Applying Patterns and Frameworks to Develop High-performance Middleware

Douglas C. Schmidt

Associate Professor &
Director of the Center for
Distributed Object computing

Computer Science Dept.
Washington University, St. Louis
www.cs.wustl.edu/∼schmidt/

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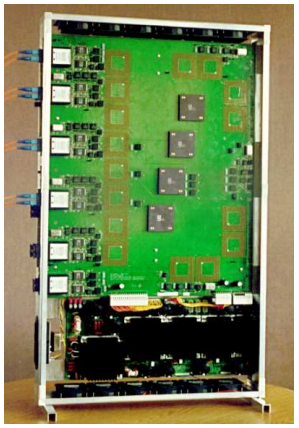
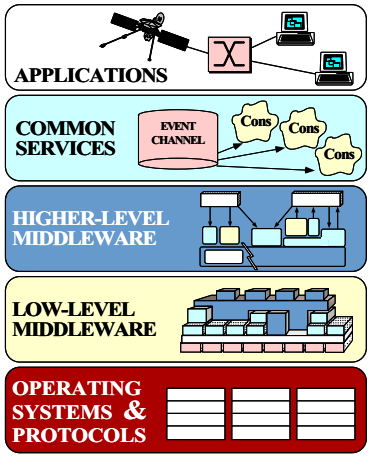
Motivation: the Communication Software Crisis



www.arl.wustl.edu/arl/

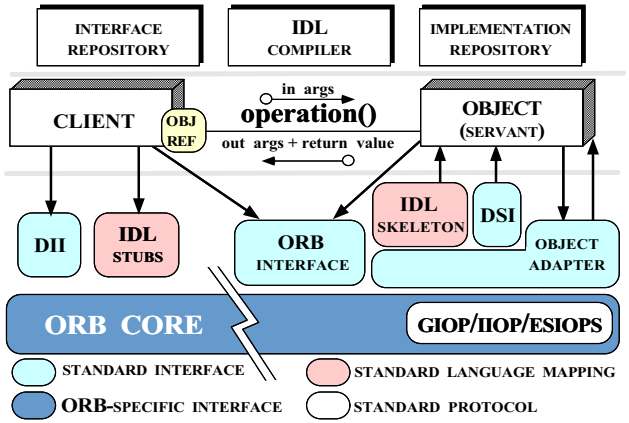
- **Symptoms**
  - Network element ***hardware*** gets smaller, faster, cheaper
  - Communication ***software*** gets larger, slower, more expensive
- **Culprits**
  - ***Inherent*** and ***accidental*** complexity
- **Solution Approach**
  - ***Standard communication middleware***

Problem: Lack of High-performance Middleware



- Many applications require performance guarantees
  - *e.g.*, avionics, interactive simulation, telecom, WWW, medical
- Building these applications manually is hard
- Existing middleware doesn't support performance effectively
  - *e.g.*, CORBA, DCOM, DCE, Java
- Solutions must be integrated horizontally & vertically

Candidate Solution: CORBA

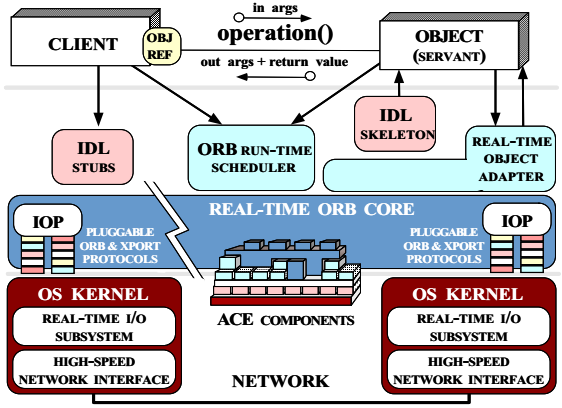


www.cs.wustl.edu/∼schmidt/corba.html

Goals of CORBA

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

Our Approach: The ACE ORB (TAO)

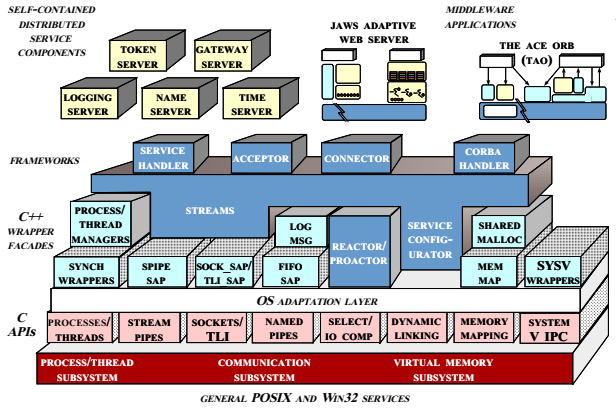


www.cs.wustl.edu/∼schmidt/TAO.html

TAO Overview →

- An open-source, standards-based, real-time, high-performance CORBA ORB
- Runs on POSIX, Win32, & embedded RT 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

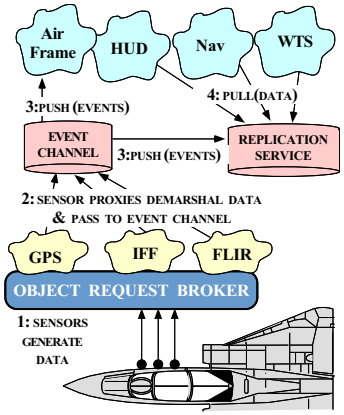
Related work →

- x-Kernel
- SysV STREAMS

ACE and TAO Statistics

- Over 30 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



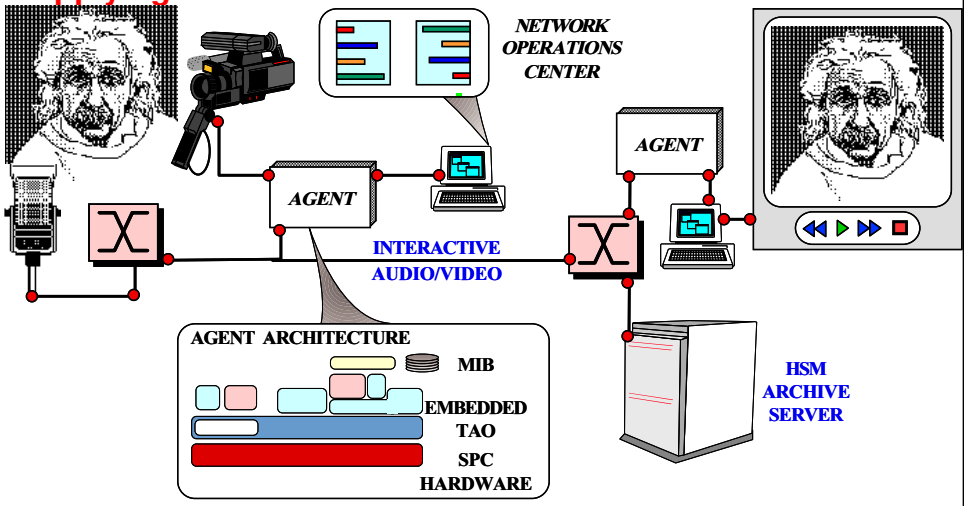
www.cs.wustl.edu/∼schmidt/JSAC-98.ps.gz

Domain Challenges

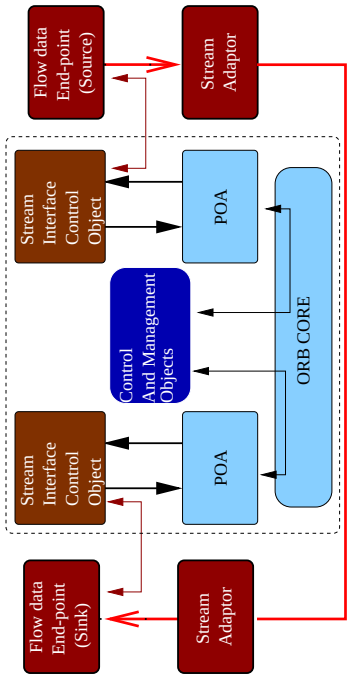
- Deterministic & statistical real-time deadlines
- Periodic & aperiodic processing
- COTS and open systems
- Reusable components
- Support platform upgrades

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

Applying TAO to Distributed Interactive Simulations



Applying TAO to Multimedia Applications



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

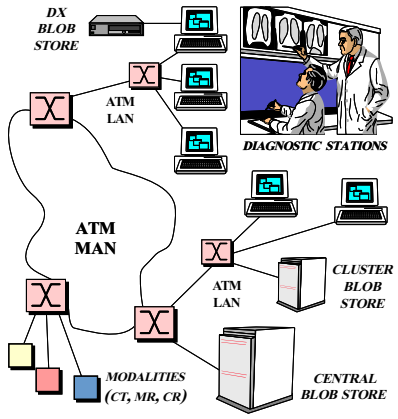
Flexibility

- Uses CORBA for control messages and properties

Efficiency

- Sockets for data transfer to get high performance

Problem: Optimizing Complex Software



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

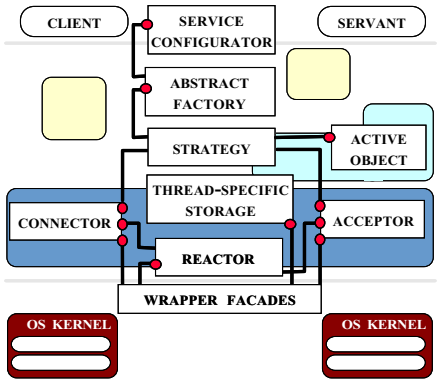
Common Problems →

- 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: 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

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

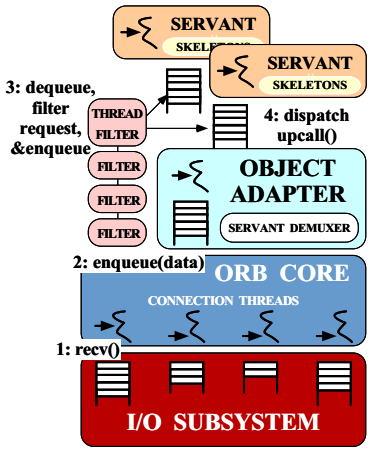
Definition

- 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

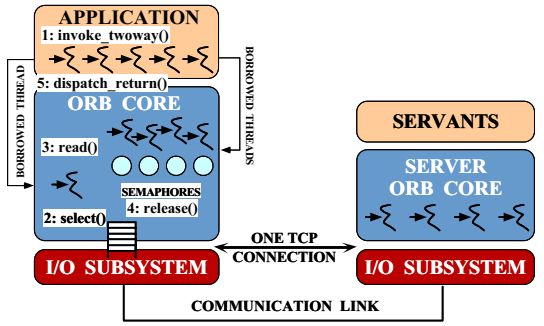


Common Problems

- 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



Common Problems

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

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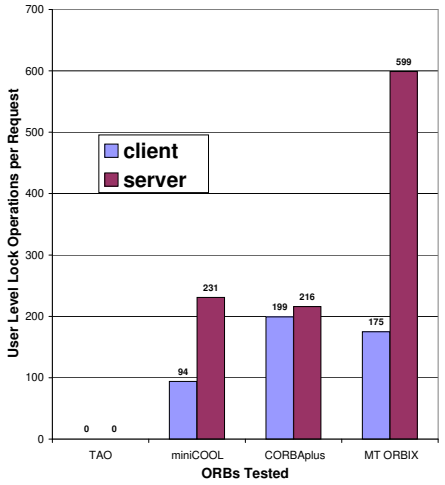
Problem: High Locking Overhead



Common Problems

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

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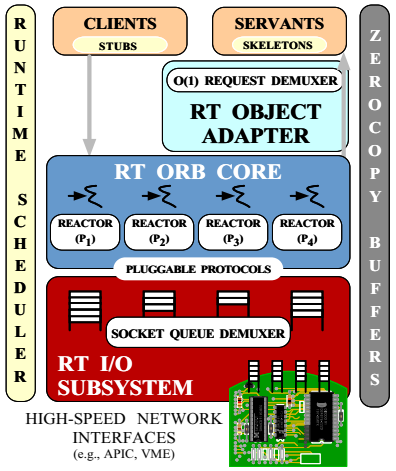
Solution: TAO's ORB Endsystem Architecture



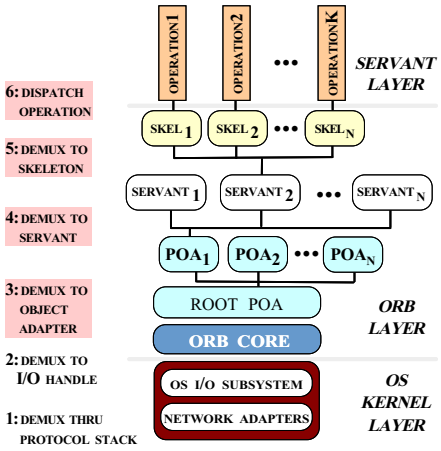
Solution Approach →

- Integrate scheduler into ORB endsystem
- Support multiple scheduling strategies
- Co-schedule threads

Principle Patterns →

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

Problem: Reducing Demultiplexing Latency

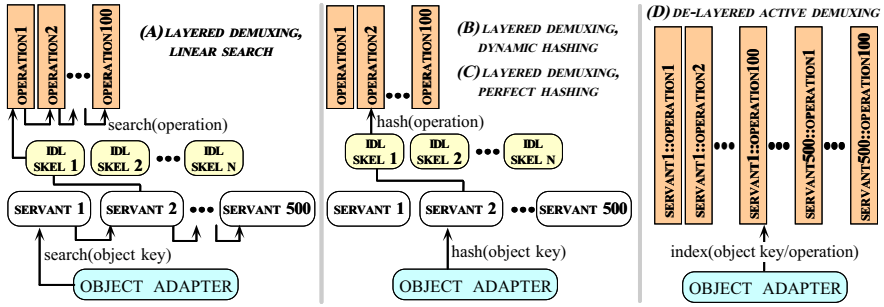


Design Challenges

- 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



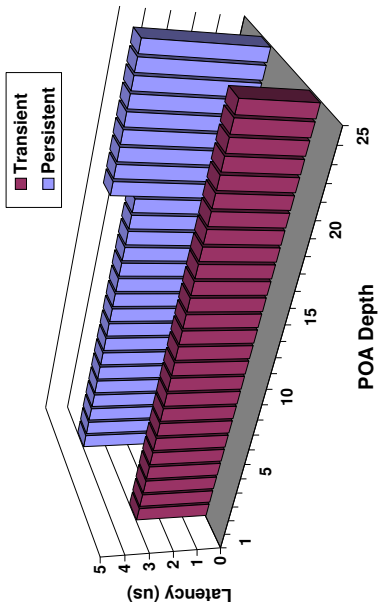
Demuxing

- 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



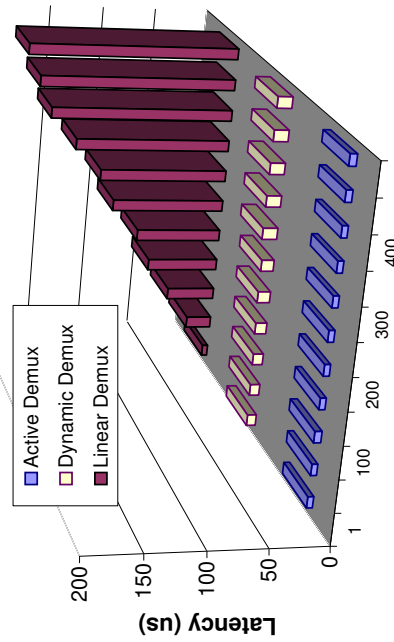
Synopsis of Results

- 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



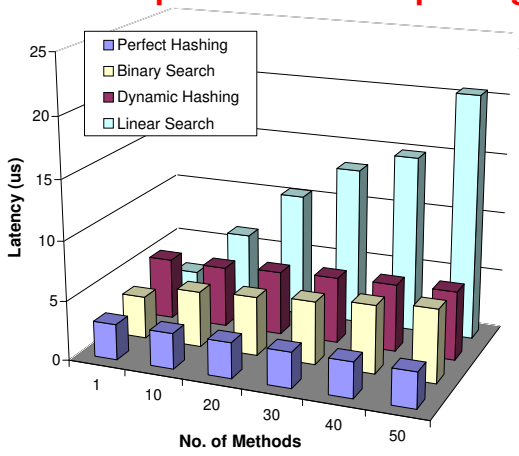
Synopsis of Results

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

Principle Patterns

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

Operation Demultiplexing Results



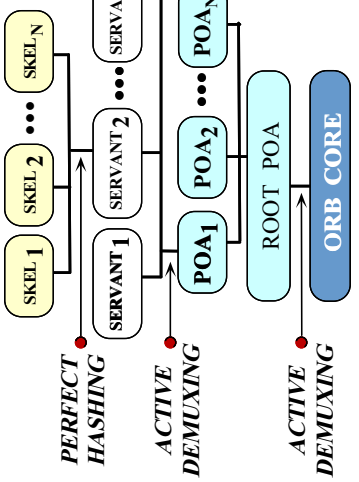
Synopsis of Results →

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

Principle Patterns →

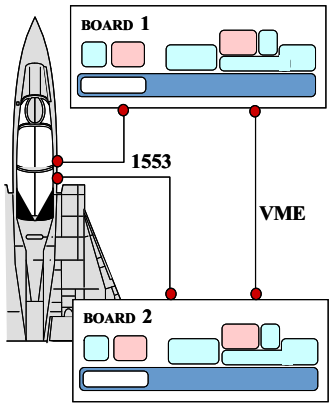
- Precompute, use predictable data structures, remove gratuitous waste

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

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 measureable 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

Principle Patterns

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

Features

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

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

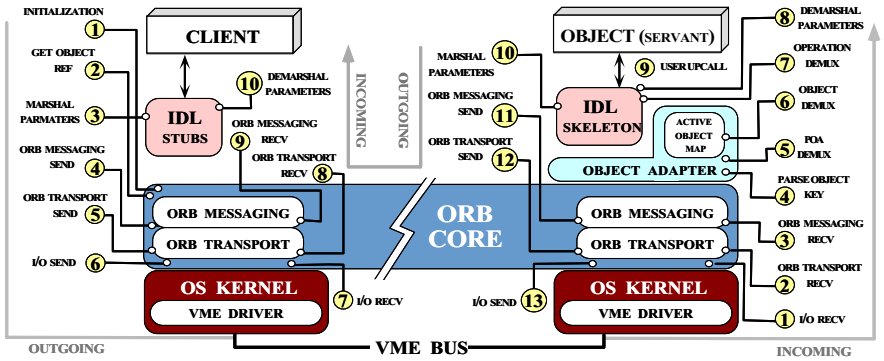
VxWorks running on 200 Mhz PowerPC over
320 Mbps VME & 10 Mbps Ethernet

Ethernet & VME Two-way Latency Results

Synopsis of Results

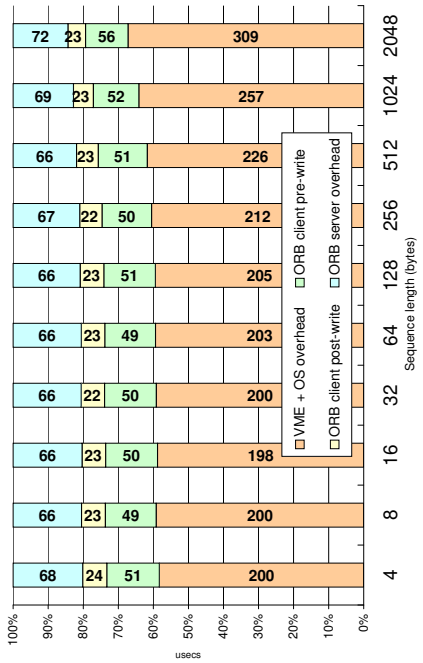
- VME protocol is much faster than Ethernet
- No application changes are required to support VME

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

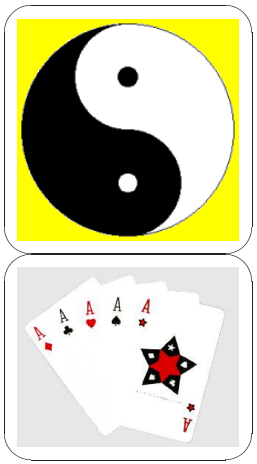


Synopsis of Results

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

Lessons Learned Developing High-performance ORBs

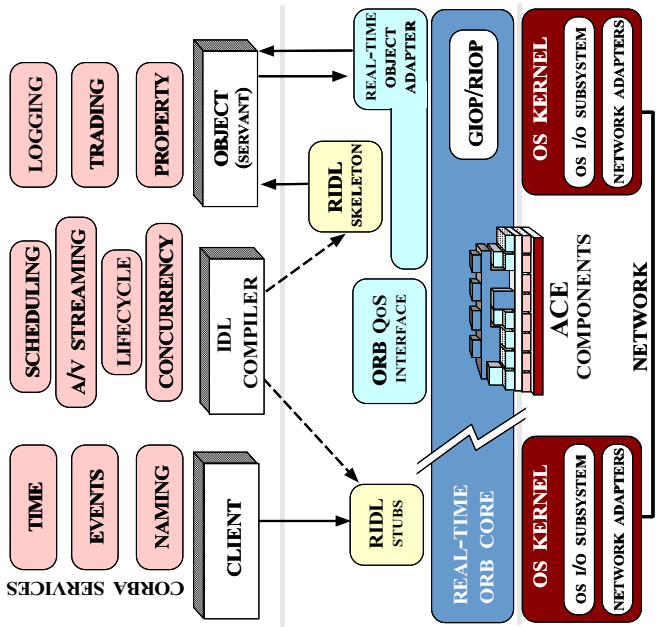
- Avoid dynamic connection management
- Minimize dynamic memory management and data copying
- Avoid multiplexing connections for different priority threads
- Avoid complex concurrency models
- Integrate ORB with OS and I/O subsystem and avoid reimplementing OS mechanisms
- Guide ORB design by empirical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



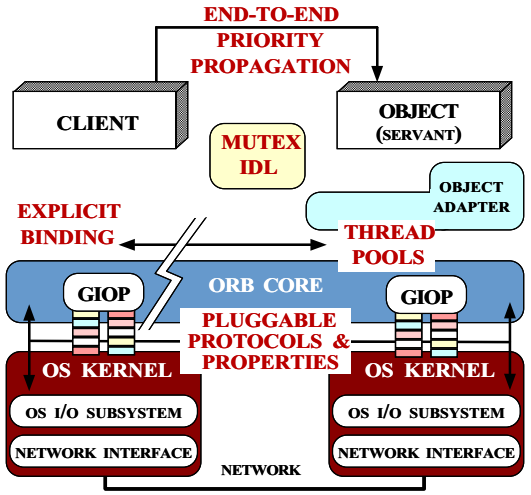
Concluding Remarks

- 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

Current Status of TAO



Next Steps: New TAO Features and Optimizations



New Features

- CORBA "branding" from Open Group and OMG
- Real-time and Minimum CORBA
- CORBA Messaging
- Fault Tolerance

URL

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

Web URLs for Additional Information

- These slides: `~schmidt/TAO4.ps.gz`
- More information on CORBA: `~schmidt/corba.html`
- More info on ACE: `~schmidt/ACE.html`
- More info on TAO: `~schmidt/TAO.html`
- TAO Event Channel: `~schmidt/JSAC-98.ps.gz`
- TAO static scheduling: `~schmidt/TAO.ps.gz`
- TAO dynamic scheduling: `~schmidt/dynamic.ps.gz`
- ORB Endsystem Architecture: `~schmidt/RIO.ps.gz`
- Pluggable protocols: `~schmidt/pluggable_protocols.ps.gz`

Web URLs for Additional Information (cont'd)

- Network monitoring, visualization, & control: `~schmidt/NMVC.html`
- Performance Measurements:
  - Demuxing latency: `~schmidt/COOTS-99.ps.gz`
  - SII throughput: `~schmidt/SIGCOMM-96.ps.gz`
  - DII throughput: `~schmidt/GLOBECOM-96.ps.gz`
  - ORB latency & scalability: `~schmidt/ieee_tc-97.ps.gz`
  - IIOP optimizations: `~schmidt/JSAC-99.ps.gz`
  - Concurrency and connection models: `~schmidt/RT-perf.ps.gz`
  - RTOS/ORB benchmarks:
    `~schmidt/RT-OS.ps.gz`
    `~schmidt/words-99.ps.gz`