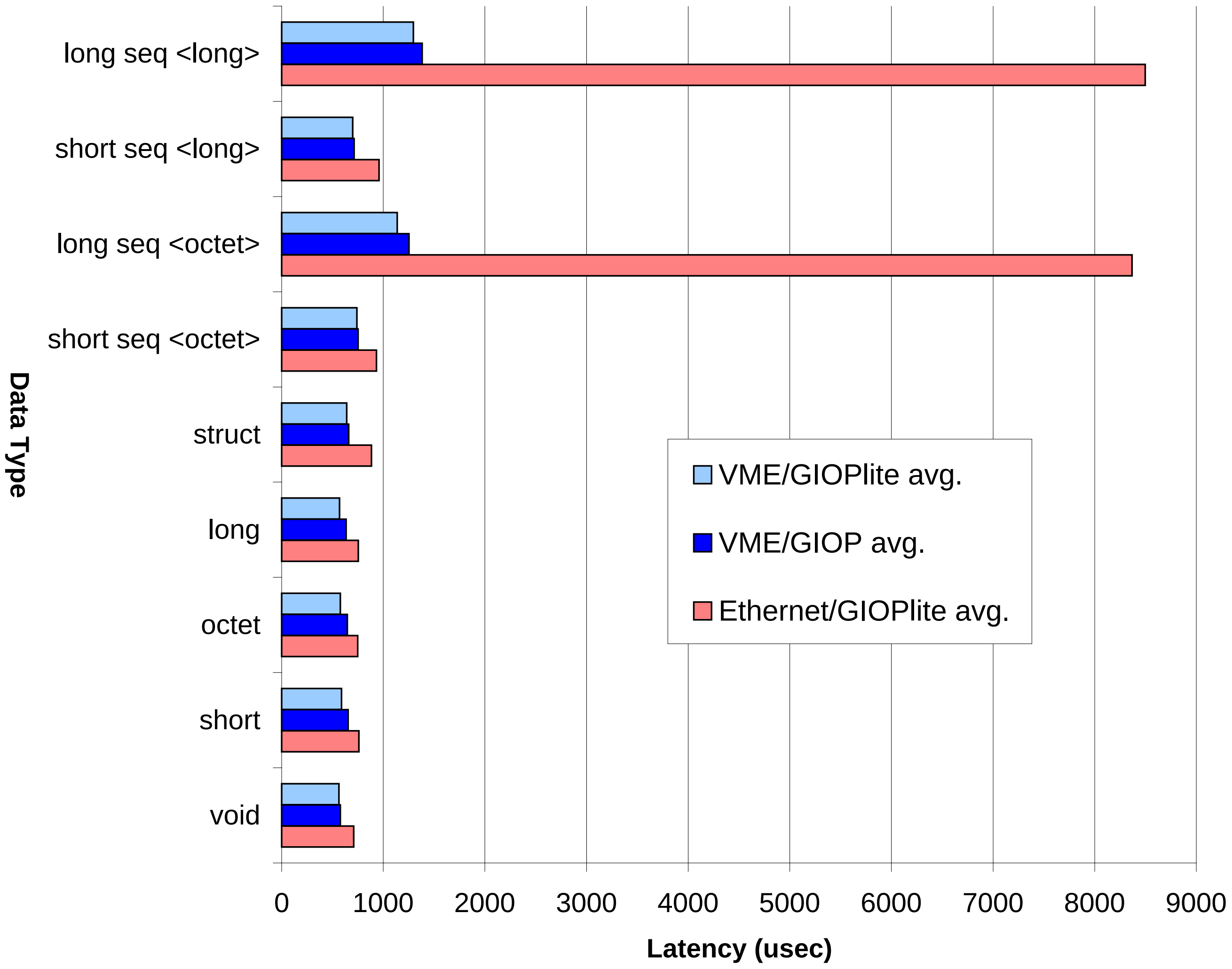
www.cs.wustl.edu/∼schmidt/pluggable_protocols.ps.gz

