A Pattern Language For Improving the Capacity of Layered Client/Server Systems with Multi-Threaded Servers

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ABSTRACT

The paper describes a set of patterns that extend the pattern language proposed in [Meszaros96] for improving the capacity of reactive systems. The intent of these patterns is to identify some specific causes that limit the efficiency of a distributed layered client-server system with multi-threaded servers, and to find appropriate corrective measures. The type of systems considered here is a subclass of the larger category of reactive systems, and the new patterns are dealing with their specific performance characteristics. The effects of the patterns are illustrated with performance measurements conducted on a layered client-server system.

INTRODUCTION

Problem Domain

Many distributed applications are based on the client-sever paradigm, and use various kinds of software servers (as, for example, name servers, databases, network file servers, web servers, etc.) The performance of such systems depends strongly not only on the contention and queueing delays for hardware devices (such as processors, I/O devices, communication networks, etc.) but also on the contention for software servers. In order to satisfy the requests of its clients, a software server needs to access the services of one or more subservient servers, which may be either hardware or software. For example, a web server executing a client requests runs on its own processor and makes alternate requests to a network file server and a database server, each of which, in turn, needs the services of a processor and of one or more I/O devices (see Figure 1). Under high load, the system capacity may be limited either by one of its hardware resources or by one of its software servers. A typical (but not the only) class of such systems is known as a three-tier client/server architecture, used particularly for large business applications [Aarsten+96], [Hirschfeld96]. The system functionality is distributed into three tiers: front-end clients, middle application servers and back-end database server.

For performance analysis purposes, it is useful to represent a system with software servers as a *layered client/server model* (see Figure 1), in the form of a directed acyclic graph whose nodes represent clients and servers, and whose arcs denote service requests. The software entities are represented as parallelograms, and the hardware devices as circles. The nodes with outgoing and no incoming arcs are the

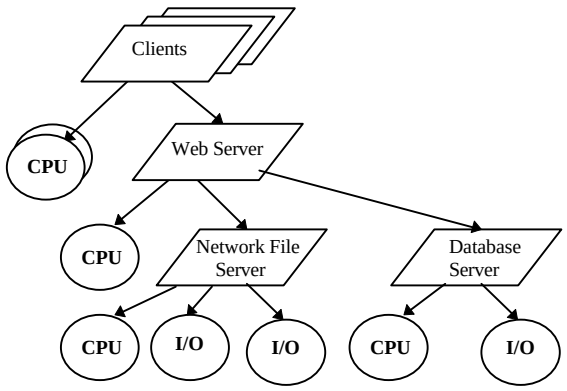


Figure 1. Example of a layered client/server system

clients, the intermediate nodes with both incoming and outgoing arcs are usually software servers, and the leaf nodes are hardware servers. It is worth to mention that a layered system does not imply a strict layering of servers (for example, servers in the same layer can call each other or can skip over layers).

The layered client/server model has been developed in previous work as a performance modelling approach that extends the well-known Queueing Network model in order to capture and solve analytically the performance characteristics of systems with software servers [Woodside+95], [Rolia+95], [Franks+96].

Set of Proposed Patterns

The layered client/server systems, as all reactive systems, have to meet performance requirements at a reasonable cost under high loads. The set of patterns proposed in the paper extend the pattern language for improving the capacity of reactive systems introduced in [Meszaros96], by considering cases where the limiting capacity factor is a software server. The new patterns are also complementary to another pattern language regarding the distribution of functionality in three-tier client/server systems presented in [Aarsten+96], [Hirschfeld96].

Figure 2 shows the patterns described in the paper and their relationships with some of the patterns (shown in boxes) from [Meszaros96] (the patterns in plain boxes are described in detail in the reference, those in dashed boxes only mentioned briefly). In order to limit the size of the diagram, only those patterns from [Meszaros96] which have a direct relationship with the newly proposed patterns are shown here.

