

# Using Magpie for request extraction and workload modelling

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## Abstract

Tools to understand complex system behaviour are essential for many performance analysis and debugging tasks, yet there are many open research problems in their development. Magpie is a toolchain for automatically extracting a system's workload under realistic operating conditions. Using low-overhead instrumentation, we monitor the system to record fine-grained events generated by kernel, middleware and application components. The Magpie request extraction tool uses an application-specific event schema to correlate these events, and hence precisely capture the control flow and resource consumption of each and every request. By removing scheduling artefacts, whilst preserving causal dependencies, we obtain canonical request descriptions from which we can construct concise workload models suitable for performance prediction and change detection. In this paper we describe and evaluate the capability of Magpie to accurately extract requests and construct representative models of system behaviour.

## 1 Introduction

Tools to understand complex system behaviour are essential for many performance analysis and debugging tasks, yet few exist and there are many open research problems in their development. Magpie provides the ability to capture the control path and resource demands of application requests as they are serviced across components and machines in a distributed system. Extracting this per-request behaviour is useful in two ways. Firstly it gives a detailed picture of how a request was serviced, throwing light on questions such as what modules were touched and where was the time spent? Did the request cause a disk access or was data served from the cache? How much network traffic did the request generate? Secondly, the per-request data can be analyzed to construct concise workload models suitable for capacity planning,

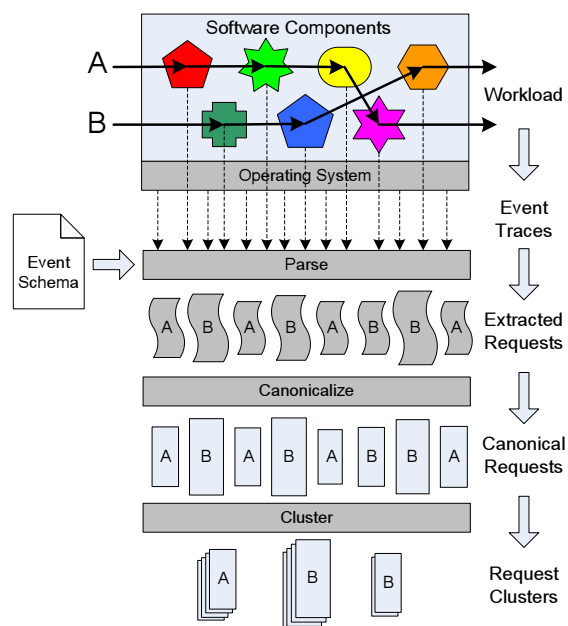


Figure 1: The Magpie toolchain: as requests move through the system event traces are generated on each machine. These are then processed to extract the control flow and resource usage by each individual request and scheduling variations removed. Finally, the canonical requests are clustered to construct models of the workload as a whole.

performance debugging and anomaly detection. These models require the ability to measure a request's resource demands, discarding the scheduling artefacts due to OS multitasking and timesharing. In effect, we obtain a picture of how the request *could* have been serviced (and apply this information toward modelling the workload), in addition to the data on how it *was* serviced (which is useful for detailed analysis of individual request behaviour).

The contributions of our work can be summarized as follows:

1. An unobtrusive and application-agnostic method

of extracting the resource consumption and control path of individual requests. Unlike other approaches to request tracking, for example [1, 8], Magpie does not require a unique request identifier to be propagated through the system, and it accurately attributes actual usage of CPU, disk and network to the appropriate request. This is achieved by correlating the events that were generated while the requests were live, using a schema to specify the event relationships and carrying out a temporal join over the event stream.

2. A mechanism for constructing a concise model of the workload. Each request is first expressed in a canonical form by abstracting away from the scheduling artefacts present in the original event trace. A representative set of request types is then identified by clustering the canonical request forms. This set of requests, together with their relative frequencies, is a compact model of the workload that can then be used for performance analysis purposes.
3. A validation of the accuracy of the extracted workload models using synthetic data, and an evaluation of their performance against realistic workloads.

The Magpie request tracking technique is unique in that it uses event logs collected in a realistic operating environment. It handles the interleaving of many different request types, it is impervious to unrelated activity taking place at the same time, and it is able to attribute resource usage to individual requests even when many are executing concurrently.

The request-oriented approach to understanding and characterizing system behaviour complements existing methods of performance modelling and analysis. Causes of faults or performance problems are often revealed simply by inspecting the Magpie trace of the individual request and comparing to the expected behaviour. In contrast, the traditional approach to monitoring system health is to log aggregate performance counters and raise alarms when certain thresholds are exceeded. This is effective for identifying some throughput problems, but will not catch others such as poor response time or incorrect behaviour (“why was the item not added to my shopping cart?”). Although straightforward programming errors and hardware failures are likely to be at the root of most problems, the effects are exacerbated and the causes obscured by the interactions of multiple machines and heterogeneous software components.

Even though performance modelling is of key importance for commercial enterprises such as data centers, current methods for constructing workload models are surprisingly unsophisticated. Without a tool like Magpie, workload models for capacity planning and other perfor-

mance prediction tasks have to be derived from a carefully controlled measurement environment in which the system input is contrived to stress each request type in isolation. This requires manual configuration and expert knowledge of the system behaviour, and compromises accuracy because variables such as caching behaviour are ignored. Workload models that are automatically derived using Magpie are quicker and easier to produce, and more accurately capture the resource demands of the constituent requests.

Magpie is a preliminary step towards systems that are robust, performance-aware and self-configuring (Autonomic Computing [12] is a well known articulation of this grand vision). We have previously discussed the applications and utility of Magpie’s workload models to scenarios ranging from capacity planning to on-line latency tuning [3, 11]. The emphasis in this paper is on a thorough, bottom-up evaluation of its use in practical situations. We demonstrate that Magpie accurately extracts individual requests under realistic operating conditions, and that the aggregation of this data leads to representative workload models.

The following four sections describe the design and implementation of the Magpie prototype toolchain. Then in Section 6 we evaluate the Magpie approach using simple synthetic workloads where it is straightforward to assess the results obtained, progressing to more complex workloads in Section 7.

## 2 Design and implementation

The workload of a system is comprised of various categories of request that will often take different paths through the system, exercising a different set of components and consuming differing amounts of system resources. A **request** is system-wide activity that takes place in response to any external stimulus of the application(s) being traced. For example, the stimulus of an HTTP request may trigger the opening of a file locally or the execution of multiple database queries on one or more remote machines, all of which should be accounted to the HTTP request. In other application scenarios, the database queries may be considered requests in their own right. Within Magpie both the functional progress of the request and its resource consumption at every stage are recorded. Thus a request is described by its path taken through the system components (which may involve parallel branches) together with its usage of CPU, disk accesses and network bandwidth.

The Magpie prototype consists of a set of tools that take event logs and eventually produce one or more workload models. Figure 1 illustrates the process. The intention when designing the tools has been to deploy an *online* version of Magpie that monitors request behaviour

in a live system, constantly updating a model of the current workload. Although Magpie operates both offline and online, this goal has dictated our design choices in many places.

Earlier versions of Magpie generated a unique identifier when a request arrived into the system and propagated it from one component to another [3]. The same technique is employed in other request tracking technologies such as Pinpoint [8]. Events were then logged by each component annotated with this identifier. We have since developed less invasive request extraction techniques that we describe in more detail below. Eschewing a requirement for global identifiers avoids the problems associated with guaranteeing unique identifier allocation. It also avoids the need for complicated ad-hoc state management or API modification to manage the identifiers as they are propagated. Finally, it also ensures that the instrumentation is kept independent of the definition of a “request”: it is not uncommon for two applications to share the same component, and it is desirable if one set of instrumentation can support tracing of both applications.

## 2.1 Instrumentation

The instrumentation framework must support accurate accounting of resource usage between instrumentation points to enable multiple requests sharing a single resource to be distinguished (e.g. threads sharing the CPU, RPCs sharing a socket). One consequence of this is a requirement for high precision timestamps. As events are generated by components in both user-space and kernel mode, the attribution of events to requests relies on them being properly ordered. In Windows NT based operating systems, a large proportion of kernel and device driver activity occurs inside Deferred Procedure Calls (DPCs); a form of software interrupt with a higher priority than all normal threads. It is therefore often important to know whether a particular event occurred inside a DPC or standard interrupt, or whether it occurred before or after a context switch. In order to get the required precision we use the processor cycle counter, which is strictly monotonic, as the event timestamp.

Event Tracing for Windows (ETW) [17, 18] is a low overhead event logging infrastructure built into recent versions of the Windows operating system, and is the technology underpinning the Magpie instrumentation. We make extensive use of pre-existing ETW event providers and where necessary we have added custom event tracing to components. The instrumented components in an e-commerce site that we use for prototyping are depicted in Figure 2. There are three main parts to the instrumentation:

1. Kernel ETW tracing supports accounting of thread

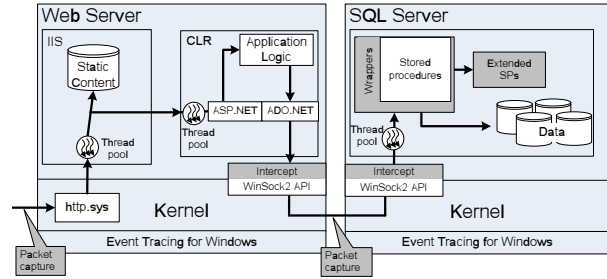


Figure 2: Instrumentation points for the web server and database server in our test e-commerce site. Some components such as the http.sys kernel module and the IIS process generate events for request arrival, parsing, etc. Additional instrumentation inserted by Magpie (shown in gray) also generates events; all these events are logged by the Event Tracing for Windows subsystem.

CPU consumption and disk I/O to requests.

2. The WinPcap packet capture library[19], modified to post ETW events, captures transmitted and received packets at each machine.
3. Application and middleware instrumentation covers all points where resources can be multiplexed or demultiplexed, and where the flow of control can transfer between components. In the prototype both platform middleware components such as WinSock2, and specific application-level components such as the ASP.NET ISAPI filter (used to generate active content), are instrumented in order to track a request from end to end.

An ETW **event** consists of a timestamp, an event identifier, and the values of zero or more typed *attributes*<sup>1</sup>. In a typical system there will be multiple event providers, and therefore event identifiers have the hierarchical form *Provider/EventName*. A typical event from the log has the form:

```
Time, Provider/EventName, Attr1=Value1, ...
```

Each ETW event provider produces an ordered stream of timestamped events. However, at any given time there will usually be a large number of requests present in the system, each generating events from a variety of components and subsystems as it is serviced. As a result the stream of events will invariably comprise a non-deterministic interleaving of events from many active requests. The first stage of workload extraction is to demultiplex this event stream, accounting resource consumption to individual requests.

<sup>1</sup>All events with the same identifier have the same set of attributes.

## 2.2 Workload extraction pipeline

The toolchain consumes events generated by system instrumentation, as described in Section 2.1. In the sections following we present the workload extraction pipeline in some detail. The *request parser* identifies the events belonging to individual requests by applying a form of *temporal join* over the event stream, according to rules specified in an event schema. During this process it preserves the causal ordering of events, allowing a canonical form of each request to be inferred that captures its resource demands (as opposed to the service the request received), and this is discussed further in Section 4. From the canonical form, a request can be deterministically serialized, leading to a representation suitable for *behavioural clustering*. In Section 5 we describe how behavioural clustering builds workload models by comparing requests to each other according to both control path and resource demands.

## 3 Request parser

The request parser is responsible for extracting individual requests from the interleaved event logs. By determining which events pertain to a specific request, the parser builds up a description of the request that captures its flow of control and its resource usage at each stage. It is written to operate either online or offline, via the public ETW consumer API [17].

The parser considers each event from the stream in timestamp order and speculatively builds up sets of related events. It relies on an *event schema* to describe event relationships for the particular application of interest. For example, it may be the case that events occurring in sequence on the same thread belong to the same request, and this will be expressed in the schema by specifying those events related by thread id. The thread may post the identical event sequence for any number of different requests. The idea of *temporal joins* ensures that only those events that occur while the thread is working on the one request are joined together. Some of the resulting event sets will eventually be identified as describing a complete request, others can be discarded. Because the way in which events are related is defined out-of-band in an application-specific schema, the request parser itself contains no builtin assumptions about application or system behaviour.

### 3.1 Event schema

For every event type, the schema specifies which attributes connect it to other events. As each event is processed by the parser, its type is looked up in the schema and the event is then added to the appropriate set of re-

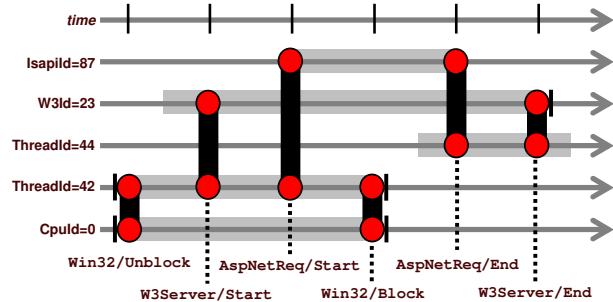


Figure 3: Illustration of how the parser joins a sequence of IIS events. Each event is shown as a black vertical line that binds two or more attribute-value pairs (represented as circles on the horizontal attribute-value lines). The joining of events is depicted with transparent gray lines, and valid-intervals are displayed with a vertical line to the left of the BIND\_START and to the right of the BIND\_STOP join attributes. This portion of the request does not show where the valid-interval for *W3Id*=23 is opened, nor the opening or closing of the valid-interval for *ThreadId*=44.

```
EVENT("W3Server", "Start");
ATTRIBUTE("Tid", BIND_BASIC, 0);
ATTRIBUTE("W3Id", BIND_BASIC, 0);

EVENT("W3Server", "End");
ATTRIBUTE("Tid", BIND_BASIC, 0);
ATTRIBUTE("W3Id", BIND_STOP, 0);

EVENT("AspNetReq", "Start");
ATTRIBUTE("Tid", BIND_BASIC, 0);
ATTRIBUTE("IsapiId", BIND_BASIC, 0);

EVENT("AspNetReq", "End");
ATTRIBUTE("Tid", BIND_BASIC, 0);
ATTRIBUTE("IsapiId", BIND_BASIC, 0);

EVENT("Win32", "Unblock");
ATTRIBUTE("Tid", BIND_START, 0);
ATTRIBUTE("CpuId", BIND_START, 0);

EVENT("Win32", "Block");
ATTRIBUTE("CpuId", BIND_STOP, 0);
ATTRIBUTE("Tid", BIND_STOP, 0);
```

Figure 4: Portion of the IIS schema used to perform the event parsing illustrated in Figure 3. The binding types BIND\_START and BIND\_STOP instruct the parser to open or close a valid-interval.

lated events—in other words, the event is *joined* to one or more other events.

For example, an IIS web server schema specifies that one of the join attributes for both the *W3Server/Start* and the *W3Server/End* events is *W3Id*. This means that if two such events occur, both with *W3Id*=23, for example, they will be joined together. Figure 3 contains a graphical representation of this process. The same schema states that *ThreadId* is also a join attribute for those events. This allows different attributes posted by other event types to be transitively joined to the request for which *W3Id*=23. Thus, as shown in the diagram, if *ASPNetReq/Start* with *IsapiId*=87 is posted by the same *ThreadId*=42 as *W3Server/Start*, then the two events will be joined

via the shared *ThreadId* attribute. In turn, the *IsapiId* join attribute causes other events also with *IsapiId*=87 to be added to this set of related events. In this way, the set of events belonging to each request is incrementally built up as the parser processes the event stream.

In addition to identifying which attributes cause events to be joined, the schema indicates the nature of these joins. In the example description above, there is nothing to stop two *W3Server/Start* events posted by the same thread but with different *W3Id* values being joined together. A mechanism is needed to prevent all the requests being merged into one, and this is captured by the notion of temporal joins.

### 3.2 Temporal joins

As a request progresses, relationships between attribute values are broken as well as created. For example, a worker from a thread pool may be re-tasked from one request to another, or an HTTP/1.1 connection may be reused for more than one request. In the above example *ThreadId*=42 is a worker thread that posts a *W3Server/Start* event on behalf of each request before handing the request processing off to another thread. The period during which we know that *ThreadId*=42 is working exclusively on one request defines a *valid-interval* for the attribute-value pair (*ThreadId*,42).

This terminology is borrowed from the temporal database community [10], where it is used to denote the time range during which a row of a table was present in the database. In such databases, arbitrary SQL queries can be executed against the database as if at a particular time. Theoretically it should be possible to implement the Magpie parser as queries against a temporal database in which each table holds the events of a given type. Finding all the events relating to a request would be an n-way relational join, where n is the number of event types involved in the request.

During a valid-interval, events are joined together as usual. However once the valid-interval is closed for a particular attribute-value pair, no more events can be added to the same event set via that pair. Therefore the IIS schema specifies that the event *Win32/Block* closes the valid-interval for the *ThreadId* attribute of that event, and likewise the *Win32/Unblock* event opens the valid-interval. In the example above, a new valid-interval for *ThreadId*=42 is opened for each request, thus preventing the merging of disjoint requests.

The opening and closing of valid-intervals is controlled in the schema by the use of *binding types* for the join specifications. A *BIND\_START* begins a new valid-interval for an attribute-value pair and a *BIND\_STOP* terminates the current valid-interval. An attribute that joins an event without affecting the valid-interval has

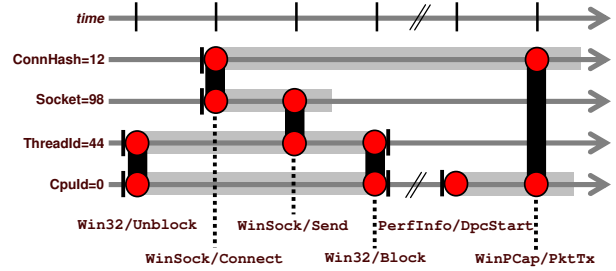


Figure 5: Transitive joins enable packet bandwidth and CPU consumption by the network stack to be correctly attributed, even though the thread that issues the send request is swapped out at the time the packet is transmitted. The diagonal pair of lines crossing the horizontal lines indicate the passing of an arbitrary amount of time.

a *BIND\_BASIC* binding type. In the theoretical implementation using a temporal database, when a valid-interval is closed by an attribute-value pair, all the corresponding events would be deleted from the relevant table<sup>2</sup>.

A fragment of the IIS schema matching the example discussed above is shown in Figure 4. In our prototype parser implementation, the schema is written as C macros. The *EVENT* macro takes the name of the provider and the event. Each join attribute is listed using the *ATTRIBUTE* macro, together with its binding type and any flags.

### 3.3 Resource accounting

Certain event types are associated with the consumption of physical resources. Specifically, context switch events give the number of CPU cycles used by a thread during its timeslice, disk read and write events are posted with the number of bytes read or written, and likewise packet events with the packet's size. When these event types are added to a request, it indicates that the relevant resource was consumed on behalf of that request. Figure 5 shows an example in which CPU consumption is associated with the request both while *ThreadId*=44 is running, and also during the network stack DPC (when some other thread is nominally swapped in on that CPU). The *WinPCap/PktTx* event also associates the network bandwidth used by that packet with the request. The user mode *WinSock/Connect* and kernel mode *WinPCap/PktTx* events are joined via their shared source and destination address attributes, represented in the diagram as *ConnHash*=12.

Figure 6 shows an annotated screenshot from a visualization tool that we developed to debug the parser. The highlighted sub-graph contains events from an HTTP request for the URL *shortspin.aspx*, which generates

<sup>2</sup>Hence the n-way relational join to find all events in a request would have to span multiple valid-intervals over multiple tables.

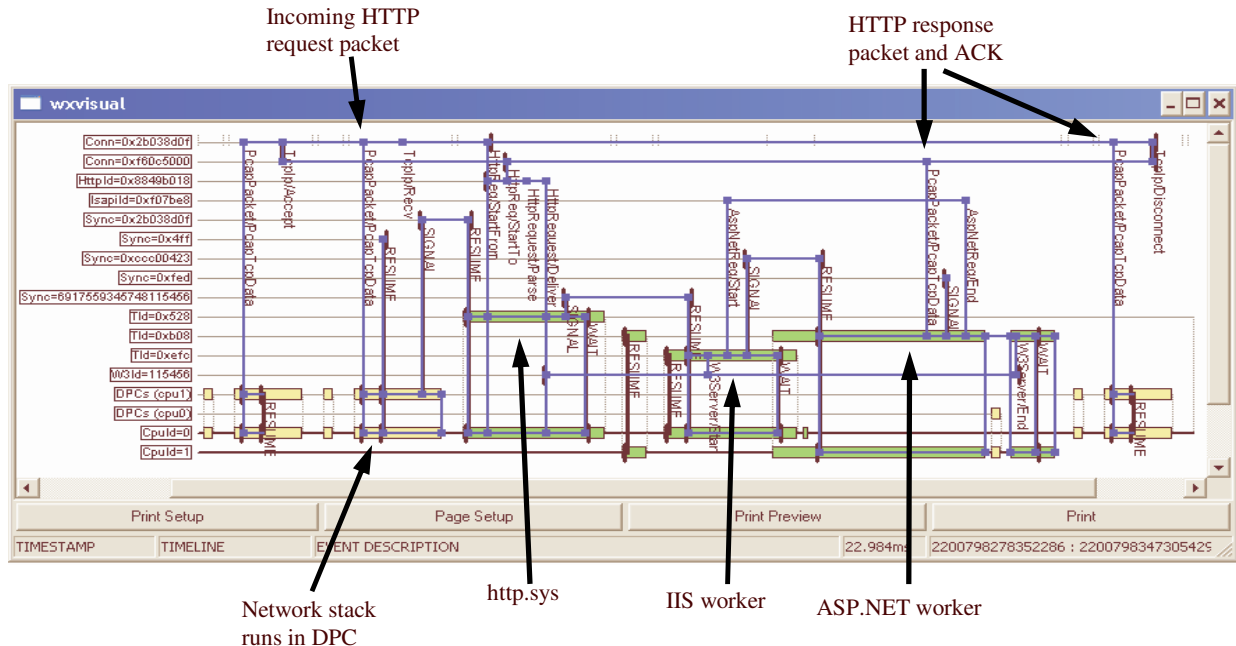


Figure 6: Annotated screenshot of parser visualization of a single request. Each of the event attribute-value pairs that is active during the displayed time period is depicted with a horizontal timeline. Events are shown as binding to one or more of these timelines, and when the binding is of type STOP or START, this is indicated with a small vertical barrier. The portions of each timeline that belong to the request are emphasized, showing that the parser is in effect doing a flood-fill of the graph formed by the join attributes of events. To make it easy to see which threads are actually running at any time, this is highlighted with a pale rectangle.

a very small amount of dynamic content that is returned in a single HTTP response packet. It also spins the CPU for approximately 15ms by executing a tight loop. This particular request is an example of a type B request as used in the experimental evaluation presented in Section 6.

### 3.4 Implementation

The design of the parser was severely constrained by the necessity for minimal CPU overhead and memory footprint, as it is intended to run *online* on production servers. Additionally, it must process trace events in the order they are delivered, since there is no way for it to seek ahead in the trace log, and this creates still more complexity.

In online mode, the kernel logger batches events from different subsystems for efficiency and delivers one buffer at a time. For example, context switch events from each CPU are delivered in separate buffers. Whilst individual buffers contain events in timestamp order, events from different buffers must be interleaved before processing. These reorderings are performed using a priority queue, and add approximately 1 second of pipeline delay to the parser.

The reorder queue is also used for some events that are posted at the end of the operation, such as those for disk I/O, which contain the start time of the I/O as an event

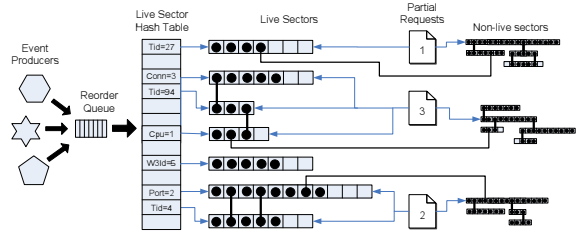


Figure 7: Parser data structures. Hash table entries represent the current valid-intervals and are known as *live sectors*. An event (shown as a black circle) is added to zero or more live sector lists according to the values of its binding attributes. Non-live sector lists, representing closed valid-intervals, are not reachable from the live sector hash table.

parameter. The parser creates a synthetic “Start” event with the correct timestamp and inserts it into the event stream in the correct place.

Figure 7 depicts the data structures used by the parser. Temporal joins are implemented by appending events to one or more time-ordered lists, each of which represents the current valid-interval for an attribute. The most recent (“live”) valid-interval for each attribute is maintained in a hash table and requests are gradually built up using event attribute bindings to connect lists together. In the example from the previous section, the parser would enter the `W3Server/Start` event onto the current list containing all events with `W3Id=23` and onto the current list containing all events with `ThreadId=42`. The

presence of the same event in both lists causes them to be joined together, forming a larger sub-graph.

The schema identifies a seed event that occurs only and always within a request, for example a web server HTTP request start event. As events are processed in timestamp order, every so often some of the sub-graphs will become unreachable because all their valid-intervals have been closed. If a sub-graph contains a request seed event, then all the connected events can be output as a complete request, otherwise it will be garbage collected. Note that there will be many lists (or graphs) that turn out not to represent any request, but instead contain events generated by other applications and background system activities. An additional timeout is used to bound the resources consumed by such activities.

Ideally a request schema should be written by someone with an in-depth knowledge of the synchronization mechanisms and resource usage idioms of the application in question, and this would preferably be done at the same time as the application is instrumented. It is much harder to retrofit a schema and instrumentation to an existing application without this knowledge (but not impossible, as we have in fact done this for all the applications mentioned in this paper). An area for future work is to explore extensions to the expressiveness of the schema. Currently an event can only affect the timelines of its own attributes: one useful enhancement would be the ability to transitively start or stop the valid-intervals on other timelines.

### 3.4.1 Performance evaluation

We assessed the performance impact of Magpie event tracing and parsing by running a web stress-test benchmark. The number of HTTP requests served over a two-minute interval was recorded for a CPU-bound workload that generated active HTML content and saturated the CPU. Measurements were repeatable to within +/- 10 requests.

With no instrumentation the server was able to complete 16720 requests, i.e. 139 requests/second. When logging was turned on in real-time mode, with no event consumer, there was no discernible difference in throughput. A dummy event consumer, which immediately discarded every event, reduced the throughput to 136 requests/second. Running the Magpie parser to extract requests online resulted in a throughput of 134 requests/second, giving a performance overhead of approximately 4%, around half of which can be attributed to the ETW infrastructure. During these experiments the average CPU consumption of the parser was 3.5%, the peak memory footprint 8MB and some 1.2 million events were parsed. Since the web server was CPU-bound during the course of the experiments, this directly accounts for the

```
SYNC("TcpIp/Recv", "ConnHash", "HttpRequest/Start");
SYNC("HttpRequest/Deliver", "W3Id", "Win32/Unblock");
SYNC("AspNetReq/Start", "IsapiId", "Thread/Unblock");
SYNC("Thread/Exit", "TId", "Thread/Join");
WAIT("Win32/Block");
```

Figure 8: Example statements from the IIS schema used to add explicit thread synchronization points to parsed HTTP requests. Each SYNC statement specifies  $(s, a, d)$  where  $s$  and  $d$  are the source and destination events, and are (transitively) joined by shared attribute  $a$ . An event pattern matching a SYNC specification will result in a Signal event being inserted on the source thread and a Resume event on the destination thread. A WAIT event type generates an additional synthetic Wait event.

observed drop in HTTP throughput.

When the ETW logging was enabled to write events to file (instead of operating in real-time mode), the server throughput was 138 requests/second, indicating that the impact of the ETW infrastructure in offline mode is negligible. For the same workload, of 2 minutes duration, a total of around 100MB of binary log file was produced. The parser extracted the correct number of requests in 5.6s, with a peak working set size of approximately 10MB. The average number of events attributed to each request was 36.

## 3.5 Synchronization and causal ordering

At the lowest level, all events are totally ordered by timestamp, leading to a trace of the execution and resource consumption that may vary depending on how the threads acting in a request happen to be scheduled. To extract a meaningful workload model we need to recover the threading structure within a request: for example, determining when one thread causes itself to block or another to unblock. This inter-thread causality tells us how much leeway the scheduler has to re-order the processing of the various stages of a request, and it also allows us to infer how portions of a request might parallelize, which is clearly of interest in multi-processor deployments.

In the web server example used for Figure 6, a kernel `TcpIP/Recv` event unblocks an IIS thread that parses HTTP requests, then unblocks an ISAPI filter thread, which eventually unblocks a third thread to run the ASP.NET active content generator. This last thread blocks after sending the HTTP response back to the client. Since these threads typically come from a thread pool, we occasionally observe the same thread processing multiple of these logically distinct segments of a request, so it is important to be aware of these synchronization points even if they are not apparent in all requests.

Many such synchronization points are implicit from the OS primitives being invoked (e.g. send and receive). In other places, thread synchronization can be performed using mechanisms for which there is no instrumentation,

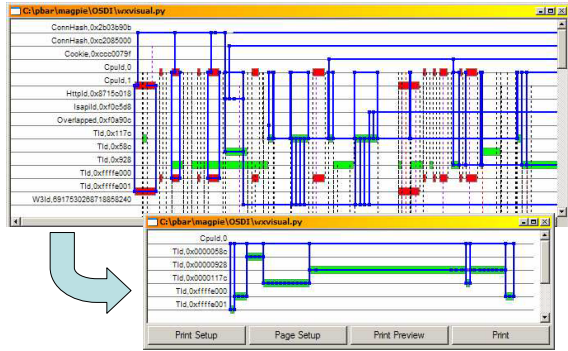


Figure 9: A canonical version of an HTTP request is produced by eliding all scheduling behaviour and retaining only thread synchronization points. The top window shows the request as scheduled in the experiment with 5 concurrent clients, and the lower window the canonical version.

e.g. in a user-level scheduler. For this reason, we provide a mechanism to explicitly insert causal dependencies into the parsed event graphs. This allows us to annotate a request with additional thread synchronization points using known semantics of the application domain.

We define three synthetic events to be inserted into parsed requests: *Signal*, *Wait* and *Resume*. There is an explicit causality between related *Signal* and *Resume* events, and so these will be connected by some shared attribute-value. This is expressed in the schema using a 3-tuple  $(s, a, d)$ , where  $s$  is the name of the source event executed by thread A at time  $t_A$ ,  $d$  is the name of the destination event in thread B at time  $t_B$ , and  $a$  is the join attribute, shared by events  $s$  and  $d$ . Attribute  $a$  is not necessarily a parameter of both event types, but may be transitively shared through other joined events on the same thread. Events from thread A with timestamps less than  $t_A$  *must* always happen before thread B events with timestamps greater than  $t_B$ , under any scheduling discipline. Figure 8 shows some example synchronization statements from the IIS schema, and in Figure 6 the synchronization events inserted by the parser can be seen in amongst the original request events.

## 4 Canonicalization

When the system is more heavily loaded, requests tend to be scheduled in a highly interleaved fashion, as shown in Figure 9. Although the request URL is identical to that of Figure 6, the way in which the request is *serviced* differs due to multiple clients competing for system resources. In Figure 6, the thread completes its work in a single quantum of CPU time, whereas in the top window of Figure 9 it is frequently preempted and its activity is interspersed with threads servicing other connections.

A detailed per-request view of system activity is un-

doubtedly useful for determining the path taken by a request, and how it consumed resources along the way. However, for constructing workload models for performance prediction or debugging purposes we would rather represent requests as a *canonical* sequence of absolute resource *demands* and ignore all the information about how the request was actually serviced.

Using the causal ordering annotations discussed in the previous section, we produce a canonical version of each request, in effect by concatenating all resource demands between synchronization points, and then scheduling this as though on a machine with an unlimited number of CPUs. The lower window of Figure 9 shows the result of this processing stage when applied to the request in the upper window. The canonical version is clearly more useful for modelling purposes.

### 4.1 Cross-machine activity

When requests cause activity on multiple machines it is necessary to “stitch” together the events collected on each computer. Since every machine in the system has a separate clock domain for its timestamps, the request parser is run once for each machine, either online or offline (we believe it ought to be straightforward to extend the parser to deal with multiple clock domains but this is not a current priority). The request fragments from each machine are canonicalized as described previously. We then run an offline tool that combines canonical request fragments by connecting synchronization events from transmitted packets to received packets.

### 4.2 Request comparison

Thread synchronization can be used to overlay a binary tree structure onto what would otherwise be a linear timestamp-ordered event stream. When two threads synchronize, perhaps by sending a message, we create a logical fork in the event tree where the original (source) thread continues whilst also enabling the destination thread to execute in parallel. When a thread blocks, perhaps to receive a message, this is treated as a leaf node. The results of applying this procedure to a contrived RPC-style interaction is shown in Figure 10.

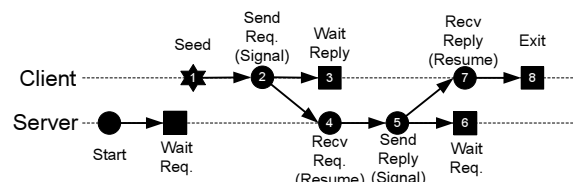


Figure 10: Binary tree structure overlaid onto RPC-style thread interactions. This tree would be deterministically serialized in the order shown.



By deterministically flattening this tree representation using standard depth-first traversal, we can cluster requests using a simple string-edit-distance metric rather than requiring elaborate and traditionally expensive graph-edit-distance metrics. Although this has produced reasonable results in our prototype, losing the tree structure before comparing requests seems likely to limit the usefulness of this approach in larger distributed systems where requests have more complex structure. Recent work has developed more suitably efficient algorithms for tree- and graph-edit-distance and also investigated graph-clustering [5]. Applying some of these techniques to improve our workload extraction process is currently under investigation.

## 5 Behavioural clustering

The clustering stage of the toolchain groups together requests with similar behaviour, from the perspective of both event ordering and resource consumption. Since we require that the processing pipeline functions online, we use a simple incremental clustering algorithm. The resulting clusters are the basis of a workload model which expresses that requests occur as typified by each cluster's representative, and they occur in proportion to their cluster's size.

The clusterer maintains a set of active workload clusters. For each cluster, we record a *representative* request (sometimes referred to as the centroid of the cluster), a cluster diameter, and the set of requests that are considered members of the cluster. Additionally, the algorithm keeps track of the average cluster diameter, and the average inter-cluster distance.

When a new request is presented to the clusterer, it computes the string-edit-distance between its serialized representation and that of each cluster centroid. The distance metric is a function of both the character edit cost (as in the traditional form of string-edit-distance) and also of the resource usage deltas associated with the two events. So for example, the comparison of two characters where both represent a disk read will give an edit cost proportional to the difference in how many bytes were actually read. The request is normally added to the cluster with the smallest edit distance, unless that edit distance exceeds a trigger threshold, in which case a new cluster is created.

## 6 Validation

To support our claim that Magpie is able to extract individual requests and construct representative workload models, we attempt to examine our techniques in isolation. In this section we present the results, which include

Type	URL	Resource
A	longspin.aspx	1 thread spins CPU 30ms
B	shortspin.aspx	1 thread spins CPU 15ms
C	small.gif	Retrieve static image 12Kb
D	tiny.gif	Retrieve static image 5Kb
E	parspin.aspx	2 threads spin CPU 15ms concurrently
F	rpcspin.aspx	1st thread spins CPU 7.5ms, signal other thread and wait, spin CPU 7.25ms 2nd thread spins CPU 15ms

Table 1: Request types and consumptions of primary resources.

an assessment of the quality of the clusters obtained, as well as checks that our resource accounting is accurate.

In all experiments, events are generated using the instrumentation described in Section 2.1 and the event streams are parsed as discussed in Section 3. Flattened representations of the requests are then clustered into similar groups using the behavioural clustering technique presented in Section 5. The machines used are all dual-processor 2.6GHz Intel P4, running Windows Server 2003, and IIS or SQL Server 2000. In all experiments we used Application Center Test [16] for the stress client.

We first evaluate the accuracy of Magpie's workload models using traces taken with a synthetic workload. In contrast to the more realistic operating conditions of Sections 7.1 and 7.2, the web site behaviour is calibrated to check that we extract the same workload as was injected. These experiments are intended to investigate the effectiveness of the request canonicalization mechanism, together with the behavioural clustering algorithm, to separate requests with different resource consumption.

The experiments were performed against a minimal ASP.NET website written in C#. Each URL consumes resources as depicted in Table 1. CPU is consumed within a tight loop of a fixed number of iterations, and network bandwidth is used by retrieving fixed size images.

## 6.1 Resource consumption

The string-edit-distance metric used by the clustering algorithm treats events annotated with their resource usage as points in a multi-dimensional space. To allow a more intuitive explanation of the resulting clusters, we first present results where resource consumption changes in only a single dimension. Concurrency is a complicating factor, and so we examine how well the request extraction and modelling tools perform, both under concurrent request invocations and when concurrent operations take place within a single request.

### 6.1.1 Processor time

We used the type A and type B requests of Table 1 (which differ only in their consumption of CPU cycles) to produce both single-varietal workloads and mixtures, using

### CPU Resource Consumption

	Exp No	Workload / #Clients	Accntd CPU %	Clusters Found	Dia.	Min. Sep.	Model Error
Single	1.1	500A x1	96.6%	499 1 †	0.6 0.0	130 130	2.4%
	1.2	500B x1	94.0%	500	0.4	0.0	2.1%
Conc.	1.3	500A x5	96.6%	498 1 1 †	1.2 0.0 0.0	21.7 21.7 13.1	3.2%
	1.4	500B x5	94.6%	500	1.2	0.0	2.8%
Mixed	1.5	500(A/B) x1	95.9%	266A 234B	1.1 1.7	8.5 8.5	0.9%
	1.6	500(A/B) x5	95.9%	244A 254B 1A 1B †	1.2 1.2 0.0 0.0	8.0 8.0 33.2 103	2.0%

**Table 2:** Clusters produced from single and mixed request type workloads consuming CPU only, for both concurrent and serialized request invocations. *Accntd CPU %* is the fraction of CPU consumed by the relevant process that was accounted to individual requests. The *Clusters Found* column gives the number of requests found in each cluster (from a total of 500 requests). *Dia.* and *Min. Sep.* are the average cluster diameter and the distance to the centroid of the nearest other cluster, respectively. *Model Error* refers to the difference in resource consumption between the derived workload model and the parsed requests.

either serialized requests from a single client, or concurrent requests from 5 clients. This gives a total of 6 different workloads, as listed in the left-hand columns of Table 2. Note that even these trivial requests exhibit fairly complex interactions between the kernel and multiple worker threads—this is apparent in Figure 6, which depicts a type B request.

Table 2 records the clusters found from each of the workloads. It also shows the average distance from the cluster centroid of each request in the cluster (*Dia.*) and the distance to the centroid of the nearest other cluster (*Min. Sep.*). In experiments 1.1 and 1.2, 500 requests of type A (`longspin.aspx`) and 500 requests of type B (`shortspin.aspx`) each produced a large cluster. Repeating these experiments with 5 concurrent stress clients produced very similar results. The clusters produced under a concurrent workload generally have a larger internal diameter than those for the serial workload. Examining the distributions of total CPU consumed by the individual requests shows that, as predicted by the clusters, the concurrent workloads exhibit slightly larger spreads, probably due to cache effects and scheduling overheads.

As a validation check, the total amount of CPU time accounted to requests by the parser was summed and compared against the aggregate CPU times consumed by processes and the kernel during the course of each experiment. In Table 2, the column entitled *Accntd CPU %* indicates the fraction of “relevant” CPU that was accounted as request activity. Relevant CPU excludes that used by background processes and the idle thread, but includes most kernel mode activity and all user mode processing by the web server threads (this information is directly

### Network Resource Consumption

	Exp No	Workload / #Clients	Accntd CPU %	Clusters Found	Dia.	Min. Sep.	Model Error
Single	2.1	500C x1	91.4%	500	0.1	0.0	12%
	2.2	500D x1	73.6%	500	0.1	0.0	8.3%
Conc.	2.3	500C x5	86.6%	498 2 †	0.9 2.1	15.3 15.3	20%
	2.4	500D x5	76.1%	498 1 †	0.9 0.0	9.8 9.8	14%
Mixed	2.5	500(C/D) x1	81.5%	246C 254D	0.1 0.1	6.9 6.9	19%
	2.6	500(C/D) x5	83.6%	267C 223D 10C	1.0 0.7 1.7	4.4 6.9 4.4	18%

**Table 3:** Clusters produced from single and mixed request type workloads differing primarily in consumption of network bandwidth, for both concurrent and serialized request invocations. See the Table 2 caption for explanation of the column headings.

available from the ETW event logs.) The reported figures are less than 100% due to non-request related web server activity such as health monitoring and garbage collection, and also the difficulty of attributing all kernel mode CPU usage correctly with the current kernel instrumentation.

The final column in Table 2 labelled “*Model Error*”, records how the resource consumption of the constructed model differs from that actually measured. This figure is computed as the percentage difference in resource consumption between the requests as parsed, and a synthetic workload generated by mixing the cluster representatives in proportion to their cluster sizes. In all cases, the cluster sizes and representatives can be used to concisely represent the experimental workload to within 3.2%.

As a useful cross-check, from experiment 1.1 we have a centroid that represents the resource usage and control flow of requests of type A, measured in isolation; from experiment 1.2 we have a similar centroid for requests of type B. Table 2 shows that experiment 1.5 contains requests with a 266/234 mix of type A and B requests, so we can compare the CPU time consumed by all requests in experiment 1.5, and the CPU time predicted by 266 type A centroids added to 234 type B centroids. The prediction falls short of the observed value by just 3.5%, presumably due to worse cache locality. Repeating this computation for experiment 1.6, the deficit is 3.4%.

### 6.1.2 Network activity

Table 3 shows the results obtained using workloads based on request types C and D, which differ in consumption of network bandwidth. The *Accntd CPU %* figures are noticeably lower for these experiments. However this is not surprising since it is common when load increases for multiple incoming network packets to be processed in the same deferred procedure call. Although 100% of the network packets are correctly ascribed to requests, there

**Internal concurrency (1)**

	Exp No	Workload / #Clients		Accntd CPU %	Clusters Found	Dia.	Min. Sep.	Model Error
Single	3.1	500E	x1	96.6%	500	0.7	0.0	1.2%
	3.2	500E	x5	97.1%	493	0.9	7.7	0.6%
					2	0.3	8.5	
					2 †	0.7	130	
					1	0.0	101	
1	0.0	7.7						
Mixed	3.3	500(B/E)	x1	95.8%	267E	0.5	8.7	0.6%
					232B	0.4	8.8	
					1E	0.0	34.7	
	3.4	500(B/E)	x5	95.8%	249B	0.7	8.8	0.4%
					244E	1.0	6.3	
					1E †	0.0	30.5	
					1E	0.0	7.3	
	2E	0.7	6.7					
	3E	1.9	6.3					
	3.5	500 (A/B/E)	x1	96.1%	172E	0.5	8.9	3.0%
	3.6	500 (A/B/E)	x5	96.2%	168A	0.6	8.1	0.3%
					160B	0.5	8.1	
187E					0.9	0.0		
152B					0.6	8.6		
160A	1.2	8.6						
1A †	0.0	130						

Table 4: Clusters produced from single and mixed request type workloads consuming CPU only, where the request contains internal concurrency, for both concurrent and serialized request invocations. See the Table 2 caption for explanation of the column headings.

are places where insufficient instrumentation is present to safely account computation to an individual request. In these cases, the parser errs on the conservative side.

## 6.2 Concurrency and internal structure

Figure 11 shows canonical versions of the four compute bound requests of Table 1 with very different internal structure. The first two requests (A and B) perform sequential computations of different lengths, the third (E) performs the same amount of work as B, but in two parallel threads. The fourth request (F) also consumes the same amount of resource as B, but this time using a synchronous RPC-style interaction with a second worker thread.

Whilst three of these requests consume exactly the same amount of CPU resource, they would have significantly different behaviour on a multiprocessor machine from a response time or latency perspective. When extracting workload models, we believe it is important to capture these differences in concurrency structure.

Tables 4 and 5 show the clustering results of a suite of experiments constructed using various combinations of the requests described above. From the tables, it is clear that our distance metric and clustering algorithm are capable of separating requests that differ only in internal concurrency structure. Note in particular, experiment 4.8 of Table 5, where the 4 request types fall into 4 well separated clusters, with just 2 outliers.

**Internal concurrency (2)**

	Exp No	Workload / #Clients		Accntd CPU %	Clusters Found	Dia.	Min. Sep.	Model Error
Single	4.1	500F	x1	96.8%	499	1.7	7.3	4.1%
	4.2	500F	x5	96.5%	1	0.0	7.3	1.2%
					496	1.3	6.4	
					2	0.6	6.4	
					1	0.0	9.3	
1 †	0.0	133						
Mixed	4.3	500(A/F)	x1	96.7%	248F	1.6	19.2	.01%
					252A	0.4	19.2	
	4.4	500(A/F)	x5	96.6%	236F	1.3	9.4	0.4%
					262A	0.7	16.9	
					1F †	0.0	131	
					1F	0.0	9.4	
	4.5	500 (A/E/F)	x1	96.8%	192F	1.8	7.9	0.2%
	4.6	500 (A/E/F)	x5	96.6%	169A	0.9	17.6	0.9%
					139E	0.5	8.1	
					195F	1.3	6.9	
					144E	1.2	9.1	
	155A	0.7	9.2					
3F †	1.2	131						
1E	0.0	9.2						
2F	2.0	6.9						
4.7	500 (A/B/E/F)	x1	96.3%	133F	1.9	5.5	1.9%	
				129A	0.8	7.4		
				120E	0.9	7.8		
				117B	0.1	7.4		
1F	0.0	5.5						
4.8	500 (A/B/E/F)	x5	96.3%	132B	1.2	7.7	4.2%	
				131F	1.2	8.0		
				119A	0.5	8.0		
				116E	0.4	5.5		
				1A	0.0	5.5		
				1F	0.0	8.3		

Table 5: Clusters produced from single and mixed request type workloads consuming CPU only, where the request contains internal concurrency and blocking, for both concurrent and serialized request invocations. See the Table 2 caption for explanation of the column headings.

## 6.3 An anomaly detection example

In several of the above experiments, we noticed occasional unexpected outlier requests, which were always placed in a cluster on their own (marked with a † in result tables). Examination of these individual requests revealed that in every case a 100ms chunk of CPU was being consumed inside a DPC. Using sampling profiler events logged by ETW during the offending intervals the problem was tracked down to a 3Com miniport Ethernet driver calling `KeDelayExecution(100000)`<sup>3</sup> from its transmit callback function!

The above example gives some concrete proof that Magpie can highlight apparently anomalous behaviour using extracted requests. Other common causes of outlier requests include JIT compilation, loading shared libraries, cache misses and genuine performance anomalies. Being able to identify and isolate these outliers is an advantage for accurate workload modelling.

<sup>3</sup>This function is implemented as a busy wait and the documentation clearly states it should not be used for delays of more than 100us.

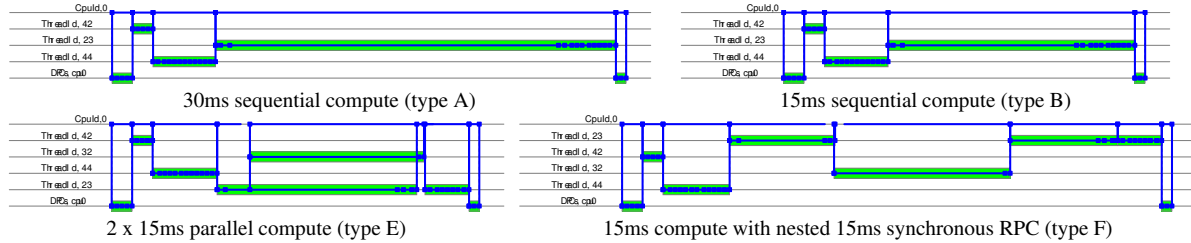


Figure 11: Canonical versions of four compute-bound HTTP requests with different internal concurrency structure.

## 7 Evaluation

We now turn to an evaluation of the toolchain with more realistic scenarios: a small two-tier web site and an enterprise-class database server.

### 7.1 Duwamish

In this section we extract requests from a distributed system and look at the accuracy of the derived workload model. The experimental setup is a two machine system running the Duwamish bookstore, a sample e-commerce application that is distributed with Visual Studio. We augmented the Duwamish database and the images stored at the web server with auto-generated data in accordance with the volume and size distributions mandated by TPC-W [21].

As in previous experiments, we first obtained results when all requests have the same URL, and then looked at the clusters produced from a mixed workload. Three dynamic HTML URLs were used, each with different characteristics:

1. The *book.aspx* page invokes a single database query to retrieve a book item and look up its associated data such as author and publisher. An image of the book cover may also be retrieved from the web server file system.
2. The *categories.aspx* page retrieves the details associated with the specified category by making three RPCs to the database.
3. The *logon.aspx* URL runs only on the web server.

As described in Section 4, a stitcher matches packet events within request fragments from individual machines to produce a single canonical form of the request across multiple machines. Table 6 shows the results of clustering on the WEB and SQL fragments alone, as well as on the entire request. For clarity, we have reported just the maximum cluster diameter and the minimum inter-cluster separation of each set of clusters. Similar to previous experiments, we report the fraction of relevant CPU that was included in the extracted requests in the “*Accntd CPU%*” column.

Two-tier e-commerce site

Exp No	Workload	Accntd CPU %	Clusters Found	Max. Dia.	Min. Sep.
5.1	Book(B)	82.8%	WEB: 404+92+4	0.8	3.6
		96.1%	SQL: 500	0.5	0.0
		-	E2E: 408+92	1.2	5.1
5.2	Logon(L)	86.5%	WEB: 497+2+1	1.2	7.3
5.3	Categories (C)	95.2%	WEB: 445+26+29	2.3	14.9
		97.3%	SQL: 1499+1	1.3	16.4
		-	E2E: 444+26+29+1	2.6	17.9
5.4	Mixed (B/L/C)	91.7%	WEB: (138L+1B)+ 220B+61C+ 31C+24C+ 10*25C	4.9	5.9
		96.7%	SQL: (141C <sub>1</sub> +122C <sub>2</sub> +141C <sub>3</sub> +221B)+ 9C <sub>2</sub> +10C <sub>2</sub>	2.3	19.7
		-	E2E: (138L+1B)+ 220B+55C+ 47C+14C+ 10*25C	5.1	8.2

Table 6: Clusters found from Duwamish requests, with both single and mixed URL workloads. Results are shown from clustering the workloads from individual machines (WEB and SQL) as well as “end-to-end requests” across both (E2E).

Closer inspection of the resulting clusters reveals that the *book* requests are primarily differentiated by whether a disk read is performed on the web server (to fetch an image of the book cover). On the *categories* page, the amount of network traffic varies between categories and hence one major and two minor clusters are formed. The three stored procedures invoked by *categories.aspx*—*GetCategories()*, *GetBooksByCategoryId()* and *GetDailyPickBooksByCategoryId()*—are identified in the table as  $C_1$ ,  $C_2$  and  $C_3$  respectively. All of these database request fragments bar one for this URL are put in the same cluster. According to the SQL Server Query Analyzer tool, the stored procedures are all of similar cost, so this is not surprising. The clusters for the mixed workload show that the *book* and *logon* pages form tighter clusters than the *categories* requests, which are spread across several clusters. These results indicate that a workload model based on per-URL measurements will be less representative than one constructed by grouping similar requests according to their observed behaviour.

**TPC-C benchmark**

#	Size	Contents	$d(0)$	$Dia.$	$Min. Sep.$
1	751	620B+100F+30D+1A	54.30	0.025	9.264
2	392	329A+56E+7D	105.05	0.119	14.393
3	302	266A+30D+3B+3E	29.16	0.116	9.264
4	30	30C	555.45	9.596	81.251
5	21	21C	111.03	4.870	78.080

Key:	A neworder	B payment	C stocklevel
	D orderstatus	E delivery	F version

Table 7: Clusters formed from TPC-C workload. The workload is a constrained ratio mix of 6 different transaction types shown in the key. The additional column  $d(0)$  shows the distance of each cluster centroid from the null request and gives an indication of the amount of resource consumption (largely disk I/O in this case).

## 7.2 TPC-C

The TPC-C benchmark [20] results presented in this section were generated using the Microsoft TPC-C Benchmark Kit v4.51 configured with 10 simultaneous clients and a single server. The resulting database would normally fit entirely in the memory of a modern machine. We therefore ran SQL Server with restricted memory to more accurately reflect the cache behaviour of a realistically dimensioned TPC-C environment.

The clustering algorithm created 5 clusters from 1496 requests. The clusters are quite tightly formed (they have low intra-cluster distances,  $Dia.$ ) and well separated (they have high inter-cluster distances,  $Sep.$ ). Although clusters 4 and 5 have somewhat higher intra-cluster distances, they are so well separated from any other cluster that this is unimportant.

Examining the make-up of the clusters reveals that the amount of I/O performed is the dominant factor in deciding the cluster for a request. Cluster 1 contains all *version* transactions and 99% of *payment* transactions, none of which have any I/O. Cluster 2 contains 95% of *delivery* transactions and 55% of *neworder* transactions: these are the transactions with a small amount of I/O. Cluster 3 holds the remaining 45% of *neworder* transactions, all of which have a moderate amount of I/O. The *orderstatus* transactions are split 45%/10%/45% between clusters 1–3 based on the I/O they contain. Finally, clusters 4 and 5 contain all the *stocklevel* transactions, predicted to be nearly 3 orders of magnitude more expensive than the next most expensive transaction by SQL Server Query Analyzer.

### 7.2.1 Shared buffer cache resources

Although the above clusters represent a reasonable summary of the benchmark workload in the experimental configuration, they also expose an area requiring further attention. In many applications, and especially in database servers, a shared buffer cache is the dominant factor affecting performance. Our instrumentation does

not yet record cache and memory references, observing only the disk I/O associated with cache misses and log writes. Given the explicit SQL buffer cache API it would be a simple matter to record the locality and sequence of pages and tables referenced by each query. We believe that this extra information will better distinguish between transaction types and may allow us to predict miss rates with different cache sizes as described in [15], but this remains an area for future work.

## 8 Related work

The most closely related work to Magpie is Pinpoint [8]. Pinpoint collects end-to-end traces of client requests in a J2EE environment by tagging each call with a request ID. This is simpler than using event correlation to extract requests, but requires propagation of a global request ID, which is not always possible with heterogeneous software components. The aim of Pinpoint is to diagnose faults by applying statistical methods to identify components that are highly correlated with failed requests. This is in contrast to the Magpie goal of recording not only the path of each request, but also its resource consumption, and hence being able to understand and model system performance.

Aguilera et al. [1] have proposed statistical methods to derive causal paths in a distributed system from traces of communications. Their approach is minimally invasive, requiring no tracing support above the RPC layer. However, by treating each machine as a black box, they sacrifice the ability to separate out interleaved requests on a single machine, and thus cannot attribute CPU and disk usage accurately. The approach is aimed at examining statistically common causal paths to find sources of high latency. Magpie’s request parsing on the other hand captures all causal paths in a workload, including relatively rare (but possibly anomalous) ones.

Distributed event-based monitors and debuggers [2, 4, 13] track event sequences across machines, but do not monitor resource usage, which is essential for performance analysis. Conversely, many systems track request latency on a single system but do not address the distributed case. TIPME [9] tracked the latency of interactive operations initiated by input to the X Window System. Whole Path Profiling [14] traces the control flow patterns between basic blocks in a running program.

Similar approaches on different operating systems include the Linux Trace Toolkit [22], which tracks request latency on a single machine. The Magpie toolchain could easily be built to consume LTT events instead of ETW events. A more sophisticated instrumentation framework is Solaris DTrace [6], which allows arbitrary predicates and actions to be associated with instrumentation points. DTrace provides an option for speculative tracing, which

could potentially be a lightweight mechanism for enabling request sampling.

Chen and Perkowitz [7] measure web application response times by embedding JavaScript in the web pages being fetched, i.e. by modifying the content being served rather than instrumenting client or server code. The aggregated data gives a view of client-side latency that would complement the detailed server-side workload characterisation obtained using Magpie.

## 9 Conclusion

In this paper we described the Magpie toolchain that takes stand-alone events generated by operating system, middleware and application components, correlates related events to extract individual requests, expresses those requests in a canonicalized form and then finally clusters them to produce a workload model. We validated our approach against traces of synthetic workloads, and showed that our approach is promising for more complicated applications.

We have shown that by using Magpie to isolate the resource demands and the path taken by requests, we can construct stochastic models that give a good representation of a workload's behaviour. A great advantage of Magpie is that these request structures are learnt by observing the live system under a realistic workload. As a consequence, the parsed event trace of each individual request is recorded, giving a detailed picture of how requests are actually being serviced within the system.

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## References

- [1] M. K. Aguilera, J. C. Mogul, J. L. Wiener, P. Reynolds, and A. Muthitacharoen. Performance debugging for distributed systems of black boxes. In *Proc. 19th ACM Symposium on Operating Systems Principles (SOSP'03)*, pages 74–89, Oct. 2003.
- [2] E. Al-Shaer, H. Abdel-Wahab, and K. Maly. HiFi: A new monitoring architecture for distributed systems management. In *Proc. IEEE 19th International Conference on Distributed Computing Systems (ICDCS'99)*, pages 171–178, May 1999.
- [3] P. Barham, R. Isaacs, R. Mortier, and D. Narayanan. Magpie: online modelling and performance-aware systems. In *9th Workshop on Hot Topics in Operating Systems (HotOS IX)*, pages 85–90, May 2003.
- [4] P. C. Bates. Debugging heterogeneous distributed systems using event-based models of behavior. *ACM Transactions on Computer Systems (TOCS)*, 13(1):1–31, 1995.
- [5] H. Bunke. Recent developments in graph matching. In *Proc. 15th International Conference on Pattern Recognition*, pages 117–124, 2000.
- [6] B. M. Cantrill, M. W. Shapiro, and A. H. Leventhal. Dynamic instrumentation of production systems. In *Proc. USENIX Annual Technical Conference*, pages 15–28, June 2004.
- [7] J. B. Chen and M. Perkowitz. Using end-user latency to manage internet infrastructure. In *Proc. 2nd Workshop on Industrial Experiences with Systems Software WIESS'02*, Dec. 2002.
- [8] M. Y. Chen, A. Accardi, E. Kiciman, J. Lloyd, D. Patterson, A. Fox, and E. Brewer. Path-based failure and evolution management. In *Proc. 1st Symposium on Networked Systems Design and Implementation (NSDI'04)*, pages 309–322, Mar. 2004.
- [9] Y. Endo and M. Seltzer. Improving interactive performance using TIPME. In *Proc. ACM SIGMETRICS*, June 2000.
- [10] D. Gao, C. S. Jensen, R. T. Snodgrass, and M. D. Soo. Join operations in temporal databases. Technical Report TR-71, TIME-CENTER, Oct. 2002.
- [11] R. Isaacs, P. Barham, J. Bulpin, R. Mortier, and D. Narayanan. Request extraction in Magpie: events, schemas and temporal joins. In *11th ACM SIGOPS European Workshop*, Sept. 2004.
- [12] J.O.Kephart and D.M.Chess. The vision of autonomic computing. *IEEE Computer*, 36(1):41–50, Jan. 2003.
- [13] J. Joyce, G. Lomow, K. Slind, and B. Unger. Monitoring distributed systems. *ACM Transactions on Computer Systems (TOCS)*, 5(2):121–150, 1987.
- [14] J. R. Larus. Whole program paths. In *Proc. ACM conference on Programming Language Design and Implementation (SIGPLAN'99)*, pages 259–269, June 1999.
- [15] R. Mattson, J. Gecsei, D. Slutz, and I. Traiger. Evaluation techniques for storage hierarchies. *IBM Systems Journal*, 9(2):78–117, 1970.
- [16] Microsoft Application Center Test 1.0, Visual Studio .NET Edition. [http://msdn.microsoft.com/library/default.asp?url=/library/en-us/act/html/actml\\_main.asp](http://msdn.microsoft.com/library/default.asp?url=/library/en-us/act/html/actml_main.asp), May 2004.
- [17] Microsoft Corp. Event Tracing for Windows (ETW). [http://msdn.microsoft.com/library/en-us/perfmon/base/event\\_tracing.asp](http://msdn.microsoft.com/library/en-us/perfmon/base/event_tracing.asp), 2002.
- [18] I. Park and M. K. Raghuraman. Server diagnosis using request tracking. In *1st Workshop on the Design of Self-Managing Systems, held in conjunction with DSN 2003*, June 2003.
- [19] F. