Principles and Patterns of High-performance, Real-time Object Request Brokers

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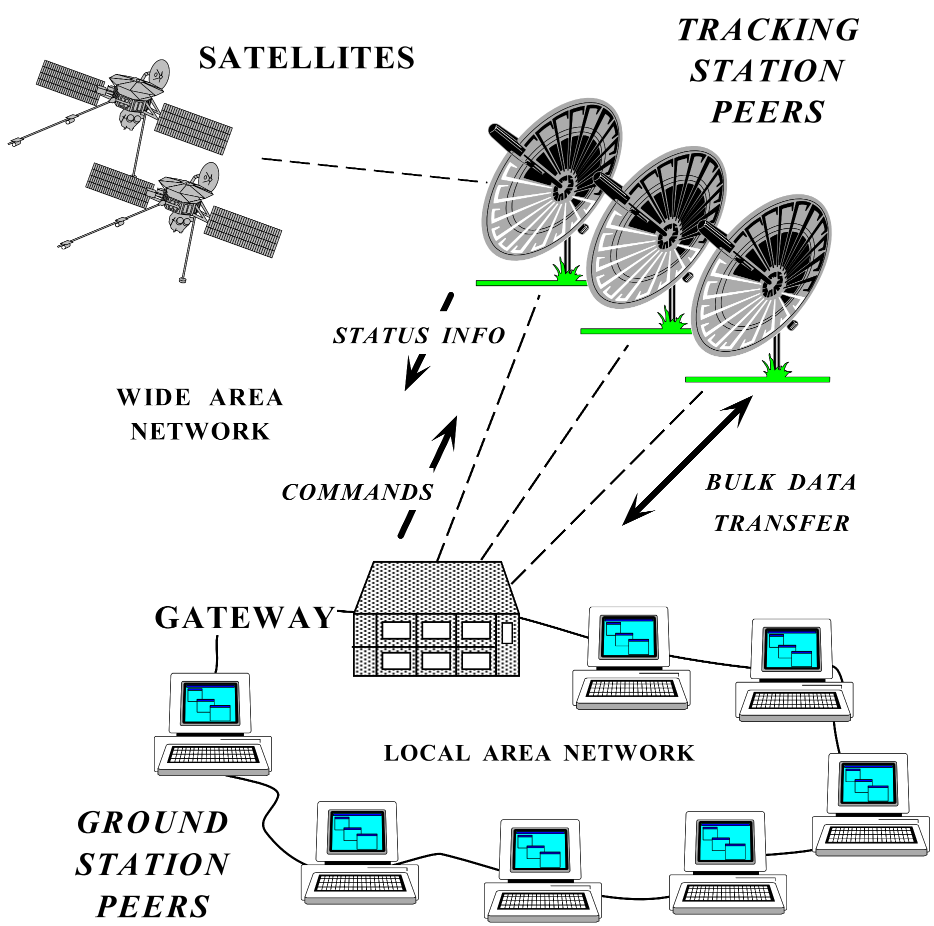
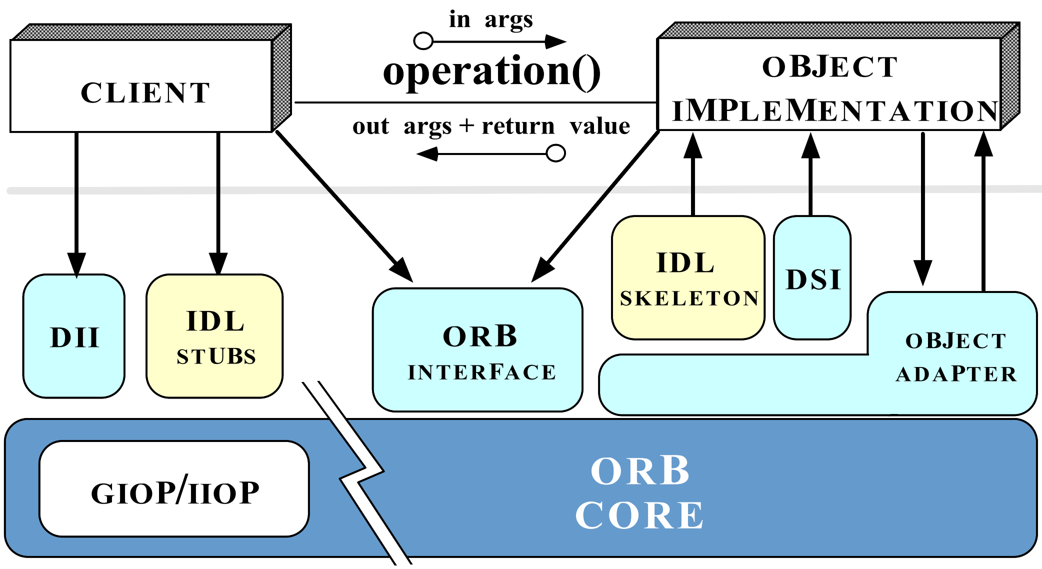
http://www.cs.wustl.edu/~schmidt/TAO.html

Motivation



- 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*

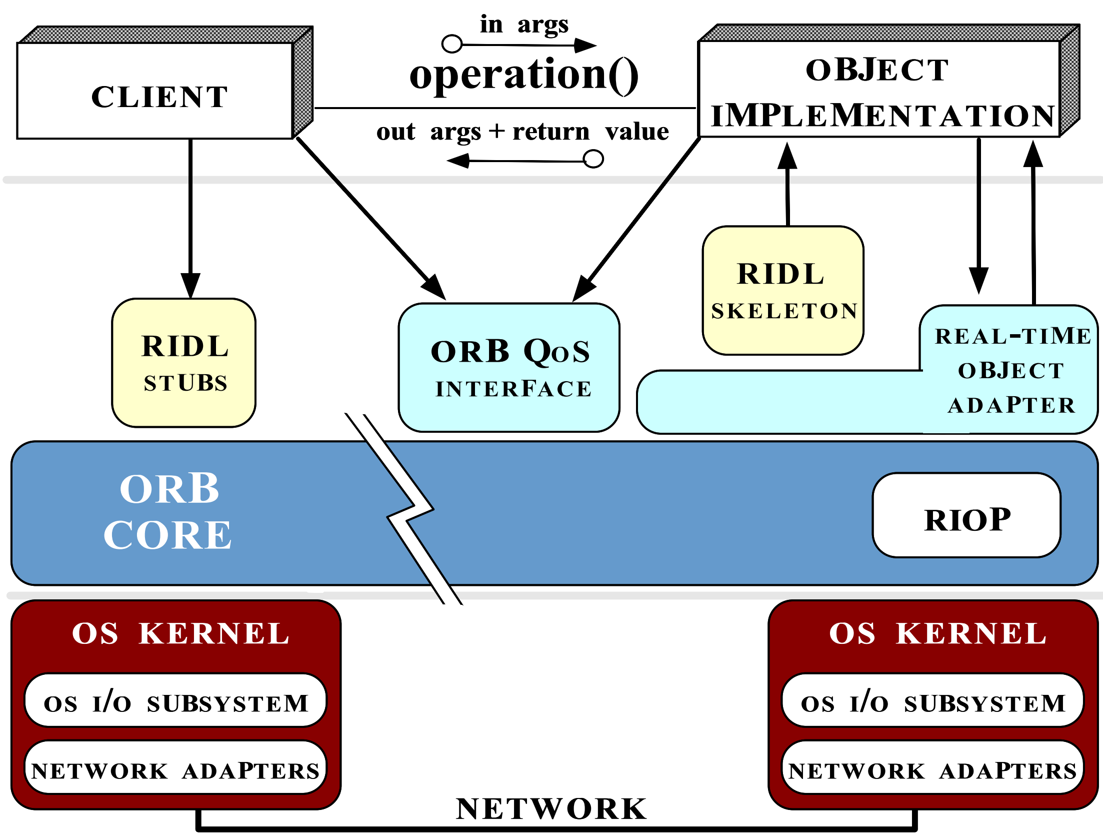
Candidate Solution: CORBA



- **Goals of CORBA**
  - Simplify distribution
  - Provide foundation for higher-level services
- **Limitations of CORBA**
  - Poor performance
  - Lack of QoS features

http://www.cs.wustl.edu/∼schmidt/corba.html

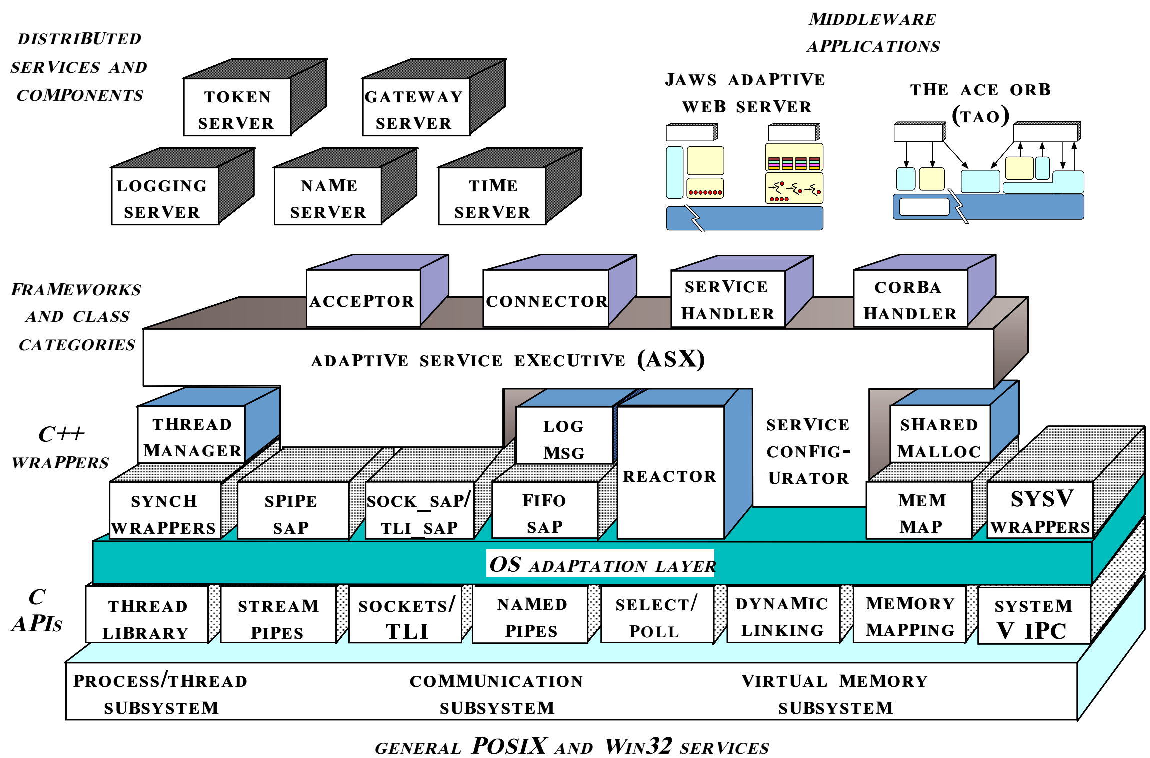
The ACE ORB (TAO)



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

- **TAO Overview**
  - A high-performance, real-time ORB
    - ∗ Networking and avionics focus
  - Leverages the ACE framework
    - ∗ Ported to VxWorks, POSIX, and Win32
- **Related work**
  - QuO at BBN
  - ARMADA at U. Mich.

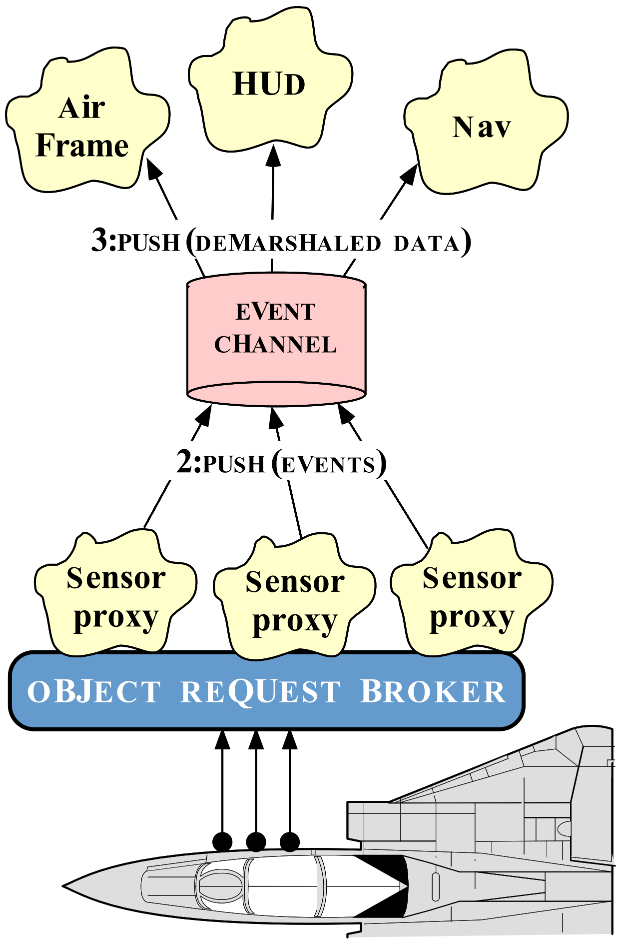
The ADAPTIVE Communication Environment (ACE)



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

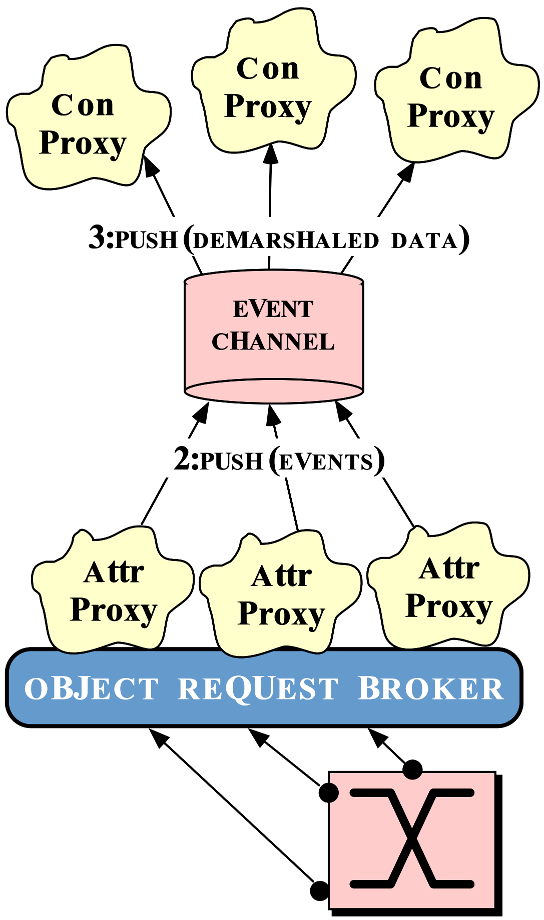
- **ACE Overview**
  - A concurrent OO networking framework
  - Very widely used in industry
  - Available in C++ and Java
  - Ported to VxWorks, POSIX, and Win32
- **Related work**
  - x-Kernel

Applying ORBs to Real-time Avionics



- **Domain Challenges**
  - Periodic hard real-time deadlines
  - COTS infrastructure
  - Open systems
- **Related work**
  - Deng, Liu, and J. Sun '96
  - Gopalakrishnan and Parulkar '96
  - Wolfe et al. '96

Applying ORBs to Real-time Network Management

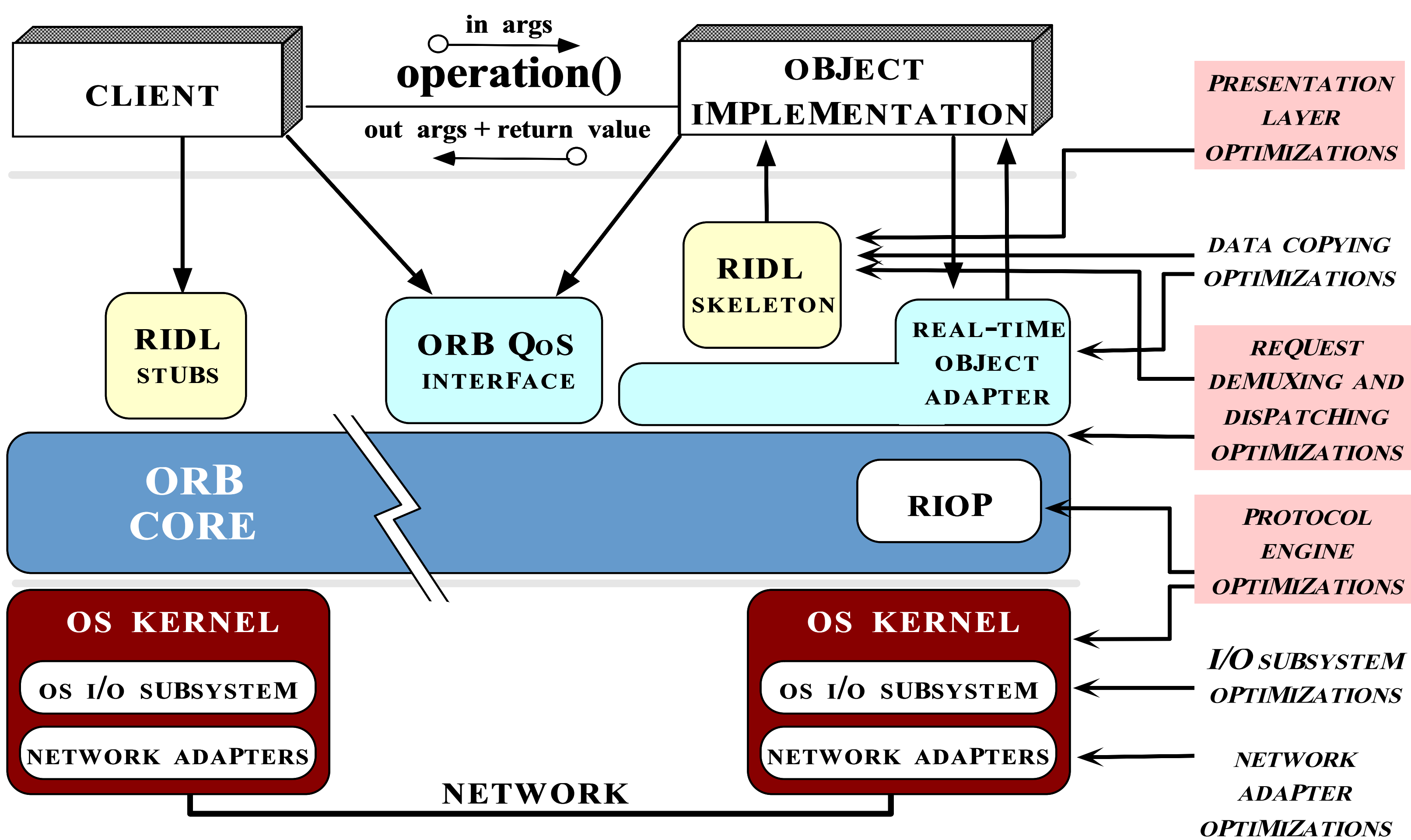


- **Domain Challenges**
  - Periodic statistical real-time deadlines
  - COTS infrastructure
  - Open systems
- **Related work**
  - Deng, Liu, and J. Sun '96
  - Gopalakrishnan and Parulkar '96
  - Wolfe et al. '96

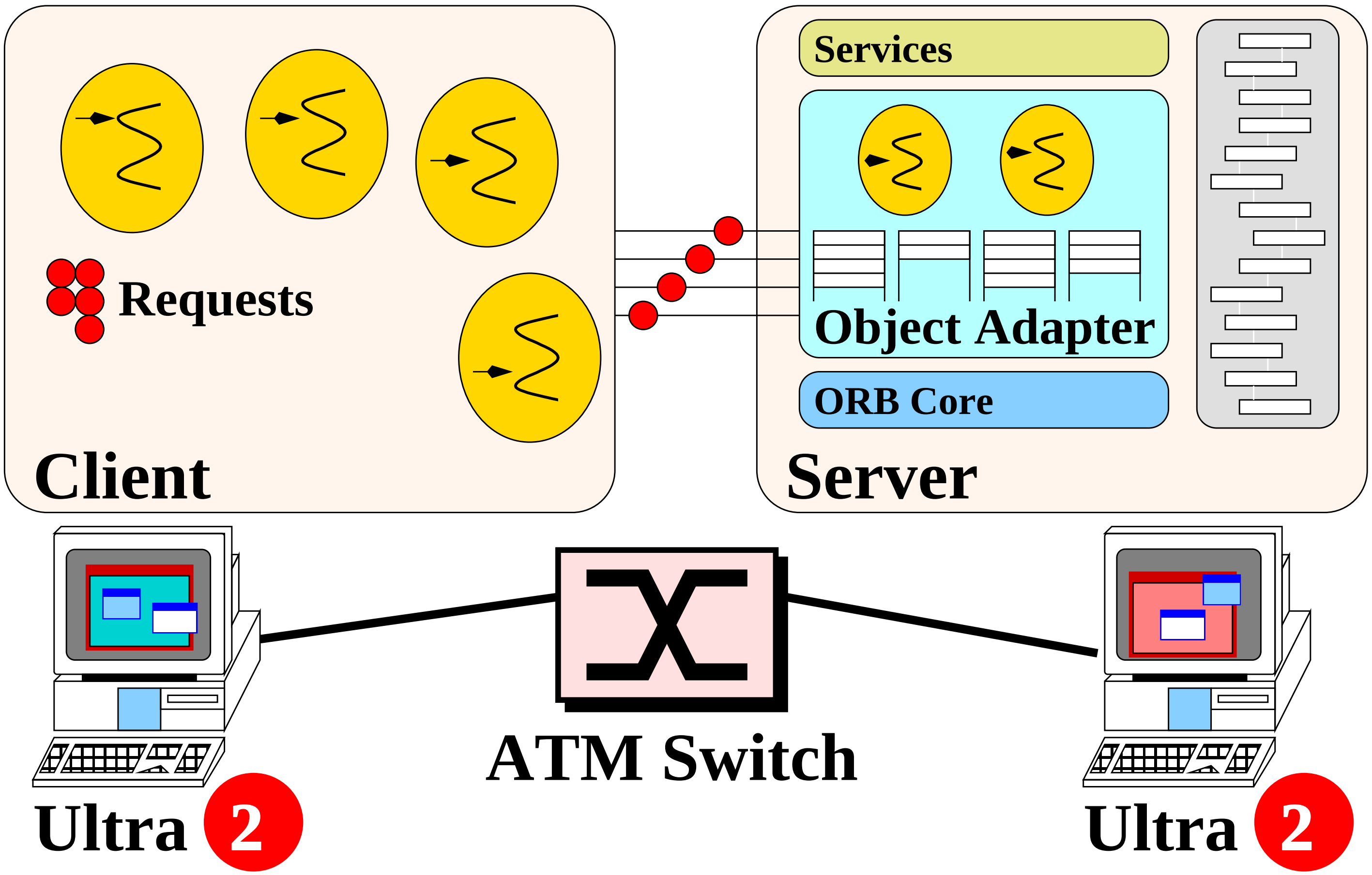
Research Objectives

- Identify features and architectural patterns needed for real-time ORBs
  - Both hard real-time and statistical real-time
- Develop optimizations required to build high-performance ORBs
  - *e.g.*, Gigabit bandwidth and $\sim$10 microsecond latency
- Determine changes needed to CORBA specification
  - *e.g.*, APIs for defining end-to-end QoS requirements

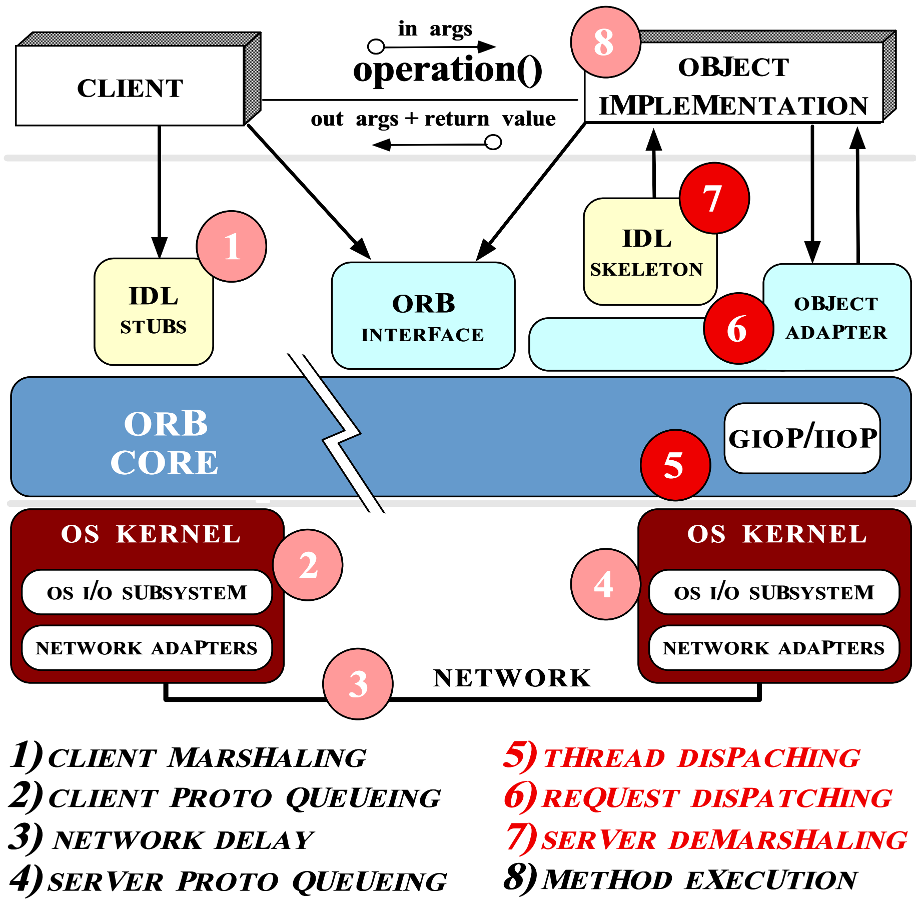
Real-time Features and Optimizations in TAO



Experimental Setup for CORBA/ATM Testbed

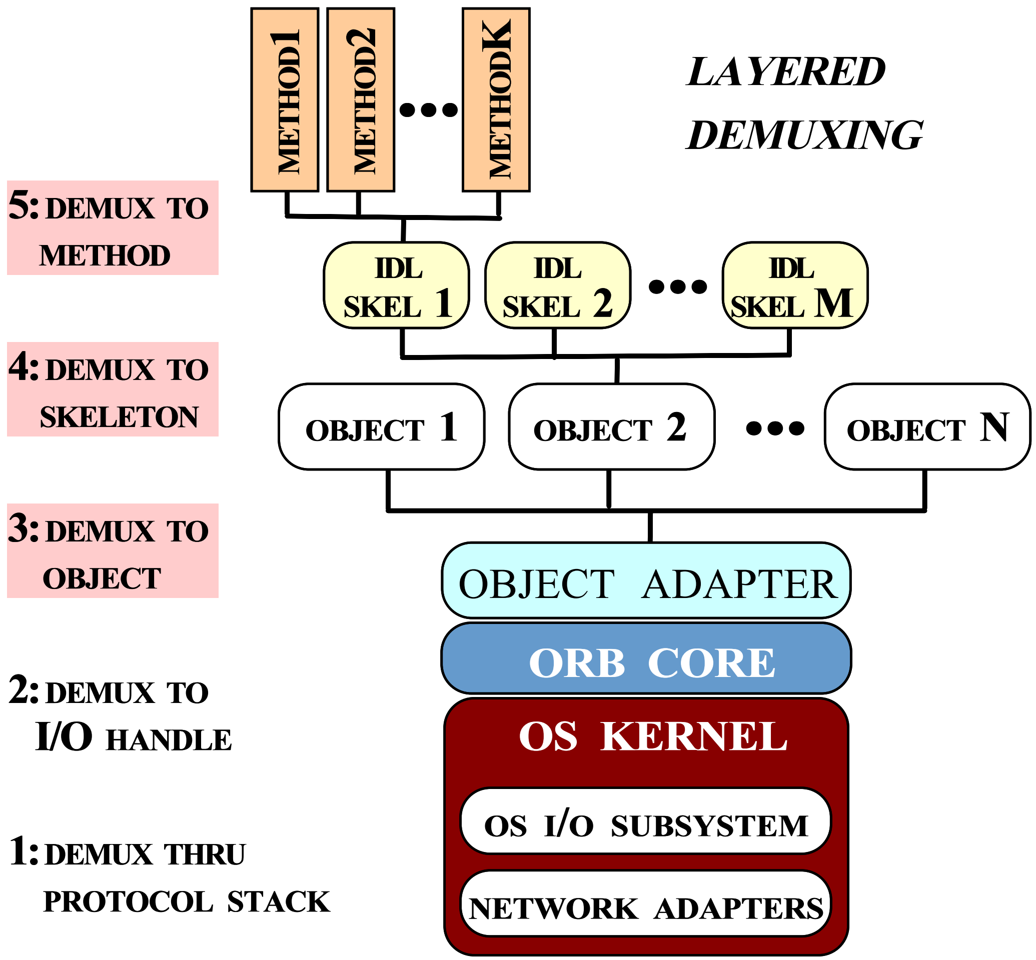


Problem: Meeting End-to-End QoS Requirements



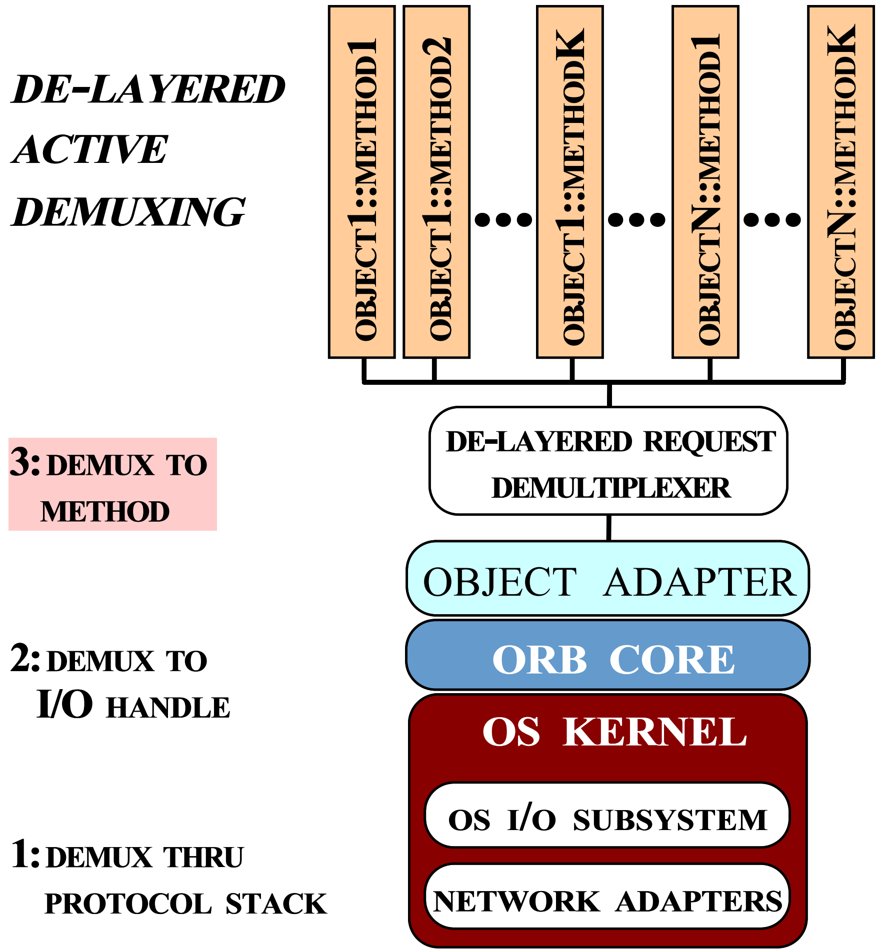
- **Design Challenges**
  - Specifying QoS requirements
  - Reducing demultiplexing latency
  - Meeting scheduling deadlines
  - Reducing presentation layer overhead

Problem: Reducing Demultiplexing Latency



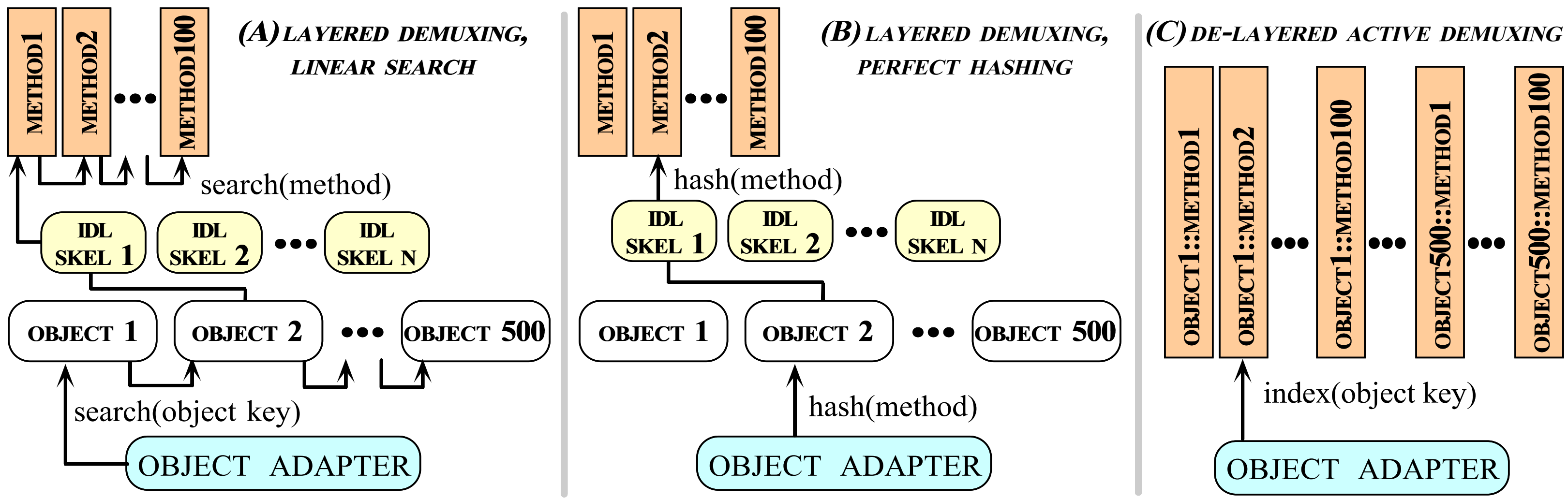
- **Design Challenges**
  - Minimize demuxing layers
  - Provide $O(1)$ operation demuxing
  - Avoid priority inversions
  - Remain CORBA-compliant

Solution: De-layered Active Demultiplexing



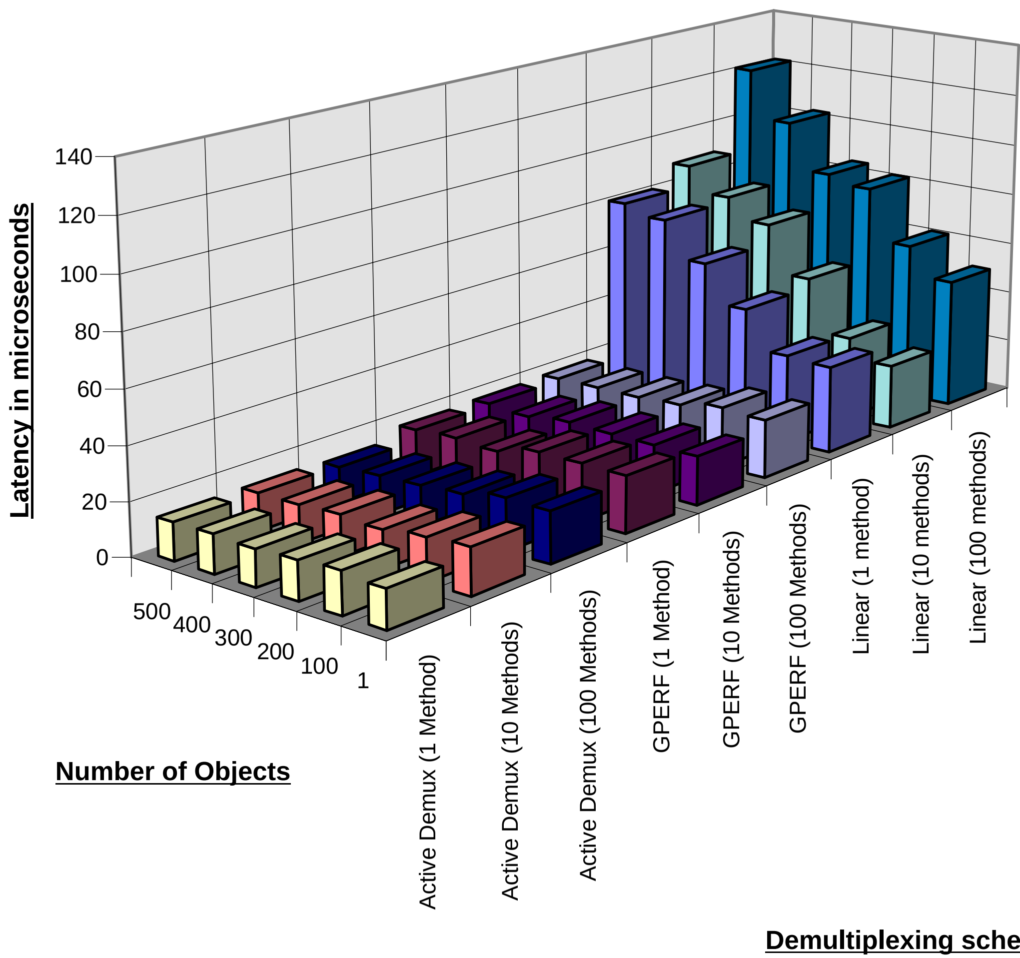
- **Solution Approach**
  - Pre-negotiate demuxing keys
  - Tunnel demuxing key with Object key
  - Use ACT pattern for validation
- **Related Work**
  - Yau and Lam '97
  - Dittia and Parulkar '97
  - Engler and Kaashoek '96

Demultiplexing Performance Experiments



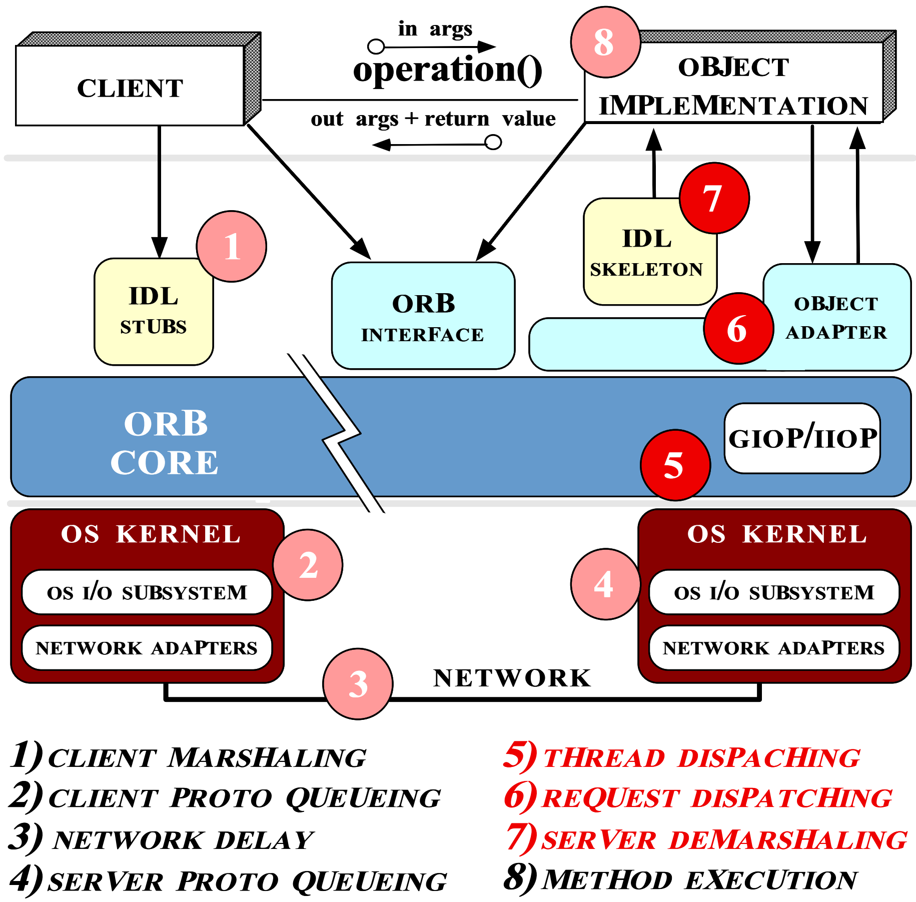
- Linear search based on `Orbix` demuxing strategy
- Perfect hashing based on GNU `gperf`
  - `http://www.cs.wustl.edu/~schmidt/gperf.ps.gz`
- Results at `http://www.cs.wustl.edu/~schmidt/GLOBECOM-97.ps.gz`

Demultiplexing Performance Results



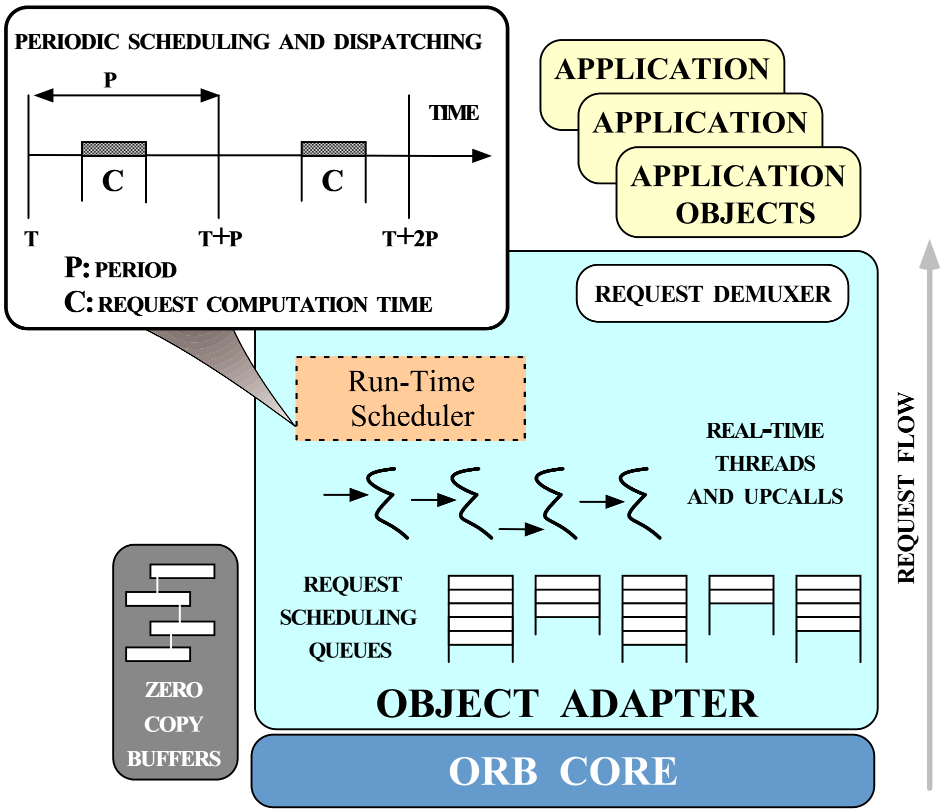
- **Synopsis**
  - `gperf` solution is 100% compatible, but static
  - Active demuxing isn't 100% compatible, but is dynamic

Problem: Meeting CORBA Request Deadlines



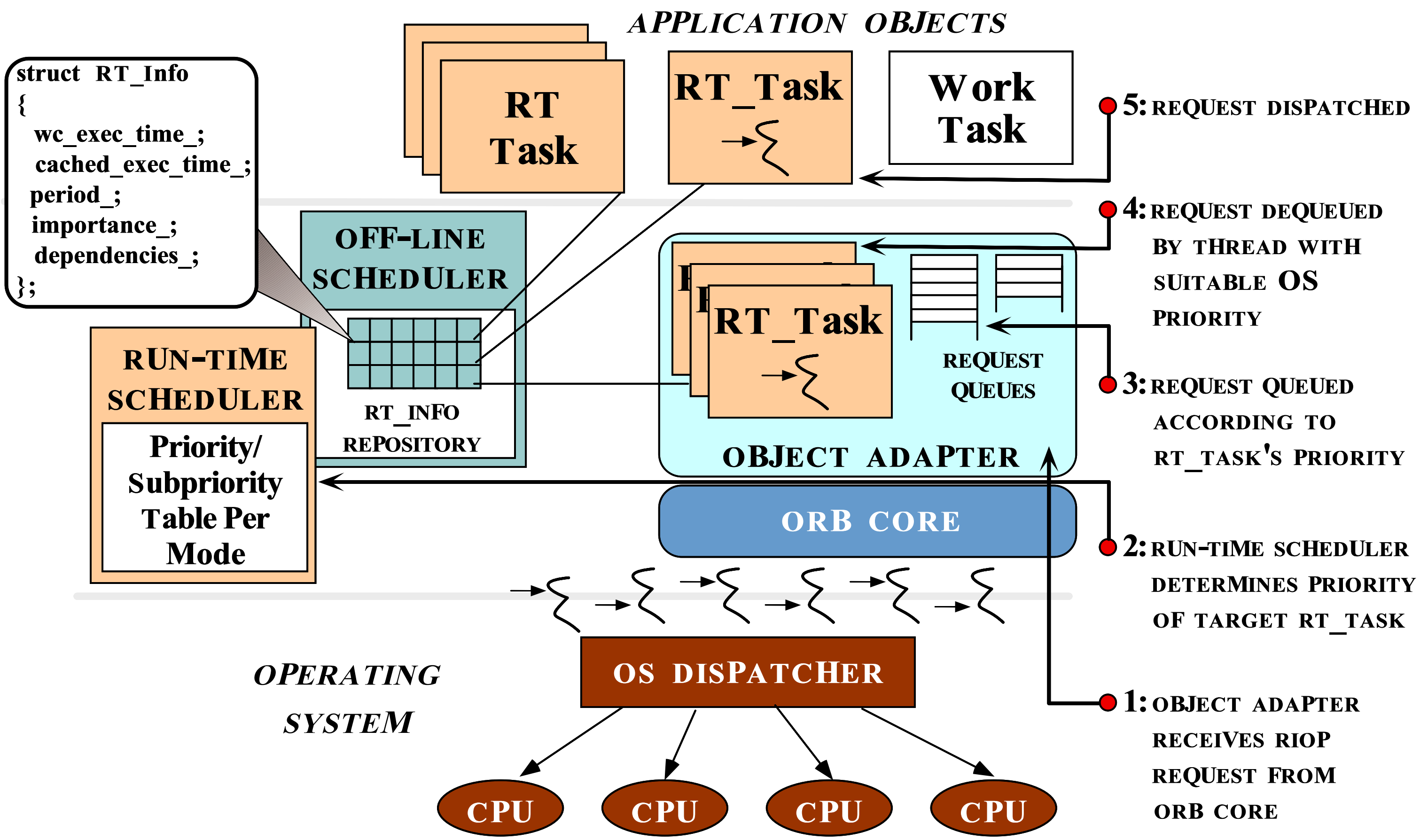
- **Design Challenges**
  - Specifying/enforcing QoS requirements
  - Focus on *Objects* and *Operations*
    - Not on threads or comm. channels
- **Assumptions**
  - Static scheduling
  - Non-distributed (initially)

Solution 1: Real-time Object Adapter

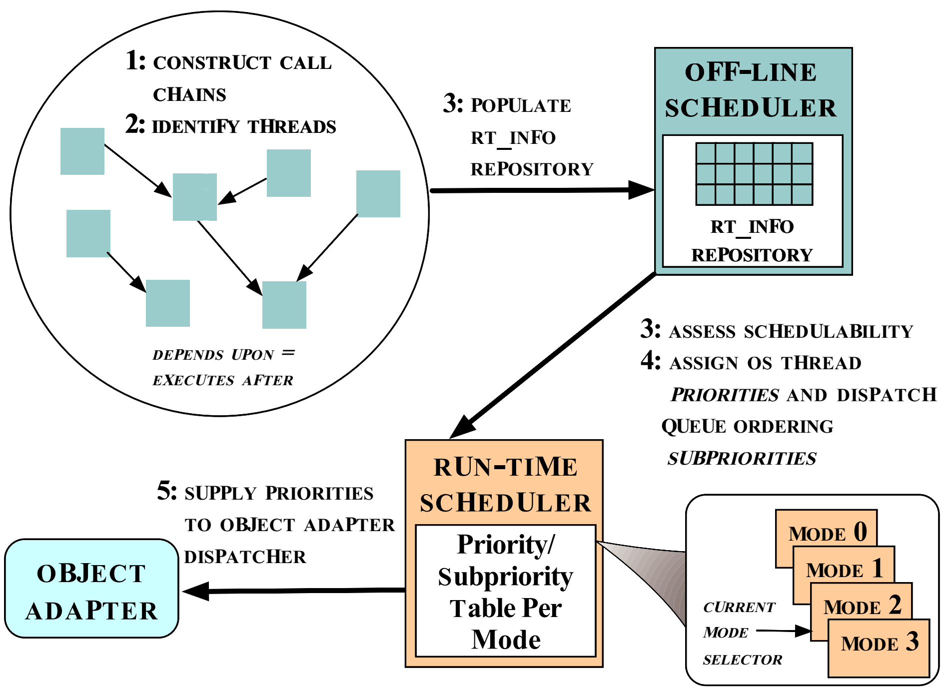


- **Solution Approach**
  - Integrate RT dispatcher into ORB
  - Support multiple request scheduling strategies
    - *e.g.*, RMS, RMS with Deferred Preemption, and EDF
- **Related work**
  - Zinky, Bakken, and Schantz, '95
  - Lee, Rajkumar, and Mercer '96

Solution 2: Real-time Scheduling Service



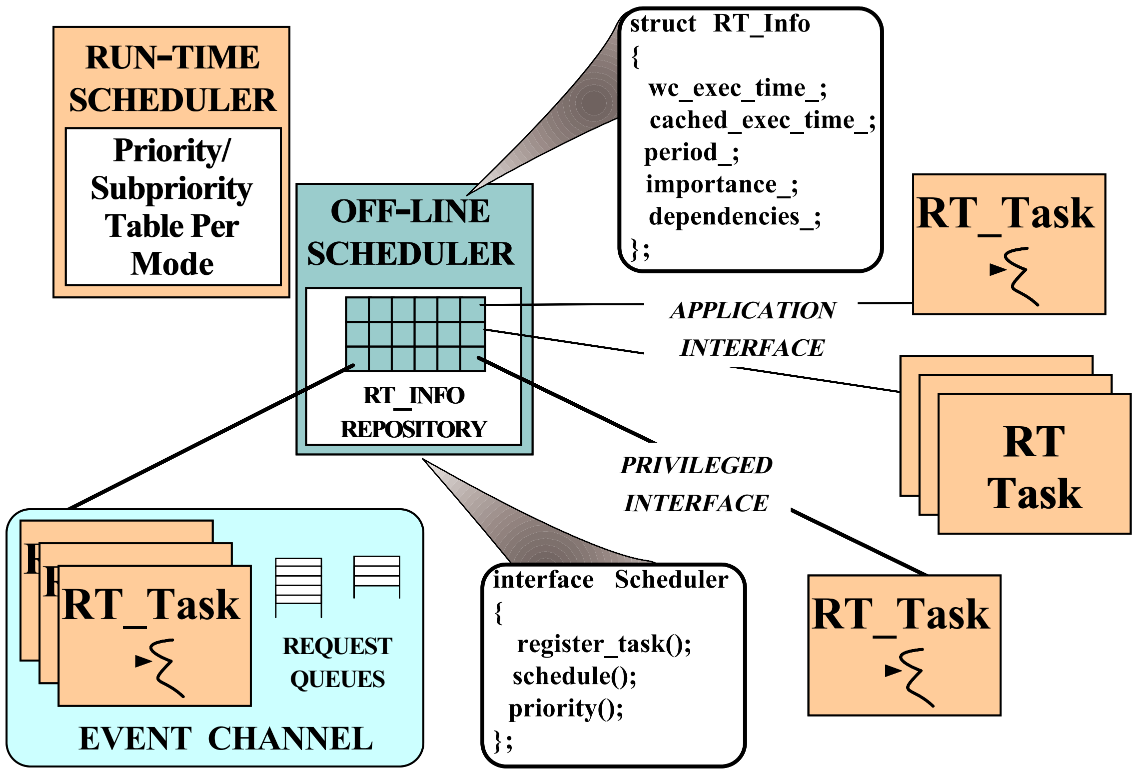
Scheduling Service Roles



- **Components**
  - Offline
    - Assess schedule feasibility
    - Assign thread and queue priorities
  - Online
    - Supply priorities to Object Adapter's dispatcher

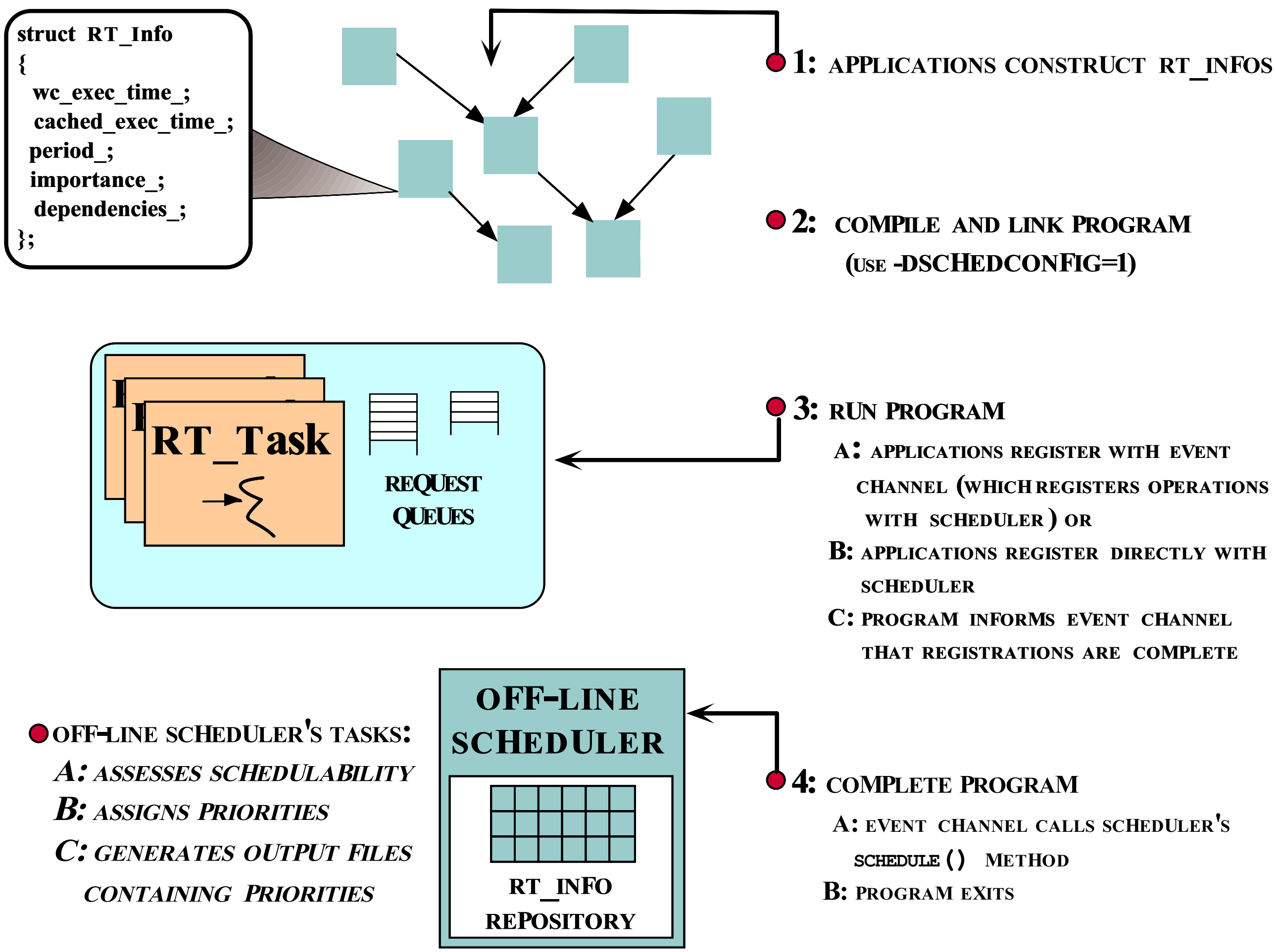
`http://www.cs.wustl.edu/~schmidt/TAO.ps.gz`

Scheduling Service Interfaces

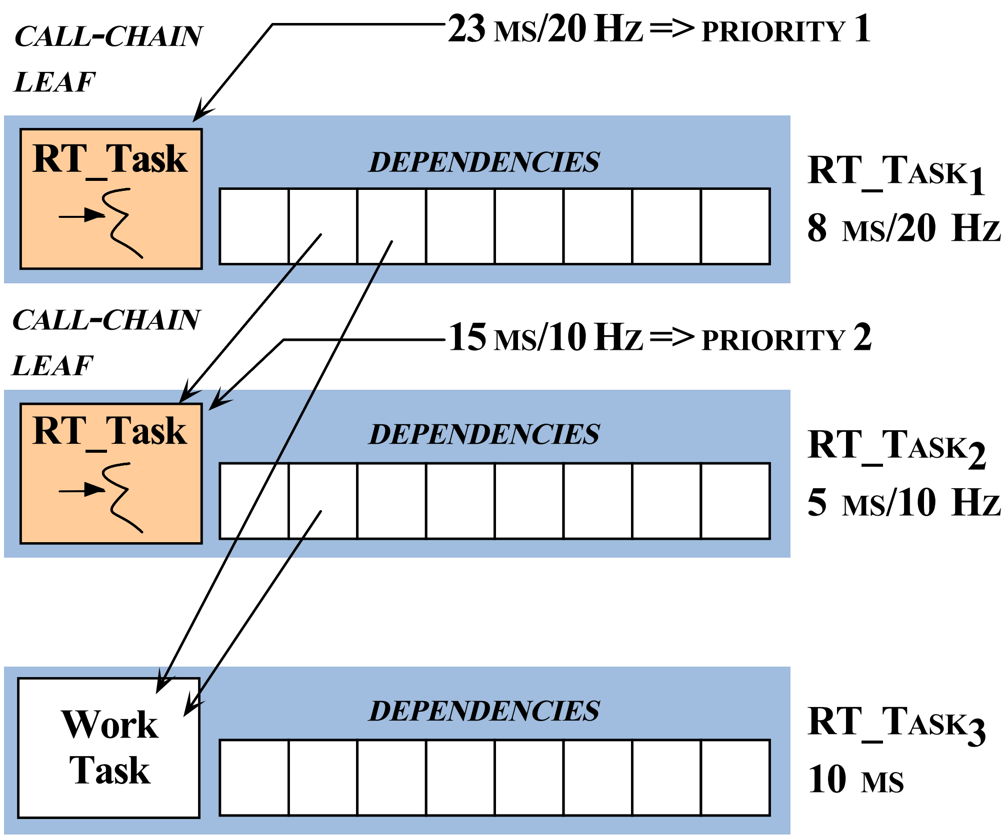


- **Components**
  - Application interface
    - ∗ Use RT_Infos
  - Privileged interface
    - ∗ Used by system tasks and services

Scheduling Steps During Configuration Run

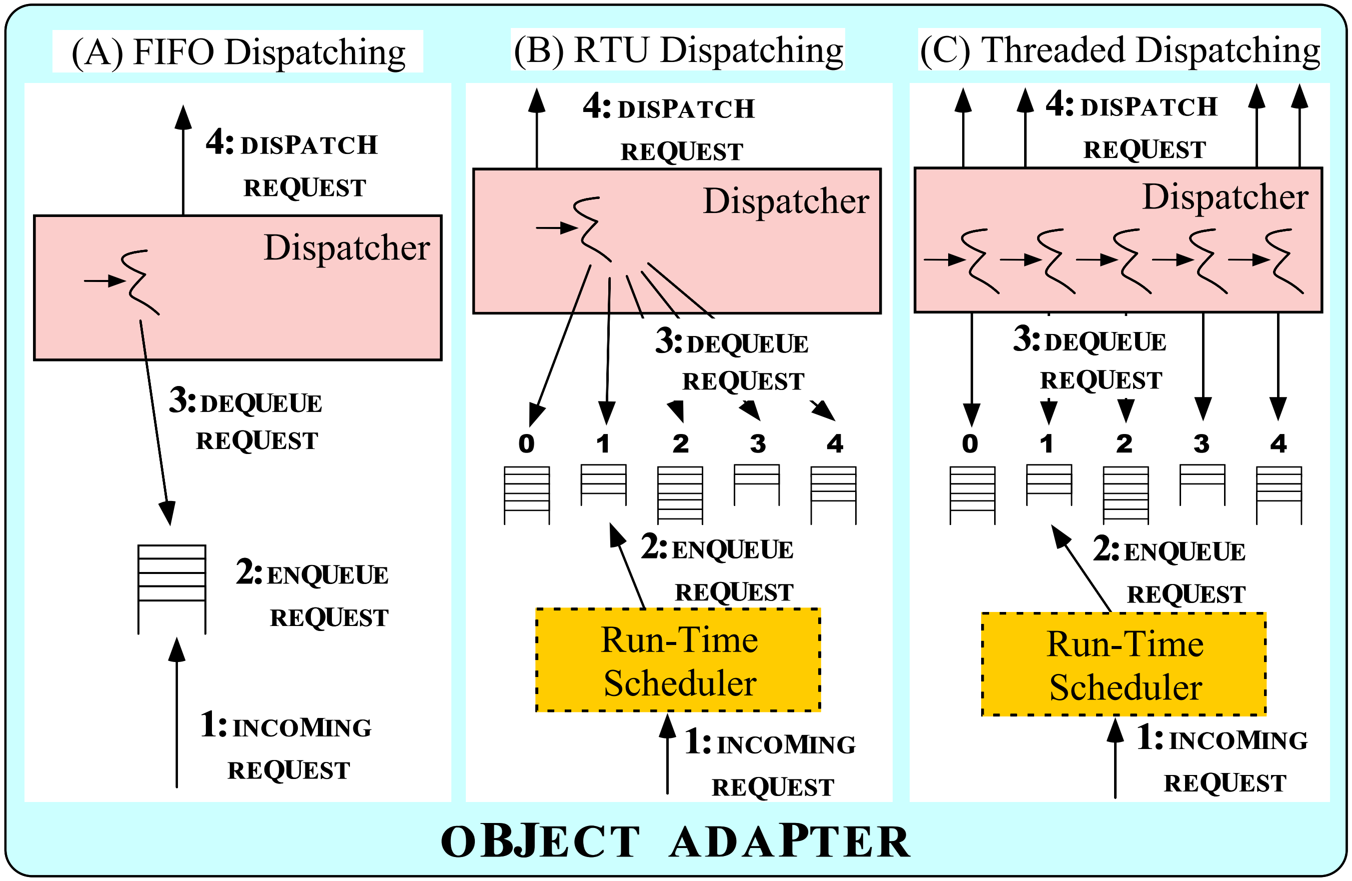


Scheduling Service Internal Repository



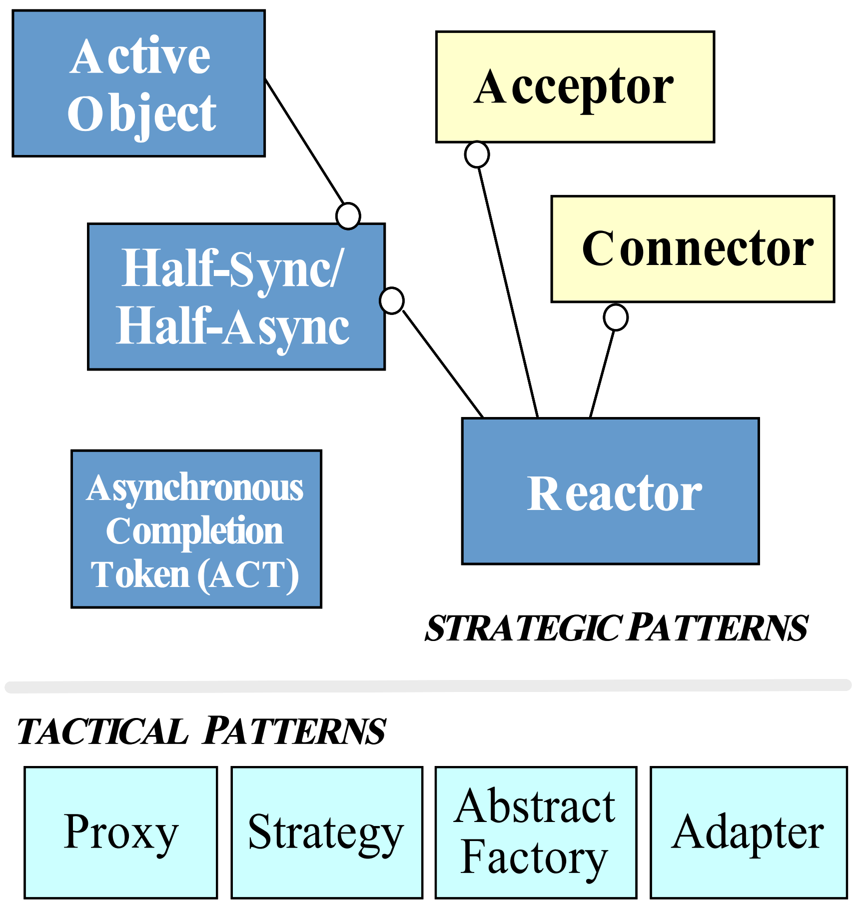
- **Components**
  - `RT_Info` references
  - Vector of `RT_Tasks` called by each `RT_Task`
    - Vector records dependencies
  - Called-task chains are traversed to compute total CPU time and minimum period

Real-time Dispatching Experiments



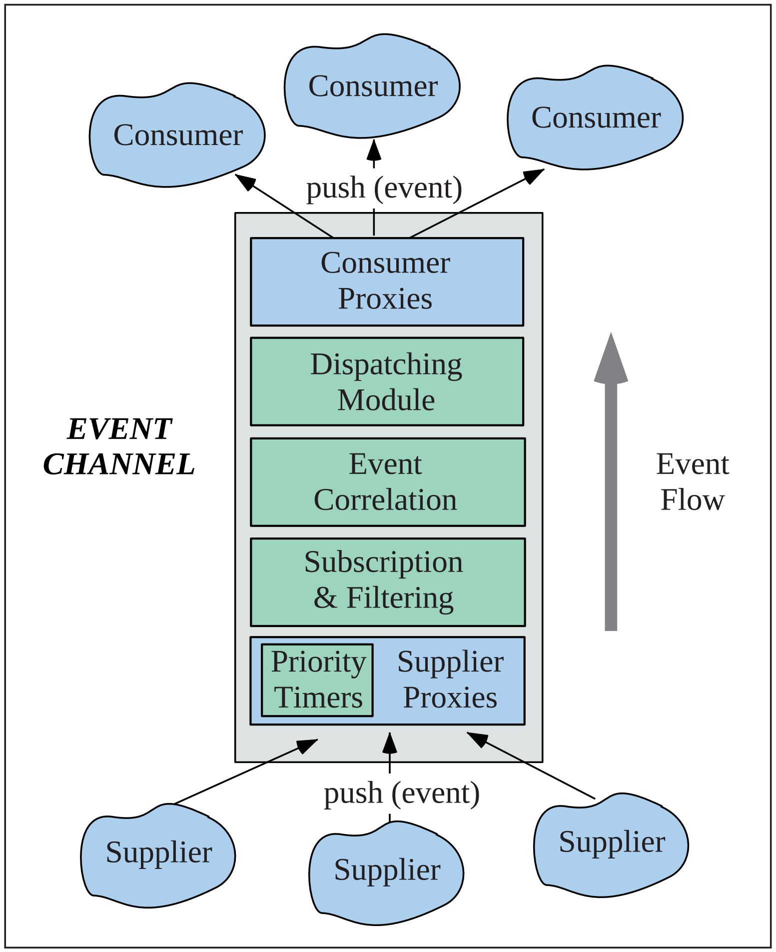
- Available at `http://www.cs.wustl.edu/~schmidt/oopsla.html`

Key Patterns in TAO



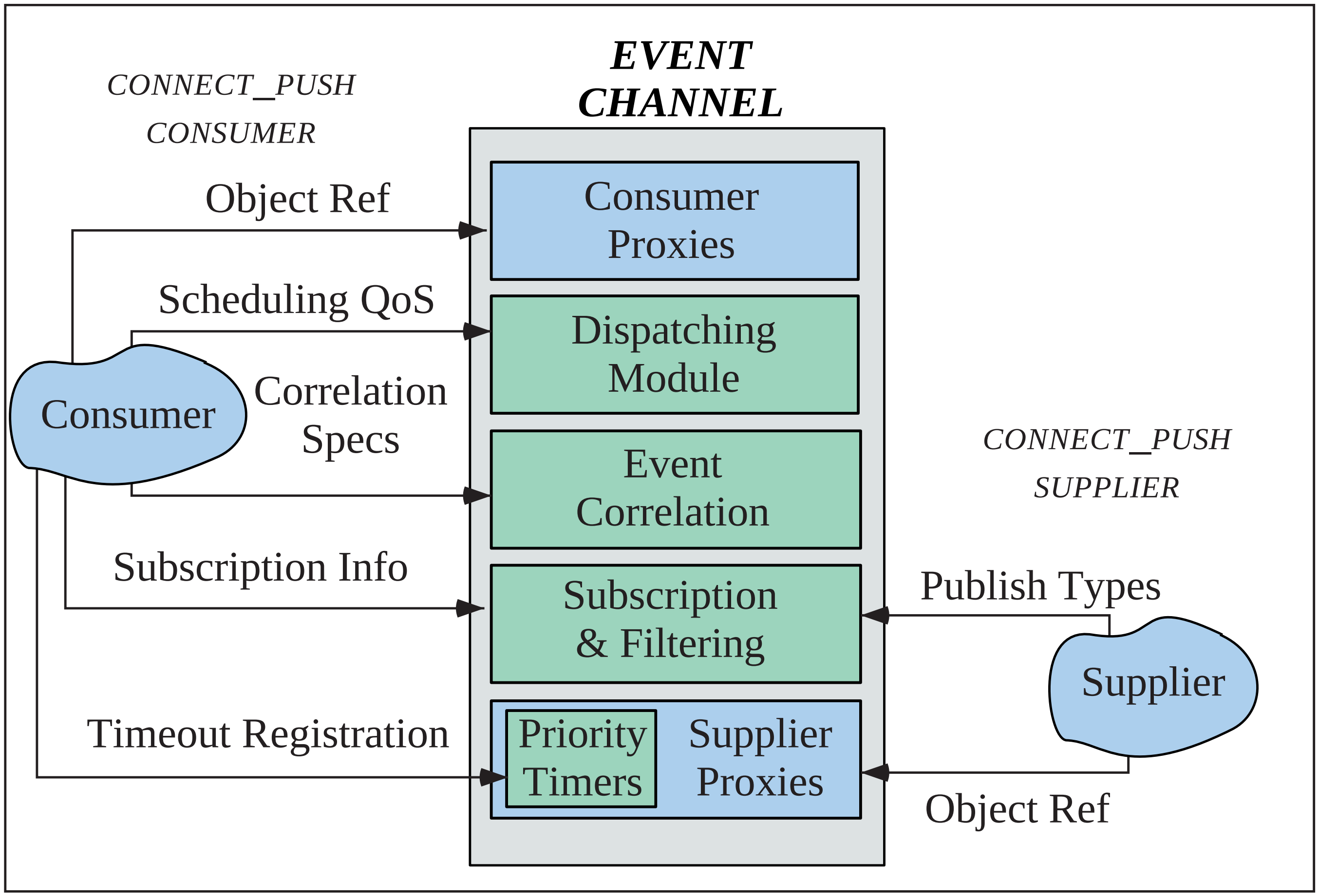
- **Definition**
  - "A recurring solution to a design problem in a particular context"
- **Benefits of Patterns**
  - Facilitate design reuse
  - Preserve crucial design information
  - Guide design choices
  - Document common traps and pitfalls

Real-time Event Channel Overview

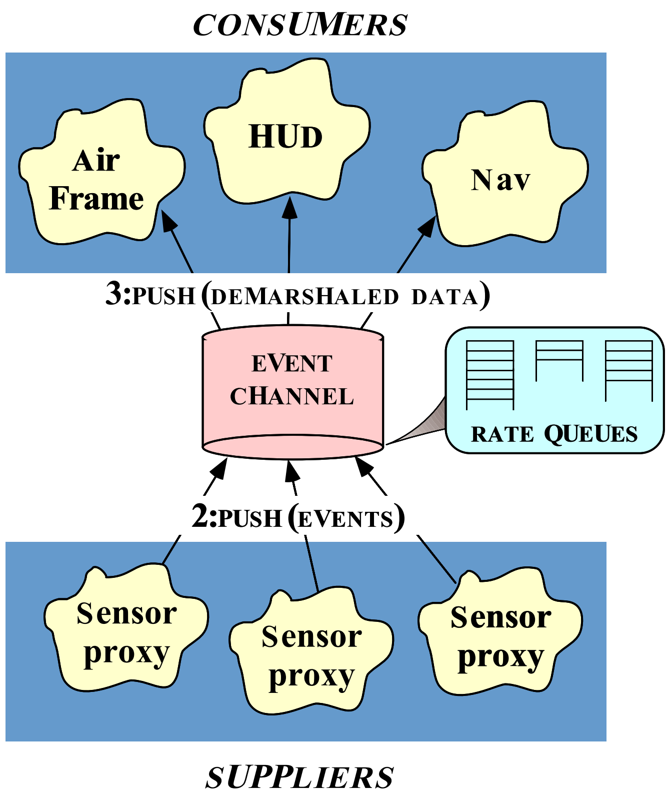


- **Real-time Event Channel Features**
  - Scheduling
  - Correlation dependencies
  - Filtering

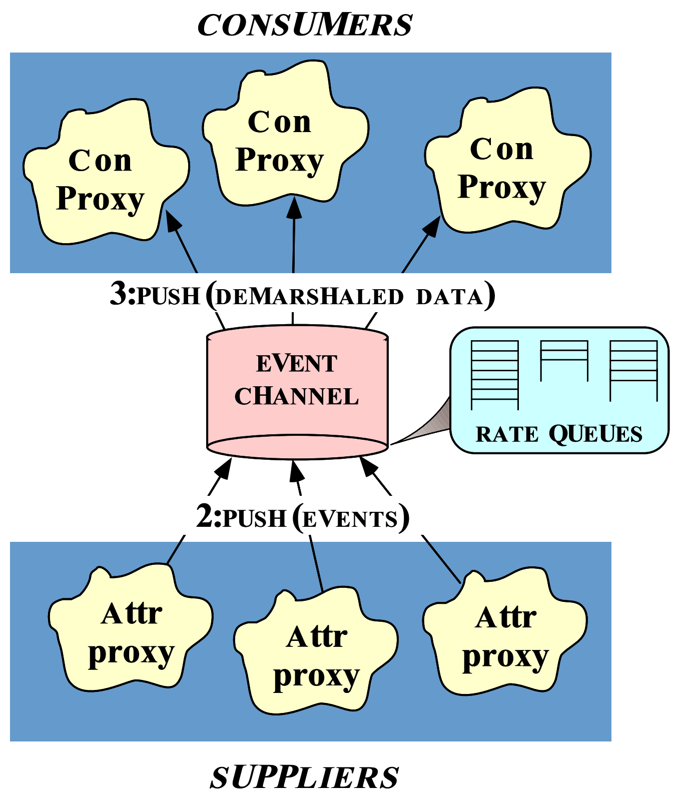
Collaboration in the RT Event Channel



RT Event Channel Use-cases

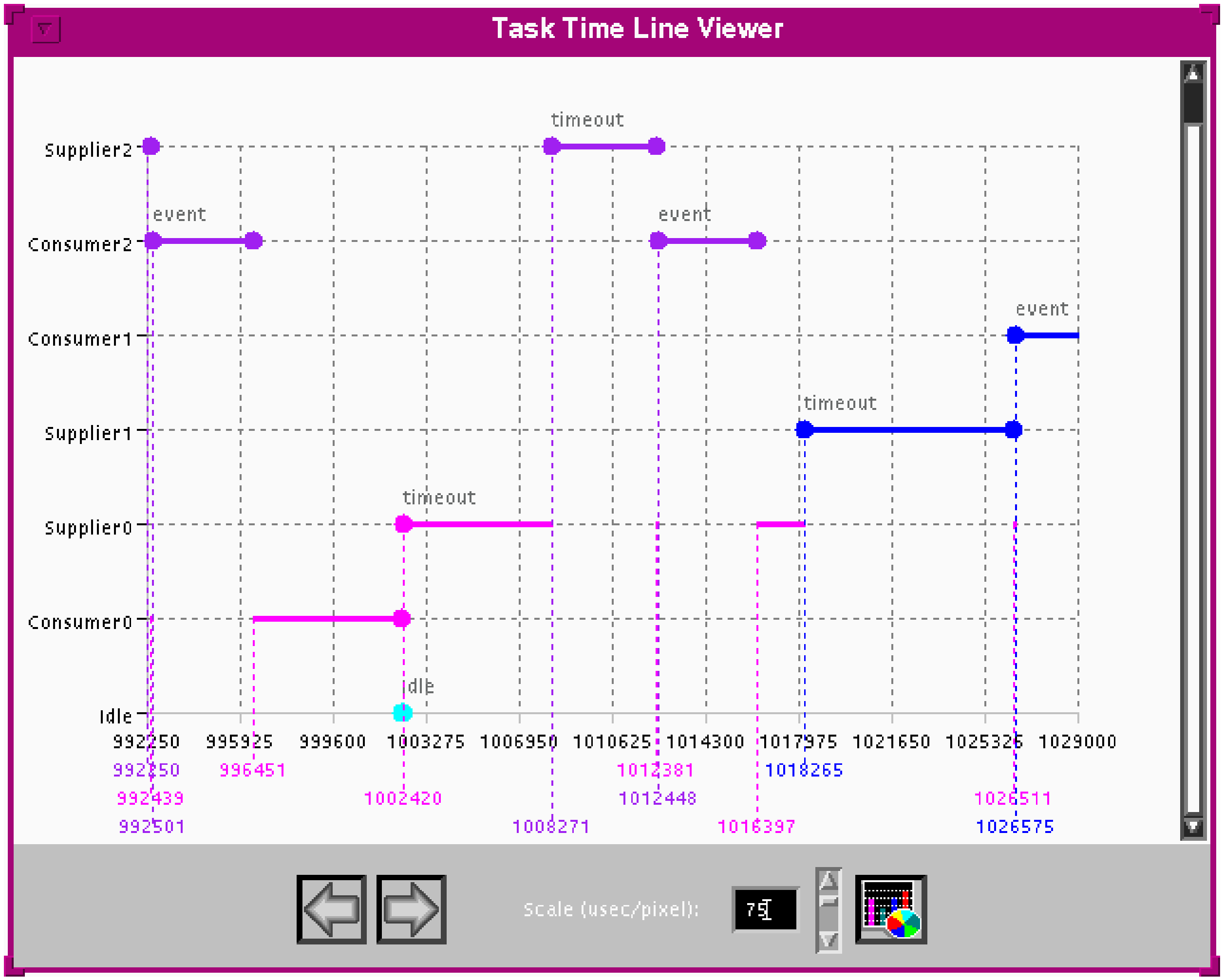


Avionics

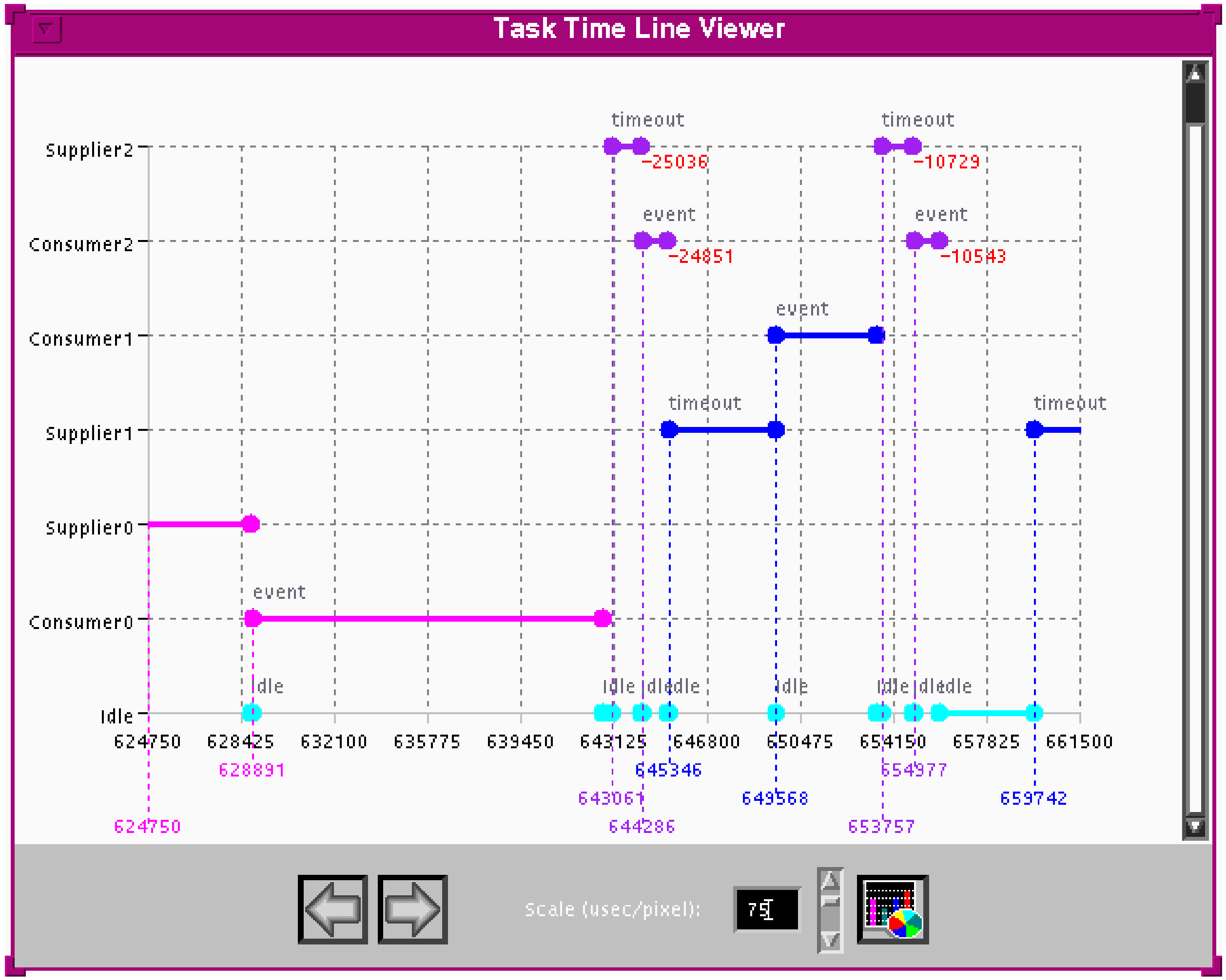


Network management

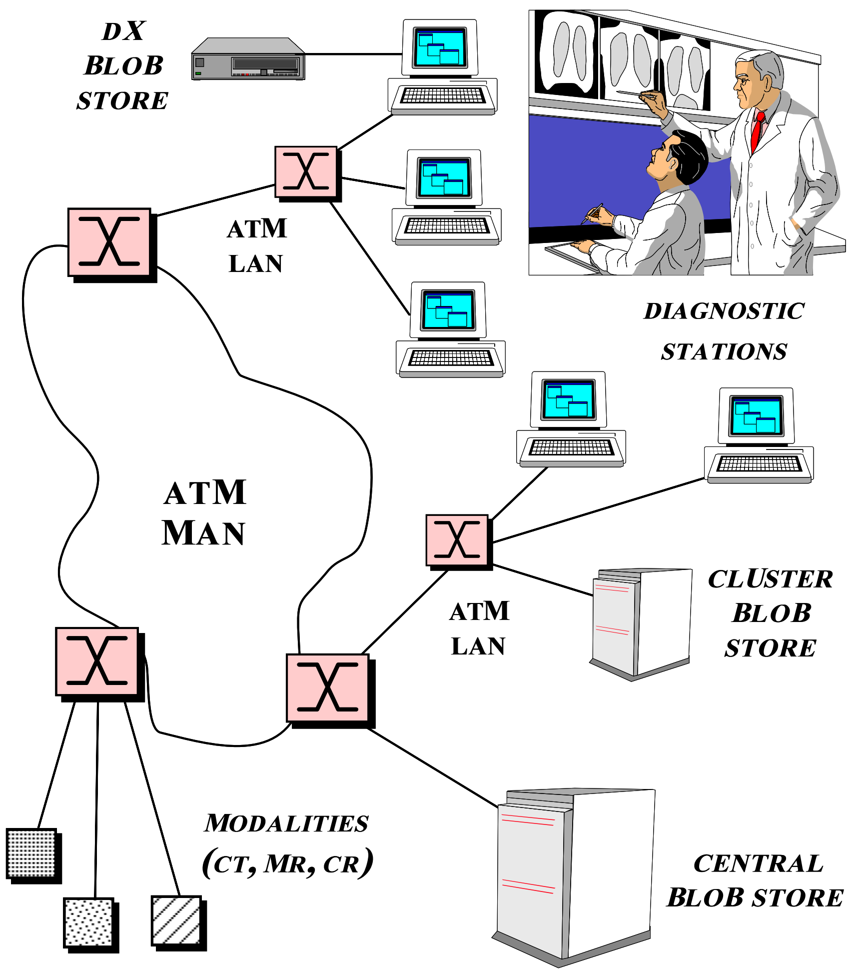
Timeline for Multi-threaded Object Adapter



Timeline for FIFO Object Adapter

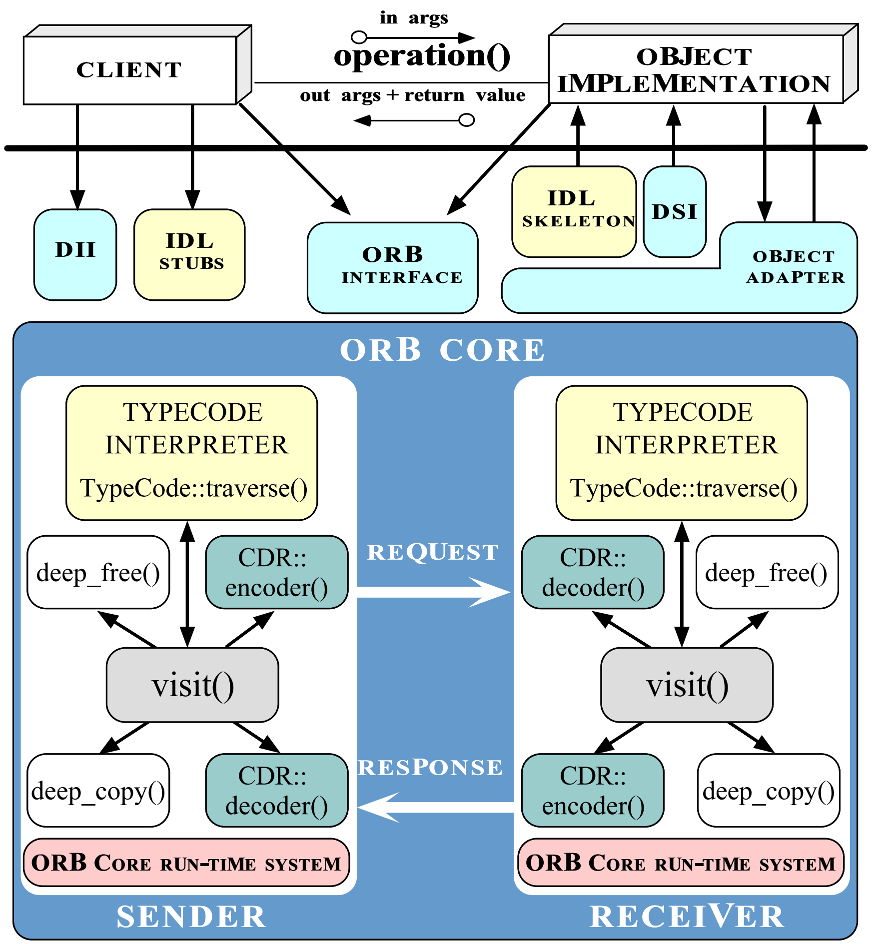


Applying CORBA to Medical Imaging



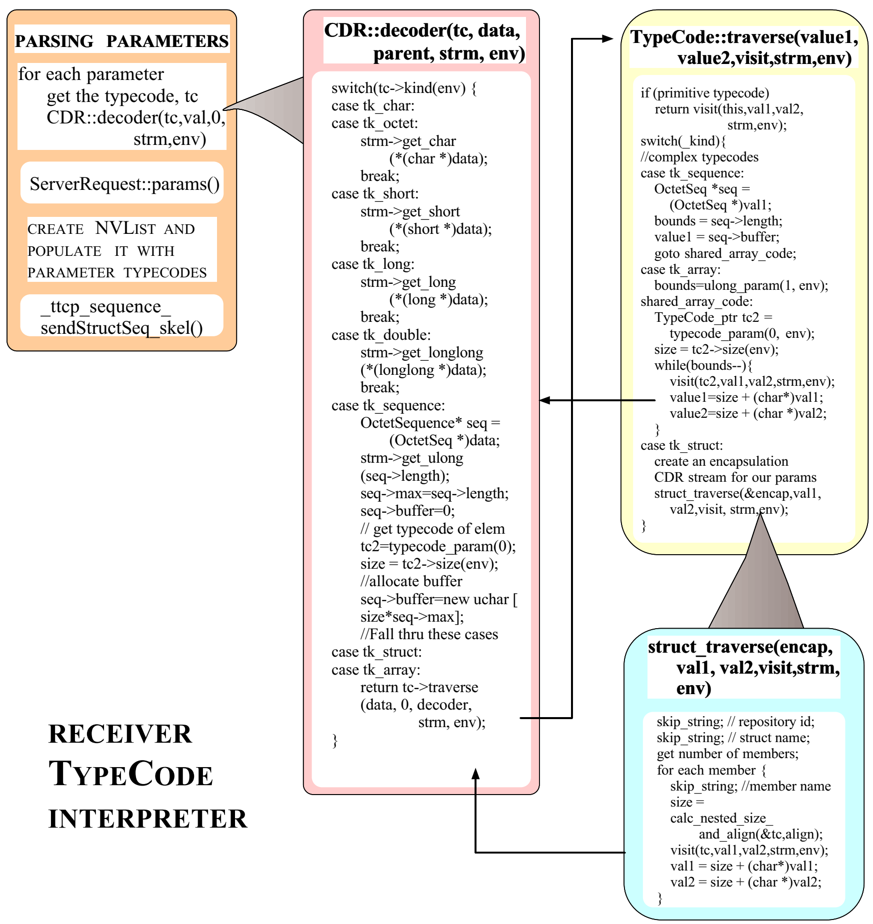
- **Domain Challenges**
  - Large volume of "Blob" data
    - *e.g.*, 10 to 40 Mbps
  - Lossy compression isn't viable
  - Prioritization of requests

Problem: Reducing Protocol Engine Overhead



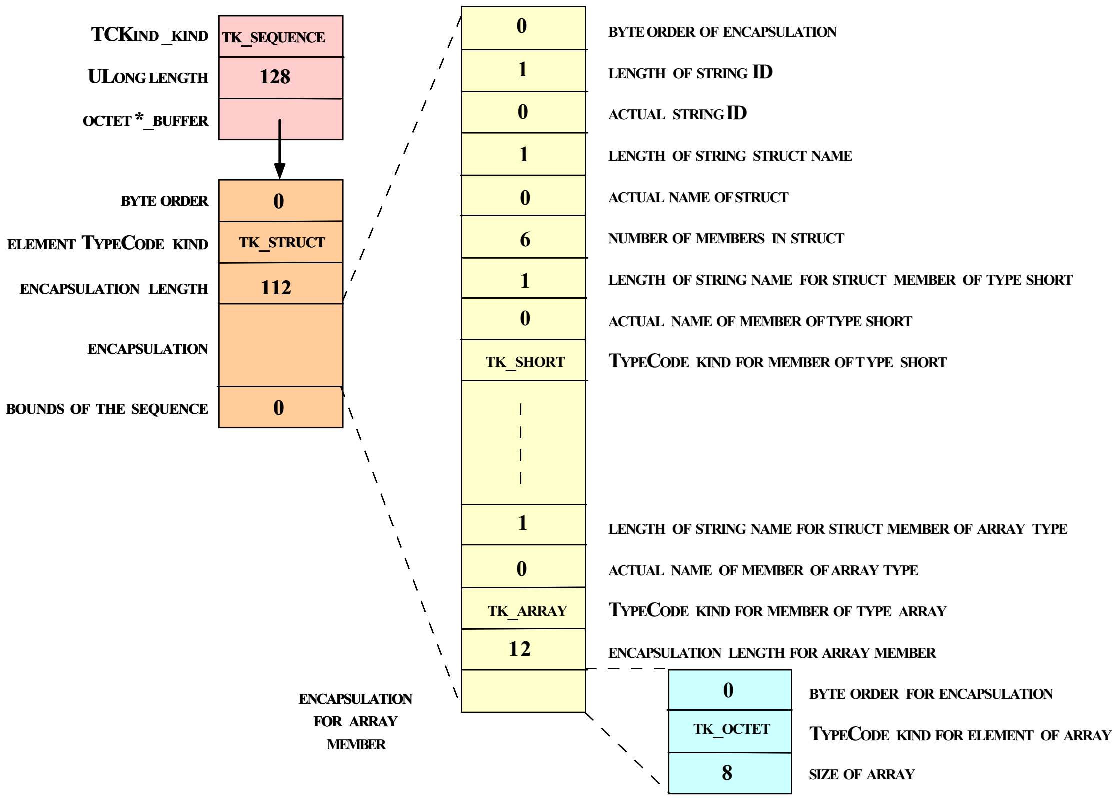
- **Design Challenges**
  - Small memory footprint
  - Predictable performance
  - Minimize the typecode interpreter overhead

Solution: TypeCode Interpreter Optimizations



- **Solution Approach**
  - Optimized Typecode Interpreter
  - Based on SunSoft IIOP engine
- **Related work**
  - Hoschka '97
  - O'Malley, Proebsting, and Montz '94

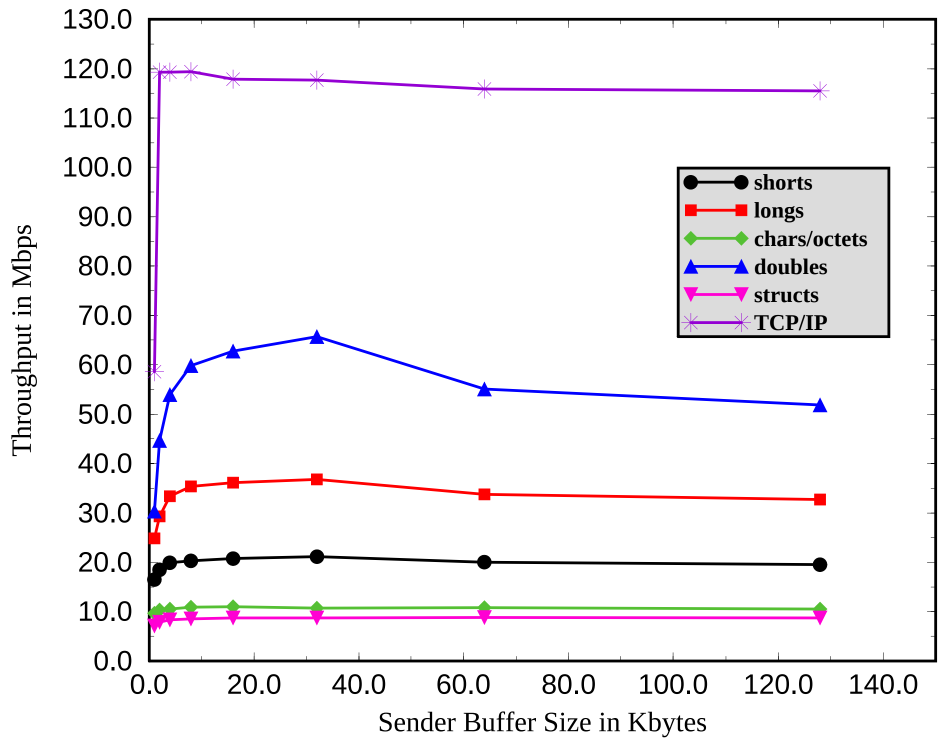
TypeCode Layout for Sequence of BinStructs



- TypeCode Description in CDR format

```
// 32 bytes
struct BinStruct{
  short s; char c; long l;
  octet o; double d;
  octet pad[8];
};
typedef sequence<BinStruct>
        StructSeq;
```

Throughput of the SunSoft IIOP Implementation



- Experimental design
  - Transfer 64 Mbytes of "oneway" data
  - Various types of data

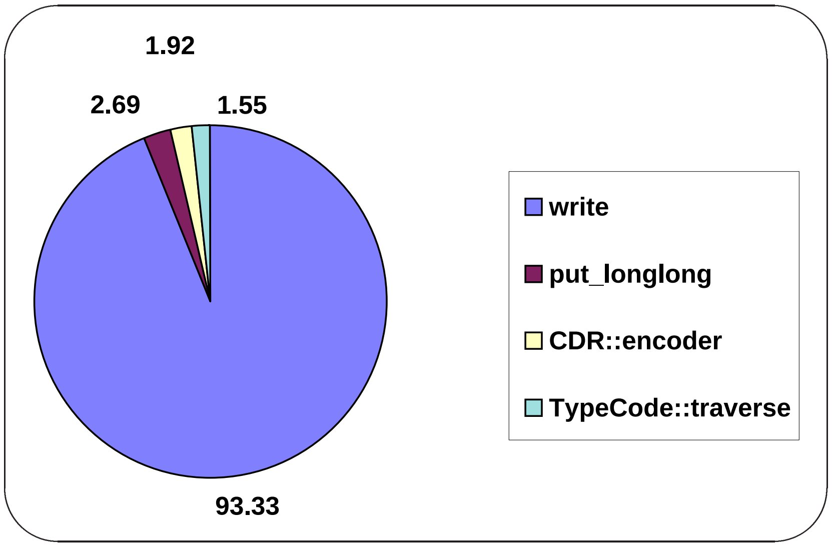
Challenges of Optimizing Complex Softare

- Problem
  - Optimizing complex software is hard
  - Small "mistakes" are costly over high-speed networks
- Solution Approach (Iterative)
  - Pinpoint sources of overhead via *white-box* metrics
    - *e.g.*, `Quantify`, `TNF`, etc.
  - Apply optimization principles
  - Validate via white-box and black-box metrics

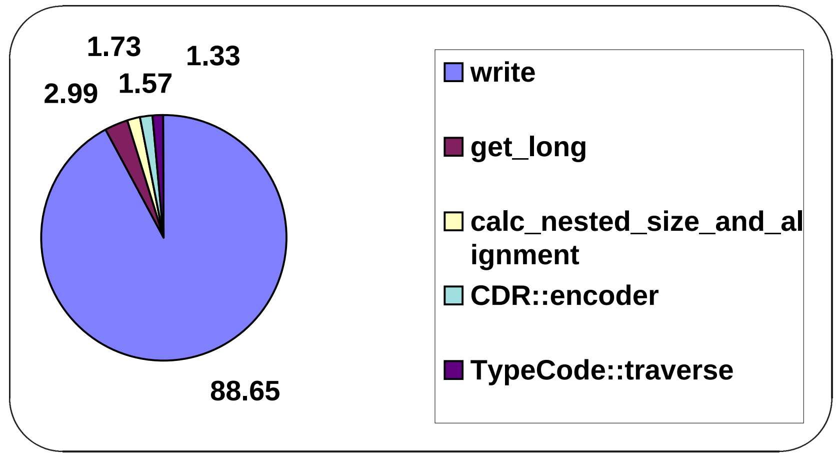
Optimization Principles

Number	Principle
1	Optimize for the common case
2	Eliminate gratuitous waste
3	Replace inefficient general-purpose methods with efficient special-purpose ones
4	Precompute values, when possible
5	Store redundant state to speed up expensive operations
6	Pass information between layers

Sender-side Analysis of SunSoft IIOP Implementation



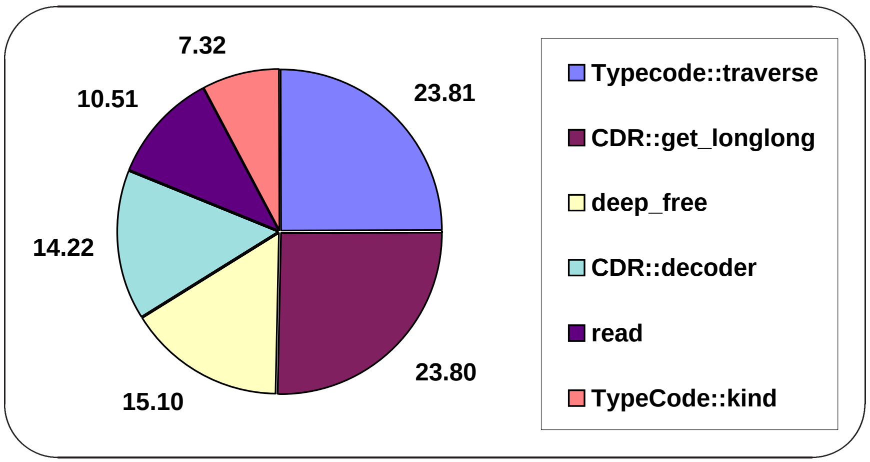
double



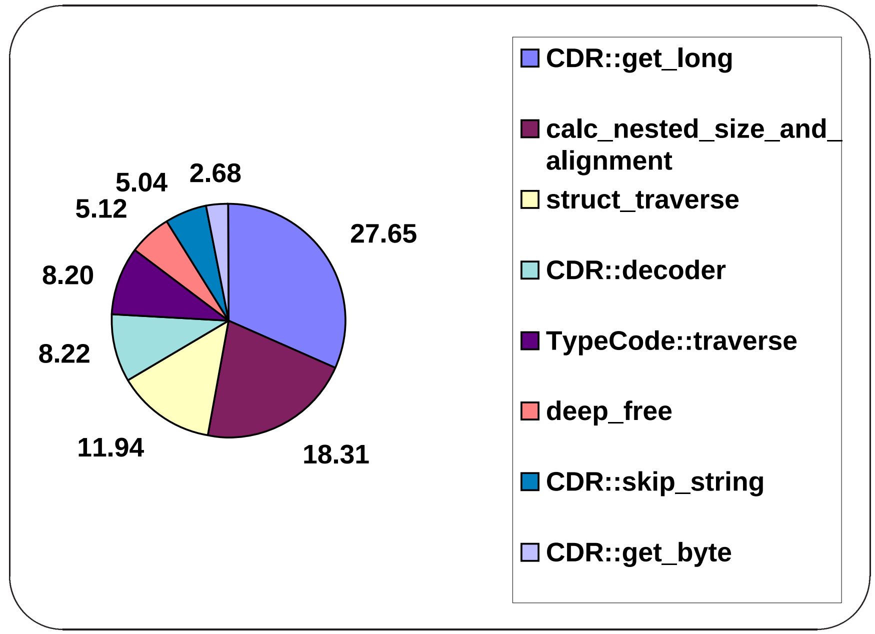
struct

Percent Execution Time for doubles and structs

Receiver-side Analysis of SunSoft IIOP Implementation



double



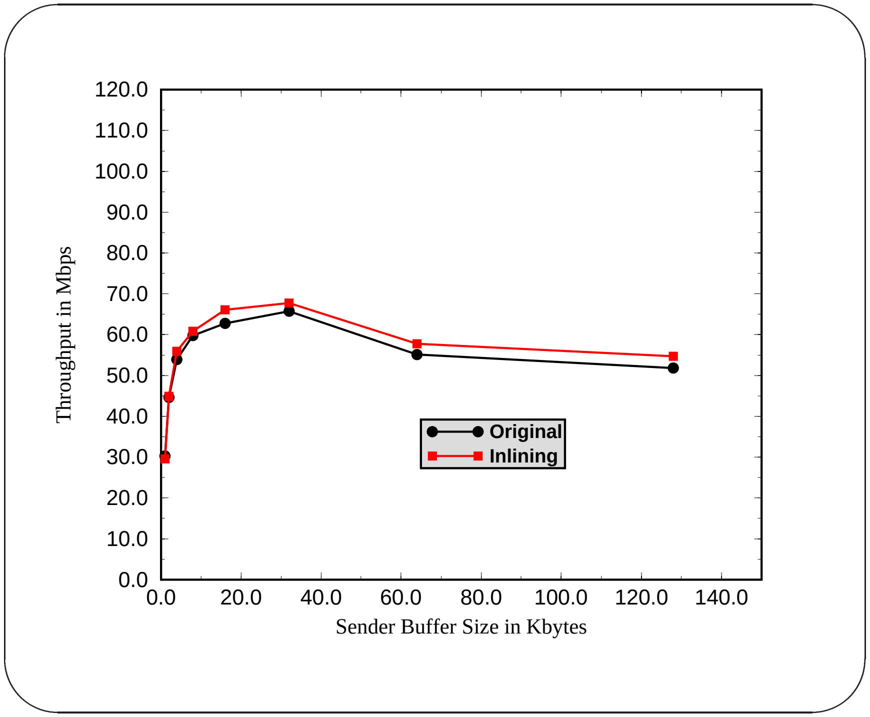
struct

Percent Execution Time for doubles and structs

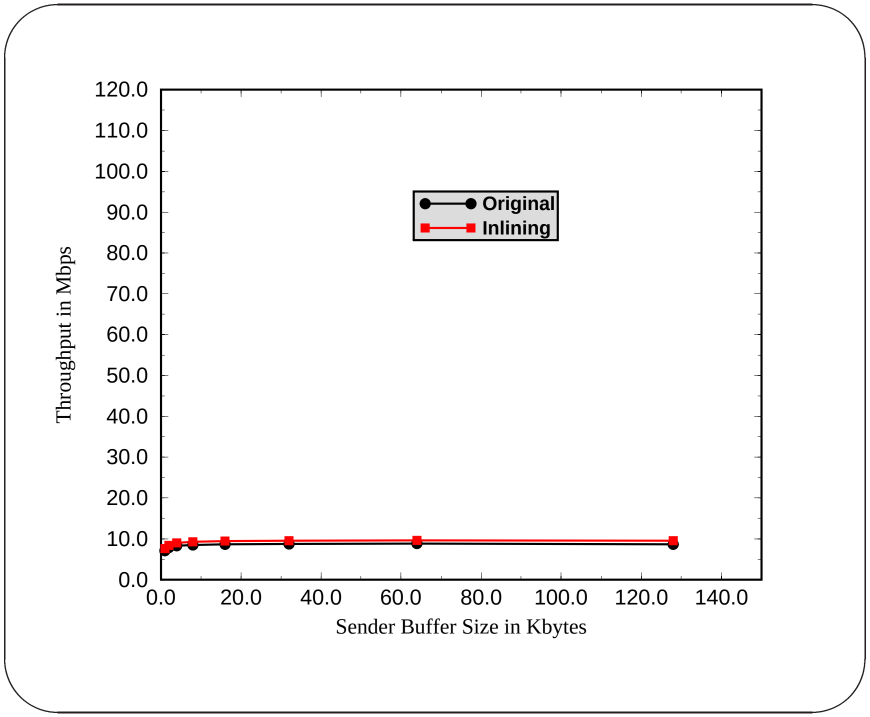
Problems and Solutions

- Problems
  - Invocation overhead for small, frequently called methods
- Solution
  - Inline method calls
- Principle
  - Optimize for the common case

Throughput After 1st Optimization



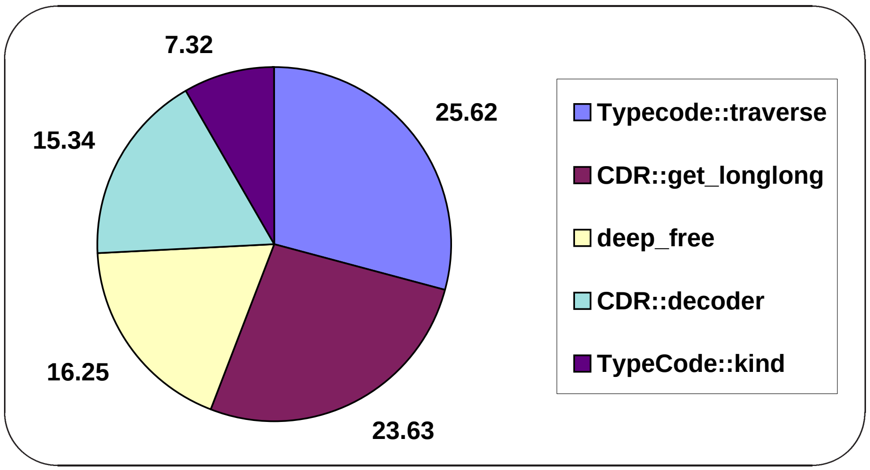
double



struct

Throughput for doubles and structs

Receiver-side Analysis of IIOP Implementation (1st Opt)



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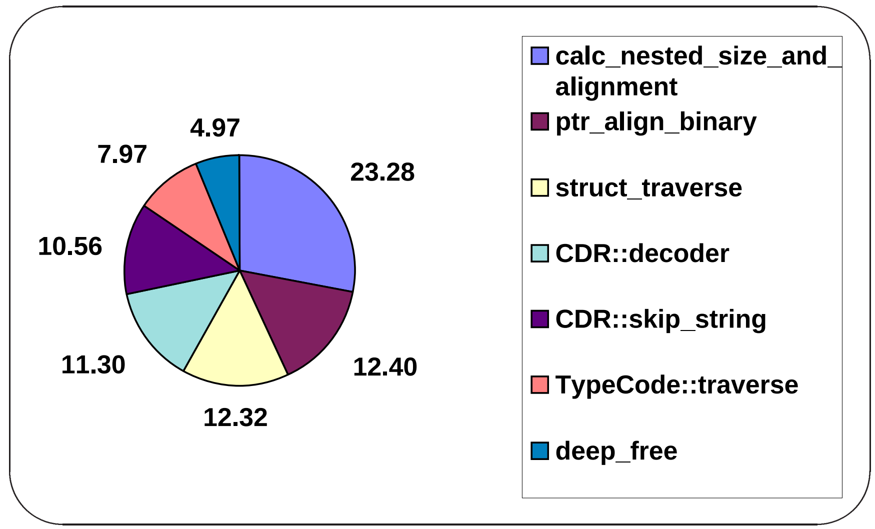


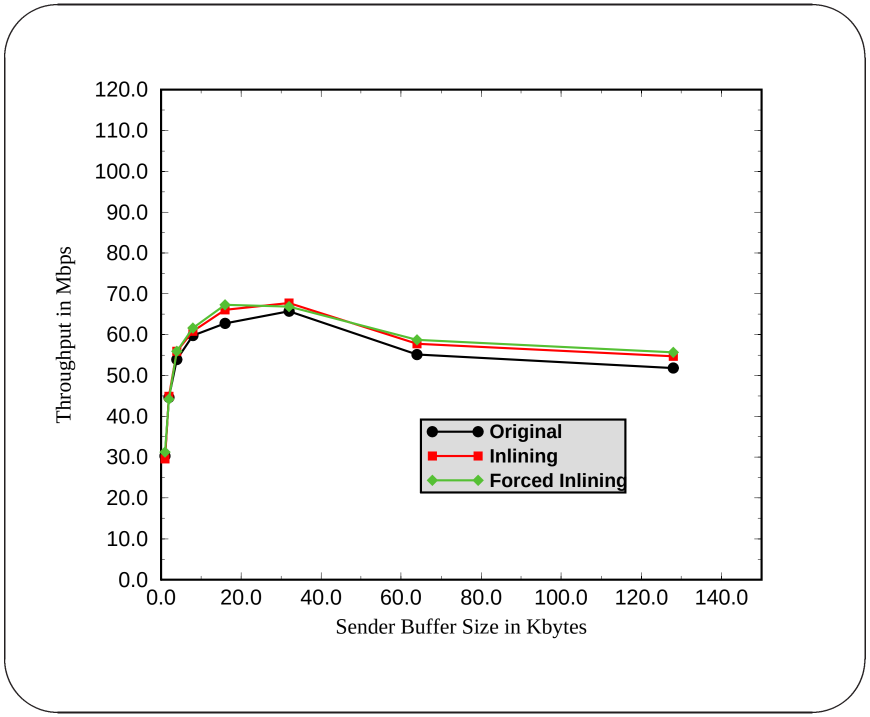
struct

Throughput for doubles and structs

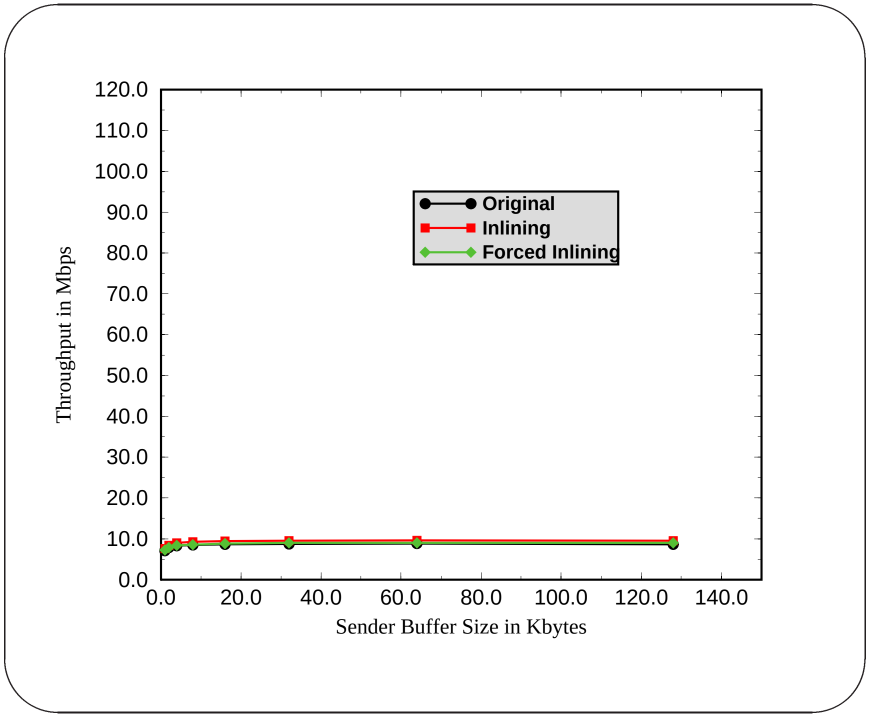
Problems and Solutions

- Problems
  - Lack of C++ compiler support for aggressive inlining
- Solution
  - Replace inline methods with preprocessor macros
- Principle
  - Optimize for the common case

Throughput After 2nd Optimization



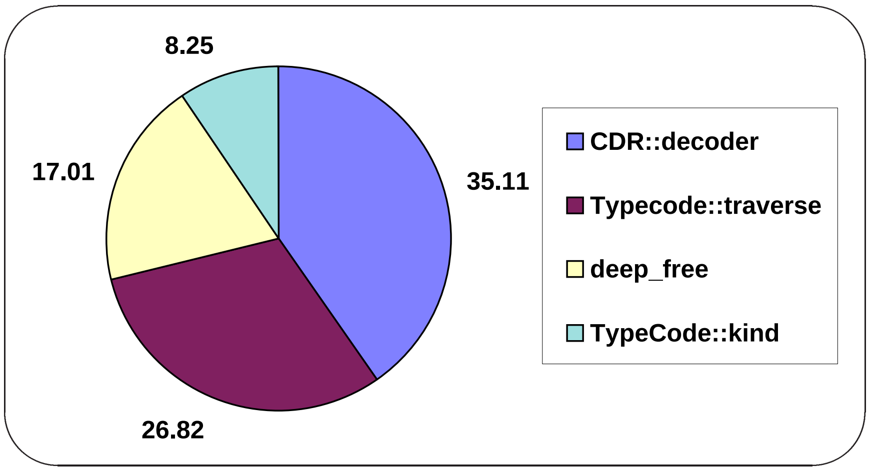
double



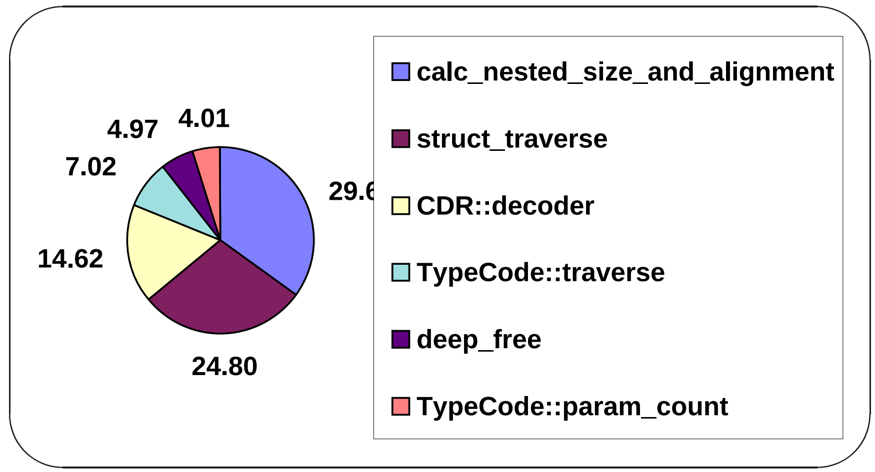
struct

Throughput for doubles and structs

Receiver-side Analysis of IIOP Implementation (2nd Opt)



double



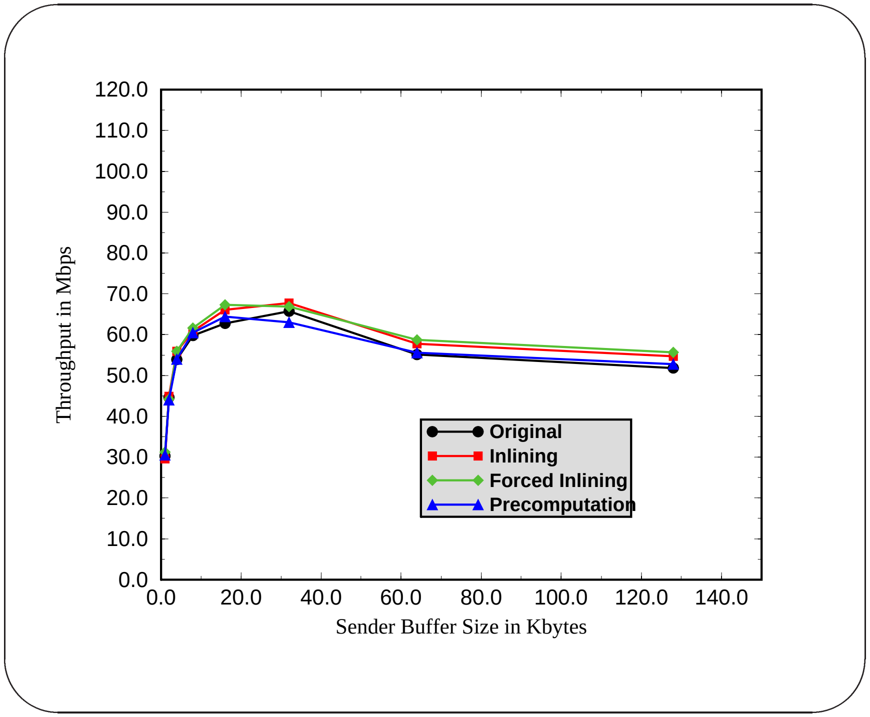
struct

Percent Execution Time for doubles and structs

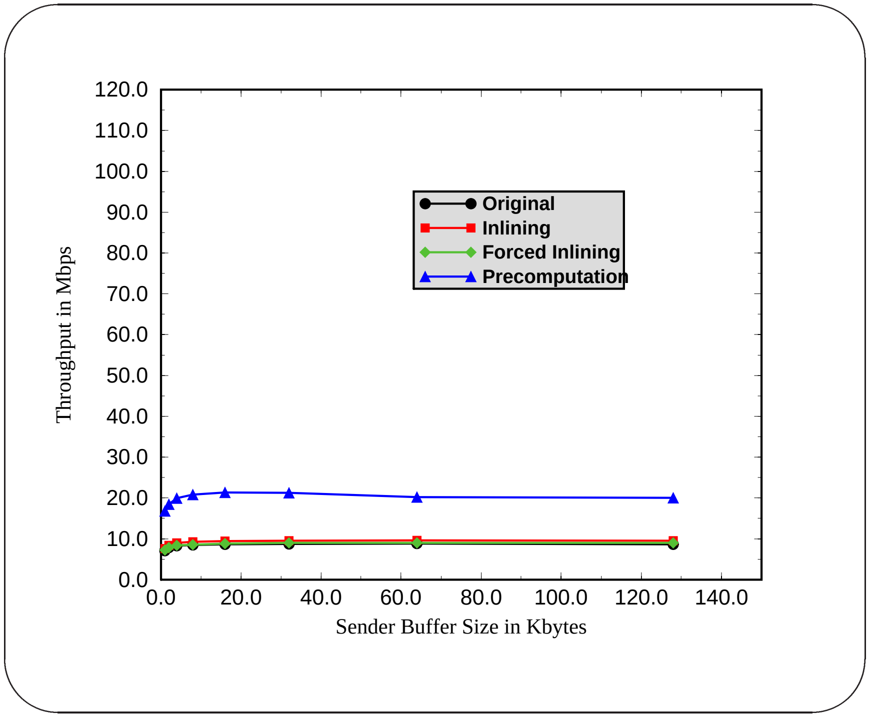
Problems and Solutions

- Problems
  - Too many method calls
  - Computing the same quantity repeatedly
- Principles
  - Precompute
  - Add extra state
  - Pass information through layers
  - Convert generic methods to special-purpose ones

Throughput After 3rd Optimization



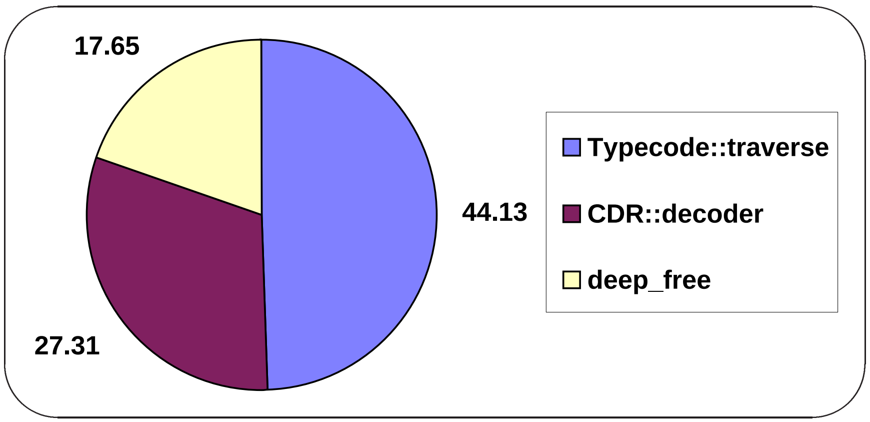
double



struct

Throughput for doubles and structs

Receiver-side Analysis of IIOP Implementation (3rd Opt)



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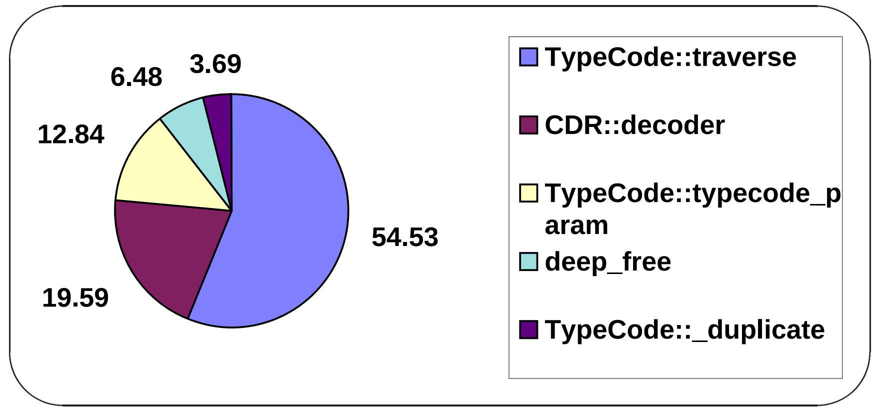


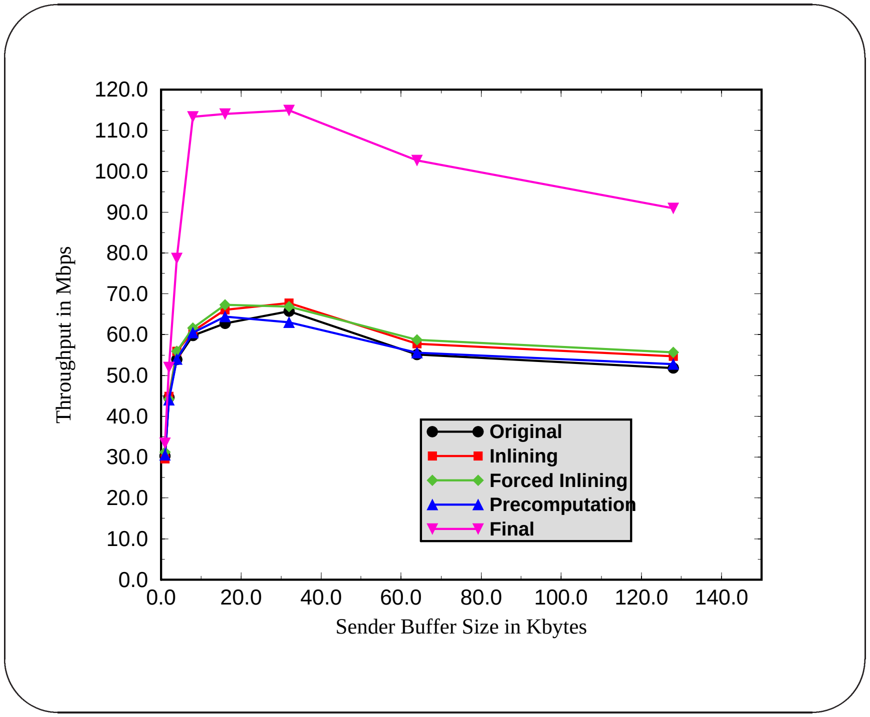
struct

Percent Execution Time for doubles and structs

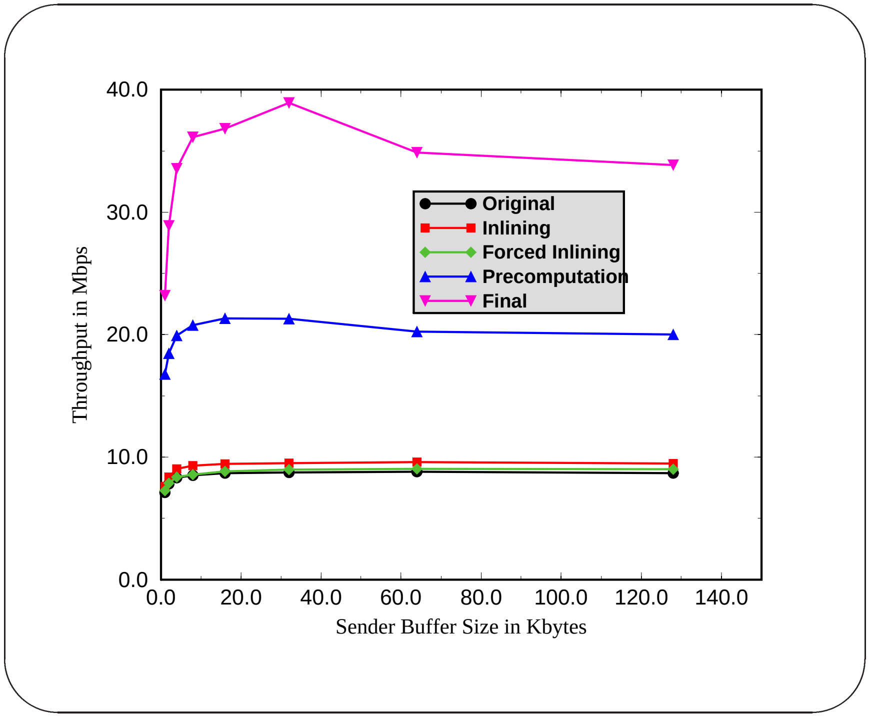
Problems and Solutions

- Problems
  - Expensive no-ops for memory deallocation
- Principles
  - Eliminate gratuitous waste
  - Specialize generic methods

Throughput After Optimizations



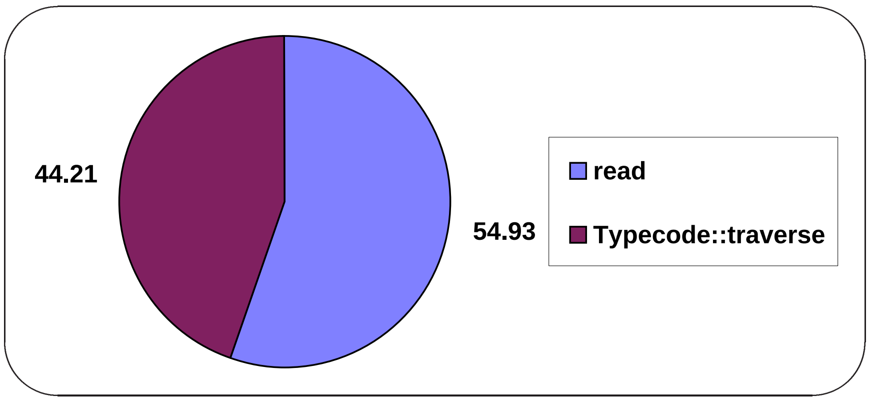
double



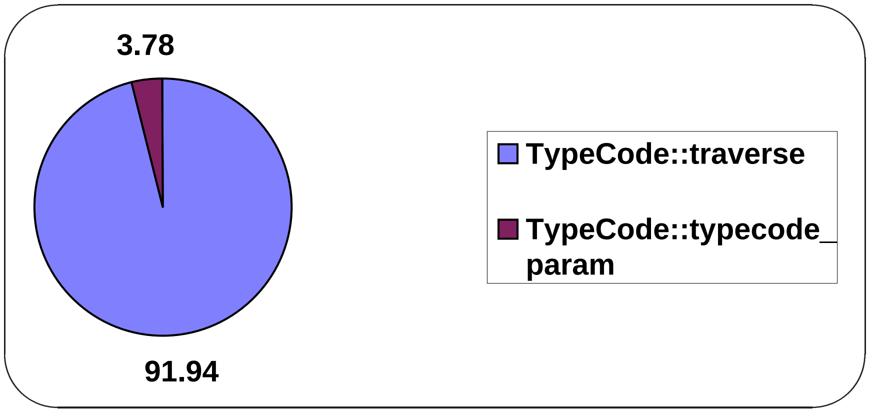
struct

Throughput for doubles and structs

Receiver-side Analysis of IIOP Implementation after Optimizations



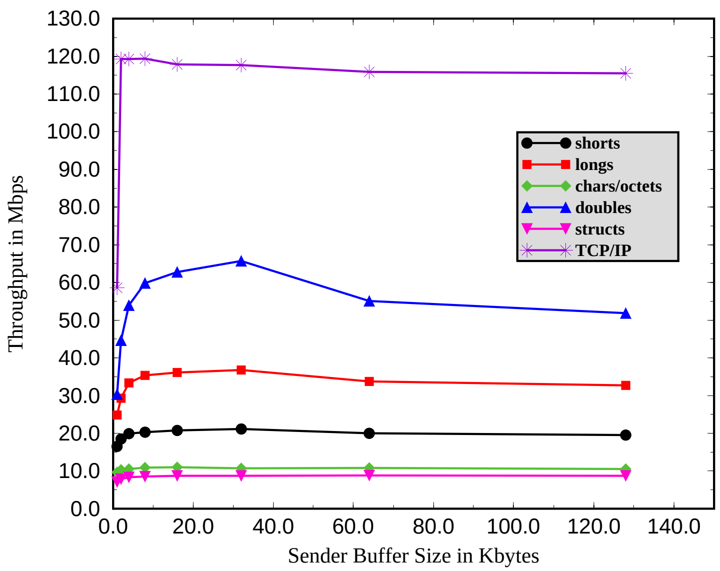
double



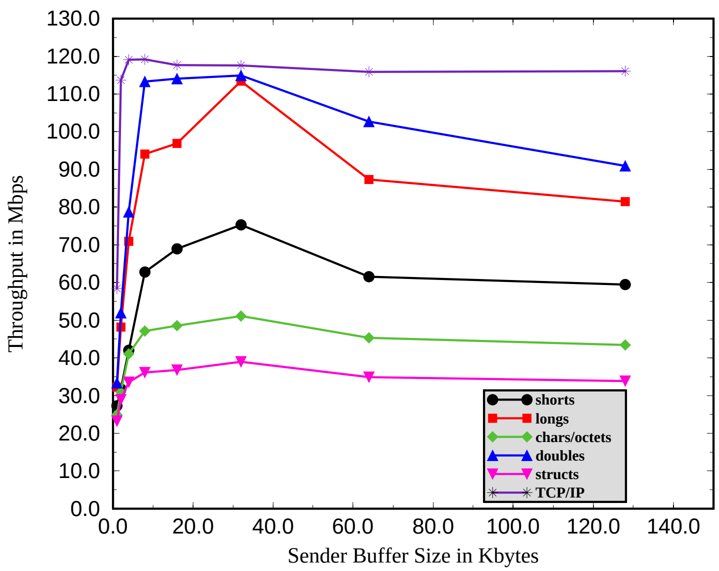
struct

Percent Execution Time for doubles and structs

Throughput Comparisons



Original SunSoft



Optimized TAO

Throughput for SunSoft and TAO Versions of IIOP

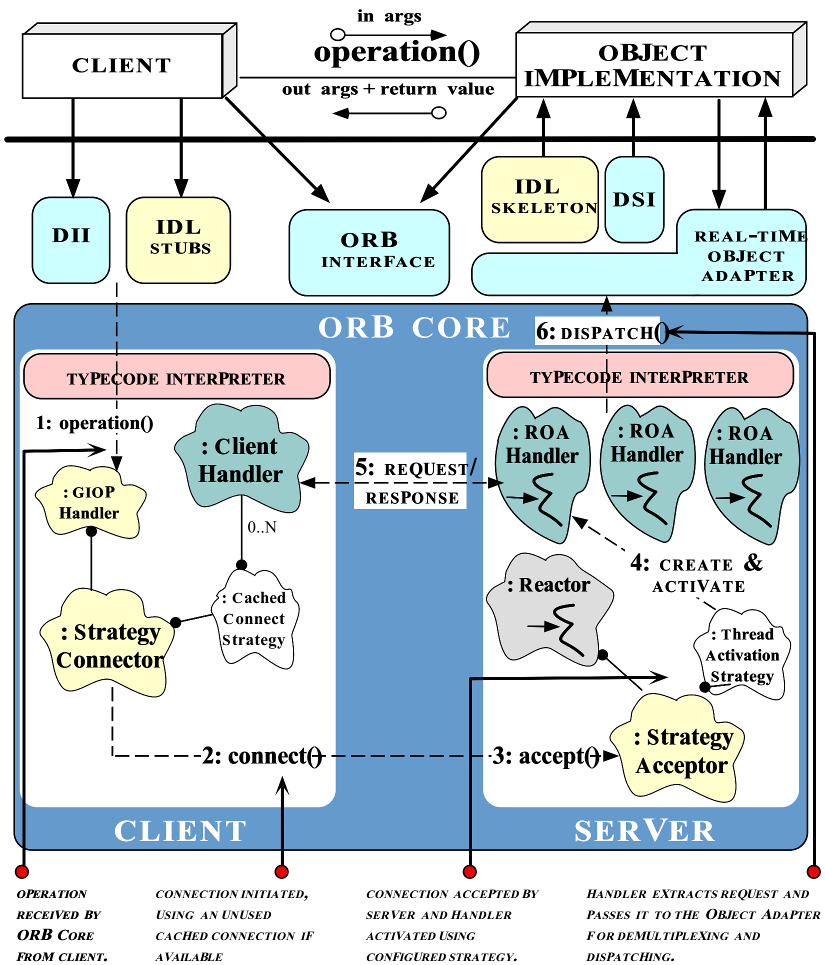
Results for Typecode Interpreter Optimizations

- Our measurement-driven, principle-based optimization process improved TAO's IIOP protocol engine performance as follows
  - 1.8 times for doubles
  - 3.3 times for longs
  - 3.75 times for shorts
  - 5 times for chars/octets
  - 4.2 times for structs
- Results available at `http://www.cs.wustl.edu/~schmidt/IIOP.ps.gz`

Current Status of TAO

- IDL Compiler
  - Based on Sun "IDL" front-end + our back-end
- RIOP Protocol Engine
  - Optimized version of Sun's GIOP/IIOP protocol engine with real-time enhancements
- ACE ORB Core
  - Multi-threaded ORB run-time system based on ACE
- Real-time Object Adapter
  - Demultiplex, schedule, and dispatch client requests in real-time
- Object Services
  - Real-time Event Channels and Multimedia Streaming Service

Developing an ORB Core with ACE



- **Components**
  - Acceptor/Connector
    - Parameterized via *strategies*
  - Reactor
    - Demuxes client requests
  - Active Objects
    - Processes client requests

Concluding Remarks

- 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 Object Adapter
    - *i.e.*, support static request scheduling
  - 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
  - TypeCode compiler optimizations