Capacity Bottleneck pattern [Meszaros96] deals with identifying the limiting factor in a system's capacity, leading to a number of patterns related to the type of resource that is the actual limit*:*

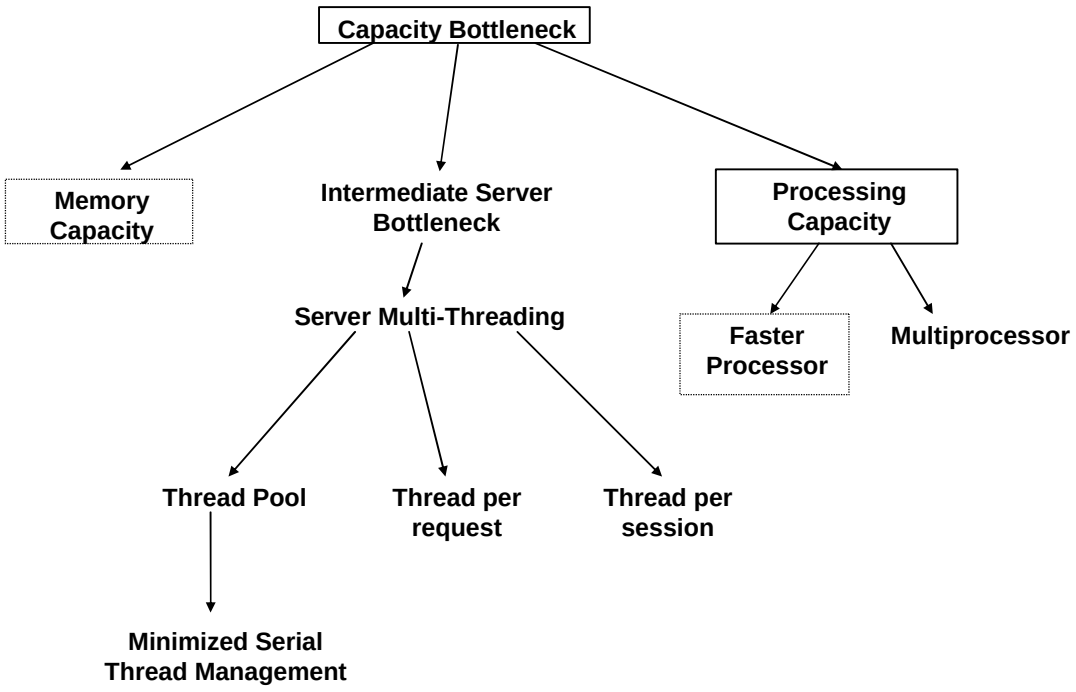


Fig. 2. The relationships between the proposed patterns and the pattern language for improving the capacity of reactive systems introduced in [Meszaros96]

Processing Capacity, Memory Capacity, Messaging Capacity. This paper shows that another type of limiting resource exists -- a software server, as shown in the *Intermediate Server Bottleneck* pattern. This kind of phenomenon was described in previous performance analysis work, such as [Neilson+95] and [Franks+96], but it was never expressed in pattern form, nor was it related to existing pattern languages. The *Server Multi-threading* pattern shows how to alleviate such a bottleneck by increasing the concurrency level of the server. This pattern is specialized by the next three patterns, *Thread per request, Thread per session* and *Thread pool*, describing three different solutions to the same problem that occur in different contexts. *Minimized Serial Thread Management* shows how to further increase the system efficiency when using the thread pool technique. The *Multiprocessor* pattern points to a hardware solution for improving the system performance. The patterns are written by following the style and techniques presented in [Meszaros+96].

In this work we have not considered shedding-the-load strategies and the related patterns from [Meszaros96], which are very appropriate for "open" reactive systems, such as telephone switches, where the arrival rate of requests varies widely and may very well go higher than the capacity of the system. We have considered here "closed" systems with a limited number of clients which do not give up on their requests, wait patiently to be served and may send a new request only after the previous one has been completed. However, the layered client-server systems may have open arrivals, in which case shedding-the-load patterns will also apply. Moreover, the patterns introduced in this paper are not limited to closed layered server systems, but apply to any reactive systems with software servers.

INTERMEDIATE SERVER BOTTLENECK

Problem

A software server receiving requests from multiple clients may be the limiting resource in the system at high request rates, becoming the system bottleneck. Its request input queue builds up faster than any other queues, and the server is the first element to saturate under increasing load by reaching its maximum utilization. An intermediate server bottleneck prevents its subservient hardware resources from being used at their full capacity. How do we recognize when the system bottleneck is a software server and not a hardware one?

Context

We are using a system with one or more software servers, that can be represented as a layered client/server model. A software server may offer a range of service types to its clients, each one with different execution times and resource requirements. The *capacity* of a software server (i.e., the maximum rate at which the server is able to complete requests) can be determined by considering that the server is busy 100% of the time. The capacity depends on the following elements:

- the number of requests *processed* simultaneously by the server (not those waiting in the input queue)
- the average time for a request that is a weighted average of service times for different request types
- the service time for a given request type that is the sum of server's own execution time plus the nested services provided by the subservient servers.

$$Capacity = Nb\_simult\_requests / Average\_service\_time$$

$$Average\_service\_time = Sum (Request\_type\_service * Percentage\_of\_this\_request\_type)$$

$$Request\_type\_service = Own\_excecution\_time + Sum (Nested\_service\_times)$$

The own execution time in the last relation includes both the actual CPU time used by the server on the behalf of a given request type, and the waiting delay for the CPU. The nested service times also include actual service plus queueing. It can be seen from these relations that the capacity of a software server cannot be easily estimated with a simple back-of-the-envelope approach, because it depends

not only on the server's requirements for resources, but also on the queueing delays in the whole system.

Forces

- We want a software system able to offer a high capacity by using the available hardware resources as efficiently as possible.
- The system bottleneck must be correctly identified, since any attempt to improve the overall performance has to deal with the bottleneck first.
- Increasing the capacity of a resource that is not the bottleneck will have little or no effect on the overall system performance.
- An intermediate server "feeds" work to its subservient servers, and may become the limiting factor in the system if it is unable to keep them busy enough. In other words, an intermediate server becomes the bottleneck if it is saturated whereas its subservient servers are under-utilized.
- While work propagates top-down (from clients to leaf servers), utilization propagates bottom-up. A saturated server tends to saturate its users. However, the primary limiting factor in such a case is the lower level server.

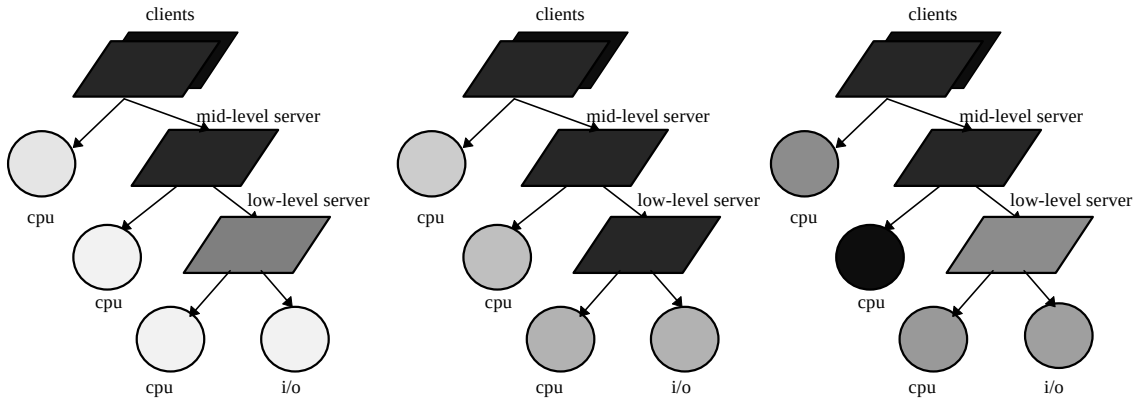
Solution

Understand which element is limiting the capacity of the system by analyzing the utilization of different servers at high load. The limiting element may be either a leaf or an intermediate node.

If all the leaf nodes in the graph are under-utilized and one or more intermediate nodes are highly utilized, then we have a case of *intermediate server bottleneck*. The bottleneck is a saturated software server whose subservient servers are all under-utilized. A larger difference in utilization means a stronger bottleneck. Figures 3.a and 3.b illustrate two cases of software bottleneck in a simple layered client/server system with a mid-level and a low-level software server. Different degrees of shading represent different utilization levels, the darkest corresponding to components that are busy all the time. Note that a bottleneck located at a higher-level software server allows for less work to be "fed" to the lower level servers, enforcing stronger limitations on the system capacity. For example, the case shown in Figure 3.a is more inefficient than the one in Figure 3.b. In order to alleviate a software bottleneck, apply the rest of the patterns presented in the paper.

If a leaf node has a very high utilization, then it represents a *hardware bottleneck* which should be treated with one of the capacity bottleneck patterns presented in [Meszaros96]. In general, a system with a hardware bottleneck is more efficient than a similar one with a software bottleneck, since the hardware resources are better utilized.

Note that a highly utilized software server with at least one saturated subservient server is not the



a) Software Bottleneck: mid-level server

b) Software Bottleneck: low-level server

c) Hardware Bottleneck: CPU of mid-level server

Fig. 3 Example of software and hardware bottleneck (degrees of shading represent utilization levels, the darkest one corresponding to saturation)

bottleneck -- the subservient server is. A special case is that of a software server using a single subservient server (as for example, a CPU-bound software server running on a single CPU). Such a software server will have the same utilization as its unique subservient server. When both are saturated, the lower server is the system bottleneck.

Example

Consider the layered system from Fig.3, implemented and measured as described in the appendix, where the mid-level server is single-threaded and can process only one request at a time. The measurements for the utilization of different servers and system throughput are shown in Figure 4. The system reaches saturation at around 11 clients, after which the throughput holds steady because the system has reached its maximum capacity. The limiting factor can be identified by looking at the utilization (i.e., the percentage of time each server is busy) at high load: the mid-level server is 100% busy, while its CPUs and the low-level server are terribly under-utilized at below 20% (the utilization curves for the CPU and the low-level server are overlapped in the figure). The mid-level server is a software bottleneck.

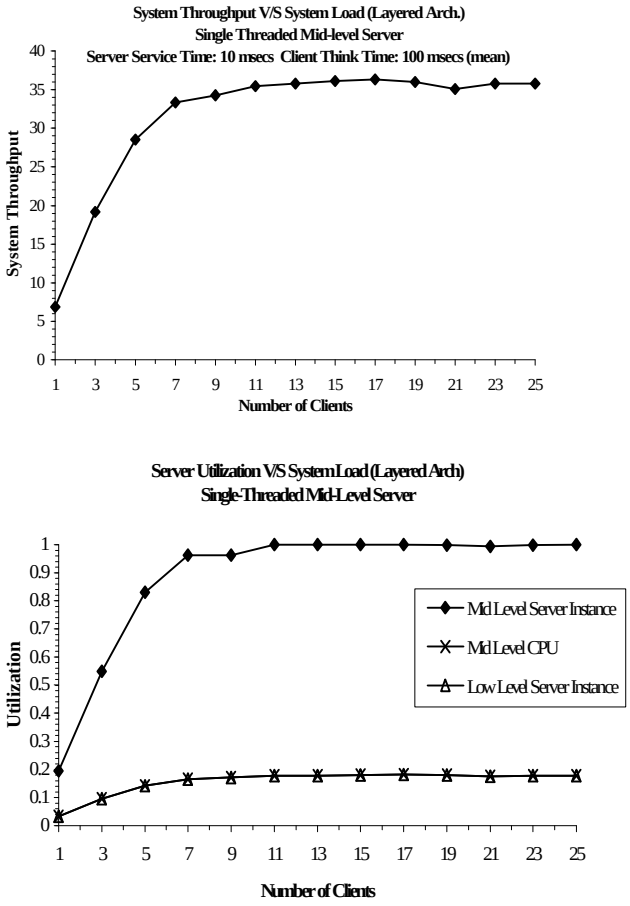


Fig. 4 Example of intermediate server bottleneck

Related Patterns

The *Intermediate Server Bottleneck* is the entry point to a number of patterns described below, whose intent is to increase the capacity of software servers and to alleviate cases of software bottleneck, improving therefore the overall system performance.

SERVER MULTI-THREADING

Problem

The capacity of a layered system is limited by one of its intermediate servers, which prevents the hardware resources from being used efficiently. How can we relieve this type of bottleneck?

Context

Apply this pattern when the following two conditions are met: the capacity of the software bottleneck server is limited because it was built as a sequential program (processing one request at a time), and more than one subservient server is used. The serializing effect of the software server behaviour prevents its subservient servers from working in parallel, and therefore they remain under-utilized.

If an intermediate server requires *only* a single CPU (without any I/O or other subservient server) then there is nothing to be gained by multi-threading, since there is no potential for actual parallel execution of concurrent requests.

Forces

- Using concurrent servers that process requests in parallel leads to more efficient systems.
- Designing and debugging a reactive concurrent server that uses a single thread of control to process more than one request at the same time is rather difficult, especially if the services are complex. Such a server may never block, so it cannot use blocking or stream I/O, which are more user-friendly than non-blocking I/O. Concurrent events must be demultiplexed and dispatched to non-blocking event handlers, the context of requests to subservient servers must be saved, etc.
- Using multiple threads allows several requests to be processed in parallel. Each thread can process one request at a time, being programmed in a sequential style. A thread can block waiting for I/O, network communication or services from other servers, and can easily store the context of the request.
- If the parallel threads need to use shared resources such as data objects, additional complexity is introduced in the form of critical section problems (and require mechanisms such as mutex and read/write locks.)

Solution

Increase the concurrency level of a software server by multi-threading**.** There are several approaches to build a multi-threaded server which can be applied in different situations (as discussed in the next three patterns). Some solutions provide better performance in certain conditions, by paying a higher price in term of system resources. These solutions have been discussed in detail in [Smith+96].
Multi-threading is efficient only if the given software server uses more than one subservient server, and thus the concurrent requests can be processed in parallel.

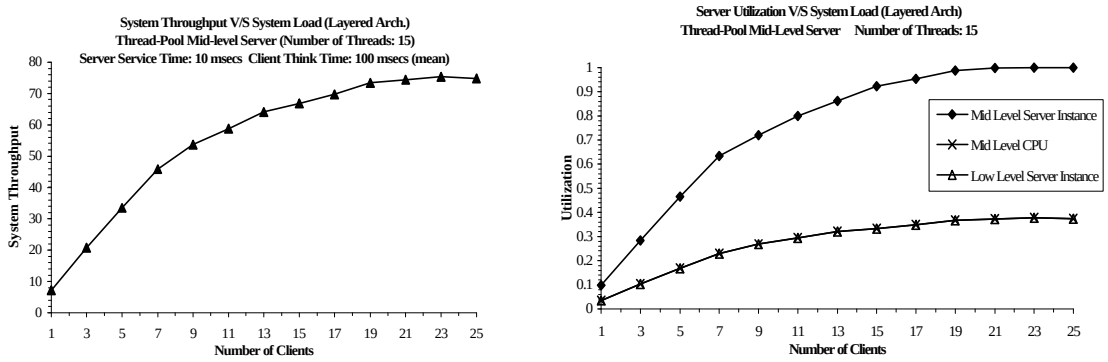


Fig. 5 Alleviate Intermediate Server Bottleneck by Multi-threading (15 threads)

The efficiency benefits brought by each additional thread tend to diminish when the number of threads increases. This effect is due to the fact that more threads lead to a higher competition for the subservient servers, and thus to longer queueing delays and nested service times.

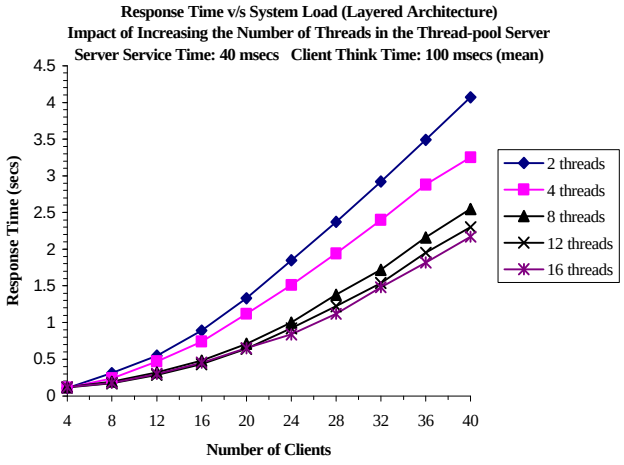


Fig. 6 Diminished returns with the increase in the number of threads

Examples

A first example in Figure 5 illustrates the effect of multi-threading the mid-level server, which was the system bottleneck in the case presented in Figure 4. The measurement results from Figure 5 illustrate the effect of using 15 threads in the mid-level server (according to the

thread pool approach discussed in one of the following patterns). The system throughput is more than double, saturation is reached for a higher number of clients, and the utilization of the two subservient servers has also doubled (the two utilization curves are still overlapped). The system bottleneck was alleviated but not completely removed, since the mid-level server still saturates first. Figure 6 shows how a gradual increase in the number of threads in the mid-level server brings diminished returns in terms of efficiency. Practitioners should use this knowledge when choosing the number of threads, such that the efficiency is increased without consuming too many system resources.

Related Patterns
The next three patterns, *Thread Per Request*, *Thread Per Session* and *Thread Pool*, specialize the current pattern, by describing three different solutions to multi-threading a server, each applicable in specific circumstances. *Thread Per Request* should be used when the requests are long and complex. *Thread Per Session* is appropriate for cases when clients make frequent requests for short services. *Thread Pool* is especially useful when a bound must be put on the consumption of system resources by the threads.

THREAD PER REQUEST

Problem
We want to apply the *Server Multi-threading* pattern in order to increase the capacity of a software server.

Context
The server must handle complex requests coming from multiple clients. Each request takes a relatively long time to process.

Forces
- We would like to apply a simple programming solution, and avoid a lot of thread management. Although each thread will take care of a single request (resembling a sequential program) the access to server data common to all threads requires synchronization primitives, which are an added complexity, can cause contention, overheads and can overwhelm the performance benefits of the concurrent execution (as shown in [McKenney96]).
- Increasing the number of threads leads to undue consumption of system resources (memory, file descriptors, etc.) and to execution overheads (thread creation and management, critical sections to protect shared data, etc.)
- Allocate resources (threads, memory, I/O ports, etc.) only when necessary, and release them as soon as possible.
- Session related data must be available to all requests related to that session.

Solution
The server spawns off a thread for each request when it arrives, and destroys the thread when the request is completed. The programming effort to spawn off the threads is quite limited, and the system resources are only held for the period the request is being served.

Resulting Context
The creational overhead for a thread is incurred for every request, which makes the technique useful only for long services. *Thread Per Session* and *Thread Pool* try to overcome this drawback in different ways. (Note that in Unix systems, which are optimized for lightweight thread creation and where performance is expressed in process-forks-per-ms, this may not be nearly as much of an issue!)
Spawning a thread for each requests may lead to excessive resource consumption when a high number of requests are served simultaneously. We know from the *Server-Multithreading* pattern that increasing the number of threads beyond a certain limit brings diminished efficiency returns, while

consuming a lot of system resources. This is a “no win” situation that must be avoided at any price. The *Thread Pool* pattern addresses this problem, as well.

THREAD PER SESSION

Problem
We want to apply the *Server Multi-threading* pattern in order to increase the capacity of a software server.

Context
The clients carry on long-duration sessions with the server, sending multiple requests per session.

Forces
- We would like to maintain program simplicity and low thread management.
- Amortize the overhead of thread creation/destruction over the length of a session.
- Session related data must be available to all requests related to that session.

Solution
The server spawns off a thread for each session started by a client, which is exclusively associated with it for the entire period of the session. This amortizes the cost of spawning a thread across multiple requests. This model is the most expensive in terms of resource consumption (especially for large numbers of on-going sessions), but given sufficient resources it can achieve the highest throughput. Resources can be held without being used if some sessions submit infrequent requests.

Resulting Context
If subsequent requests need any session-related data, we need to ensure that this data is accessible regardless of the thread used to process a particular request. (Or, we need to ensure that the same thread is used for all requests of the session, which is natural for the present approach.)

THREAD POOL

Problem
We want to apply the *Server Multi-threading* pattern in order to increase the capacity of a software server.

Context
There are too many clients, and we must put a bound on system resources consumption for multi-threading.

Forces
- Enforcing bounds on resource consumption complicates the thread management.
- Amortize the overhead of thread creation/destruction over a longer period of time.
- Request may arrive when the server is unable to start the execution of new requests due to lack of resources. Measures should be taken to store the requests for a later time.
- Session related data must be available to all requests related to that session.

Solution
The server pre-spawns a pool of threads, whose number may be fixed, or changed dynamically at a low rate. The resource consumption for threads is bounded. The requests arriving when all the threads are busy must be queued for later processing, which is an added complexity and overhead. This approach requires the most programming effort, due to thread pool management.

Resulting Context

Thread pool is really a cost-reduced version of Thread Per Request. By pre-spawning a limited number of threads, we have addressed the two consequences of using *Thread Per Request* described in the Resulting Context, namely amortizing the high cost of thread creation and bounding the consumption of system resources. However, a new overhead is introduced in this approach related to the allocation of a worker thread to every request. More exactly, the following activities are done serially in the main thread for all the incoming requests: event demultiplexing, receiving the messages from the clients, queueing the messages internally and dispatching the worker threads. The next pattern addresses the problem of minimizing the serial thread management.

MINIMIZED SERIAL THREAD MANAGEMENT

Context

The thread pool approach is one of the most attractive solution to multi-threading for systems with many clients. However, most of the thread pool management operations use shared data objects and are done serially in the main thread. Most of these activities are short, except for the receiving of messages when the messages are large.

Problem

Can the thread pool management be further improved by moving some of the serial thread management work to the parallel threads?

Forces

- Parallelizing the workload enhances the potential for performance gains, especially when longer, autonomous activities can be moved to parallel threads.
- Any work done serially on behalf of each and every request limits those gains.
- Shared data objects (as those used for the thread pool) must be used in a critical section, to protect their consistency.
- We gain nothing in term of efficiency by moving to parallel threads activities which must be performed in a critical section.

Solution

Move the actual message reception for large message sizes from the main thread to the worker threads. This is the only thread management component that can be parallelized successfully, because it is long enough (for large messages) and does not have to be performed in a critical section.

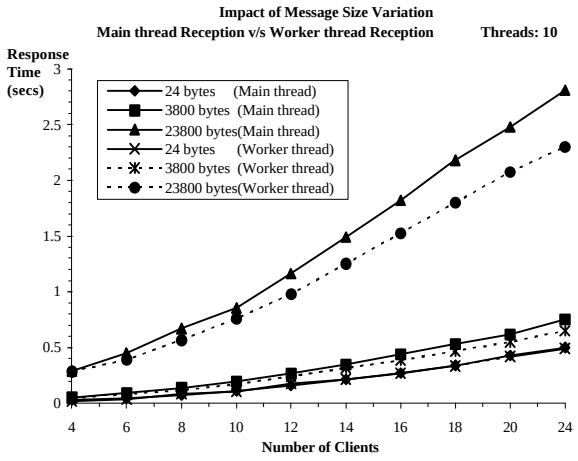


Fig. 7 Message reception in the Main Thread (serial reception) Vs. Worker thread (parallel reception)

Example

Figure 7 shows the effect on the system throughput of moving the reception of client messages from the main thread to the worker threads in a software server using a thread pool with 10 threads. It is easy to see that this parallelization has a positive effect that becomes more important with the size of the messages.

MULTIPROCESSOR PATTERN

Context
After multi-threading the servers and moving all the significant work to parallel threads, the potential for concurrency in the server went up, and the workload was "pushed down" to the subservient servers. It is possible that the effect of such measures is to move the limiting capacity factor from the intermediate server to one of the subservient servers. This pattern applies if the new bottleneck is the processor on which the server is running.

Problem
How can we further improve the system capacity ?

Forces
- We know that the efficiency of a multi-threaded server benefits from having more subservient servers (in this case, more CPUs).
- We would like to limit the programming effort to change the application code to make it suitable for a multiprocessor.
- Multi-processing primitives often change the application interface.
- Some operating systems offer the same application interface if running on a single-processor or multiprocessor. (Such an example is Solaris 2.5).

Solution
Run the multi-threaded server on a multiprocessor instead of a single processor, on top of an operating system that does not require application interface changes for going from a single processor to a multiprocessor. Take advantage of executing the concurrent threads in parallel. The increase in capacity will be considerable, but still not linear with the number of processors (due to the serial portion of the workload and to contention for common data).

Related patterns
Another alternative to increasing the processing power is the *Faster Processor* pattern from [Meszaros96]. Another pattern from the same language, *Share the load*, also adds new processors to the system, but involves code changes since it selects the functions to be moved, clearly partitioned from the ones to stay.
The *Multiprocessor* pattern presented here takes advantage of the fact that a multi-threaded server is already parallelized, so it does not require any further changes to the application code.

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APPENDIX

In order to illustrate the effect of the proposed patterns, we have implemented and measured a layered server system with an architecture as in Figure 8. The system was designed and implemented by using the Adaptive Communication Environment (ACE) toolkit [Schmidt94]. Several version of software servers with different threading models were implemented and measured [Somadder+97].

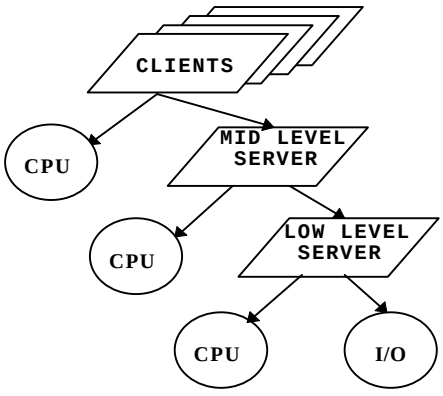

Fig. 8 Layered Client/ Server System

The measurements were performed for different workload intensities by varying the number of clients. Each point on the performance graphs was obtained by taking the average results of 10 similar experiments, each experiment having a duration of 300 request cycles of a tagged client. The repetition of the measurements was necessary to account for performance variations due to transient loads on the communication network and hosts. 95% of the results were in a confidence interval of plus/minus 2% around the mean. Even with these precautions, some curves look noisy due to external loads out of our control.