Embedded System Benchmark Configuration



VxWorks running on 200 Mhz PowerPC over a 320 Mbps VME & 10 Mbps Ethernet

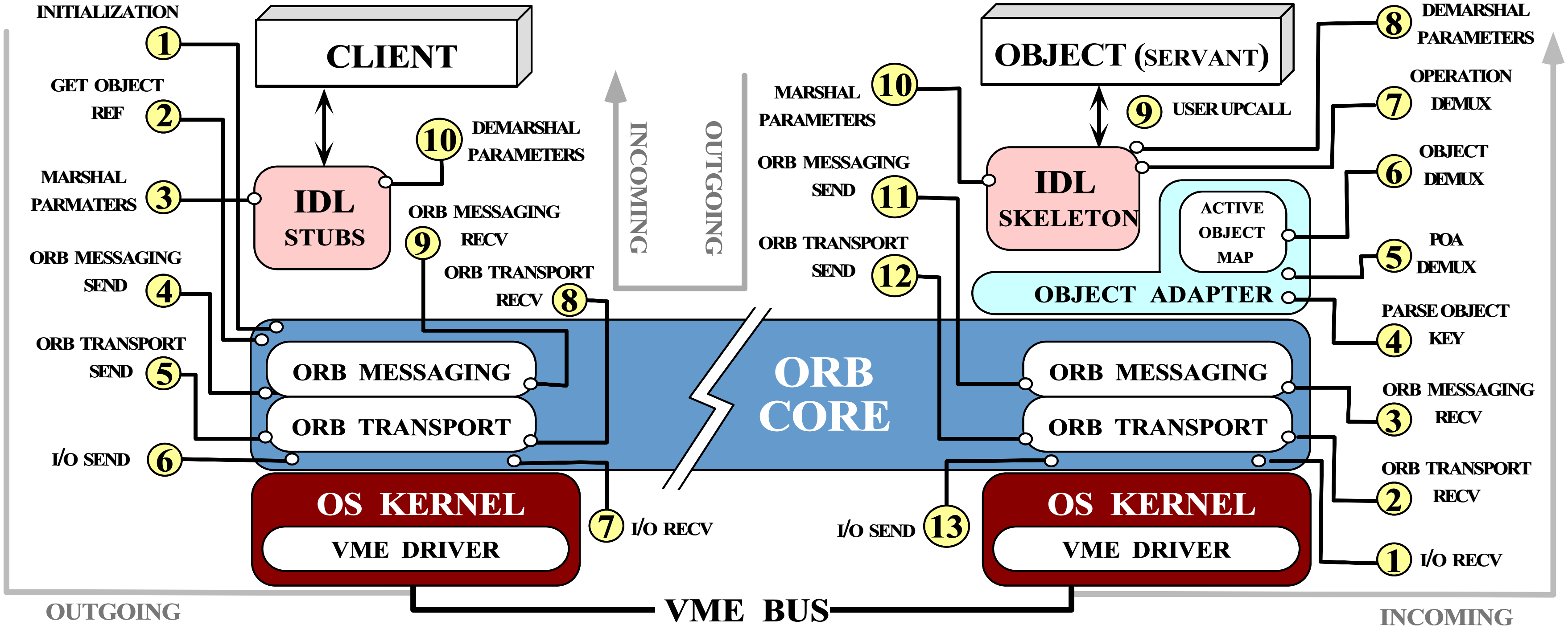
Ethernet & VME Two-way Latency Results



Synopsis of Results

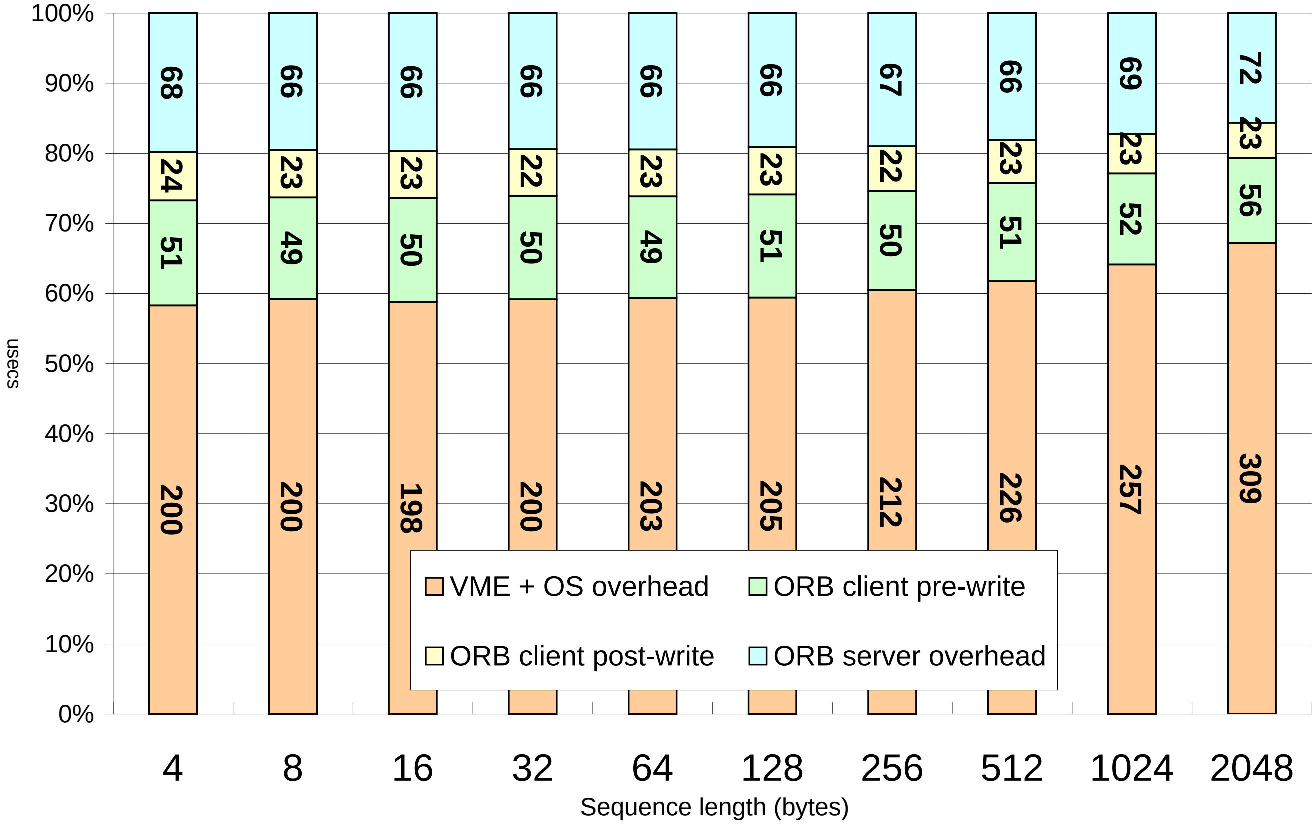
- VME protocol is much faster than Ethernet
- No application changes are required to support VME

Pinpointing ORB Overhead with VMEtro Timeprobes



- Timeprobes use VMEtro monitor, which measures end-to-end time
- Timeprobe overhead is minimal, *i.e.*, 1 μsec

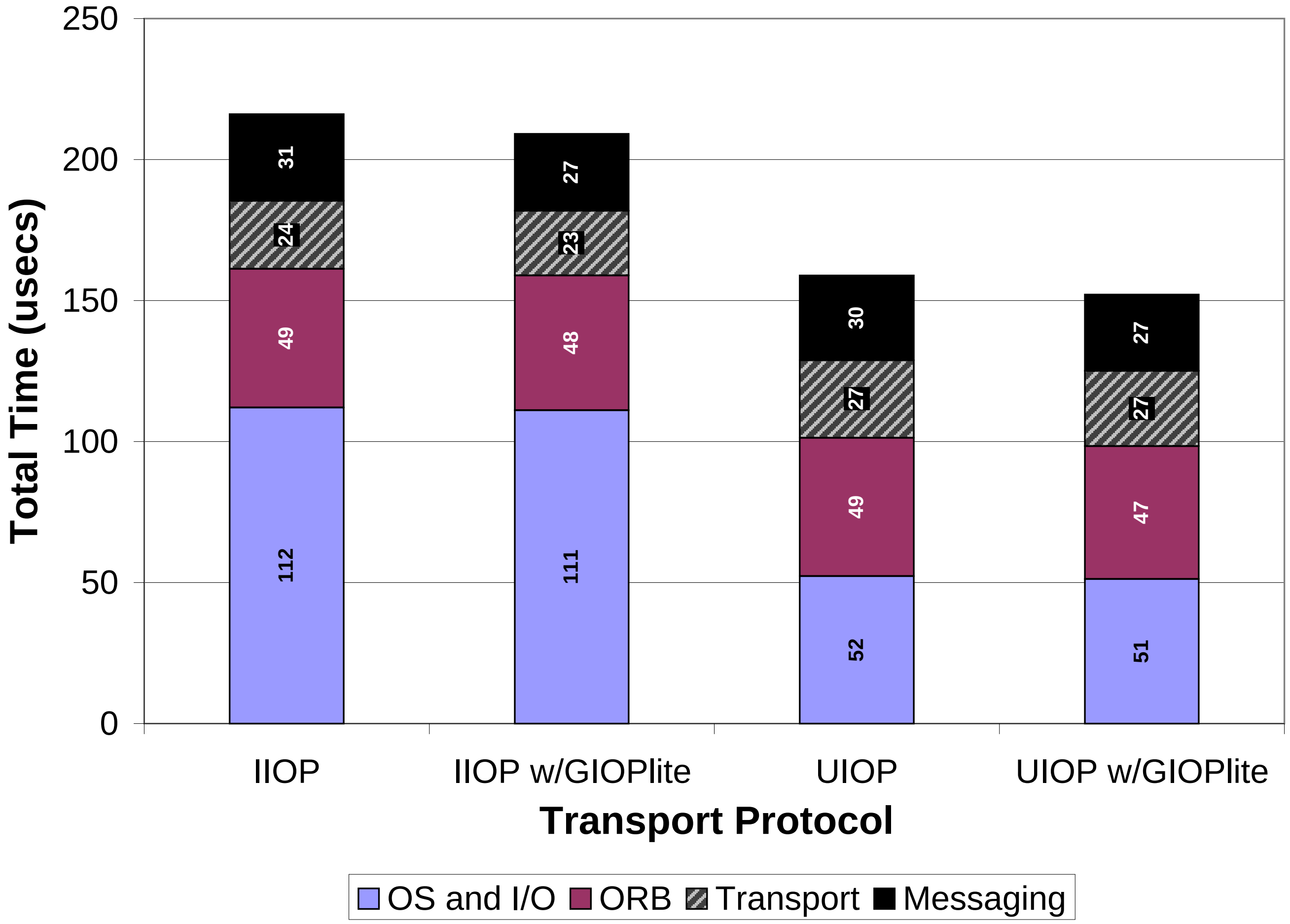
ORB & VME One-way Overhead Results



Synopsis of Results

- ORB overhead is relatively constant and low
  - *e.g.*, ∼110 μsecs per end-to-end operation
- Bottleneck is VME driver and OS, not ORB

ORB & Transport Overhead Results

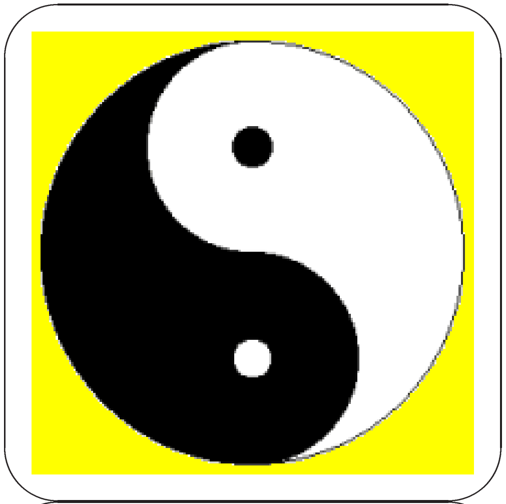


Synopsis of Results

- ORB overhead is relatively constant and low
  - *e.g.*, ~49 μsecs per two-way operation
- Bottleneck is OS and I/O operation

Lessons Learned Developing Real-time ORBs

- Avoid dynamic connection management
- Minimize dynamic memory management and data copying
- Avoid multiplexing connections for different priority threads
- Avoid complex concurrency models
- Integrate ORB with OS and I/O subsystem and avoid reimplementing OS mechanisms
- Guide ORB design by empirical benchmarks and patterns



Summary of TAO Research Project

Completed work

- First POA and first deployed real-time CORBA scheduling service
- Pluggable protocols framework
- Minimized ORB Core priority inversion and non-determinism
- Reduced latency via demuxing optimizations
- Co-submitters on OMG's real-time CORBA spec

Ongoing work

- Dynamic/hybrid scheduling
- Distributed QoS, ATM I/O Subsystem, & open signaling
- Implement CORBA Real-time, Messaging, and Fault Tolerance specs
- Tech. transfer via DARPA Quorum program and www.theaceorb.com
  - Integration with Flick IDL compiler, QuO, TMO, etc.

Concluding Remarks

- Researchers and developers of distributed, real-time telecom applications confront many common challenges
  - *e.g.*, service initialization and distribution, error handling, flow control, scheduling, event demultiplexing, concurrency control, persistence, fault tolerance
- Successful researchers and developers apply *patterns*, *frameworks*, and *components* to resolve these challenges
- Careful application of patterns can yield efficient, predictable, scalable, *and* flexible middleware
  - *i.e.*, middleware performance is largely an “implementation detail”
- Next-generation ORBs for telecom will be highly QoS-enabled, though many research challenges remain

Web URLs for Additional Information

- Real-time CORBA 1.0 spec:

  `www.cs.wustl.edu/~schmidt/RT-ORB-std-new.pdf.gz`

  `www.cs.wustl.edu/~schmidt/oorc.ps.gz`

- More information on TAO:

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

- TAO real-time event channel:

  `www.cs.wustl.edu/~schmidt/JSAC-98.ps.gz`

- TAO static scheduling:

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

- TAO dynamic scheduling:

  `www.cs.wustl.edu/~schmidt/dynamic.ps.gz`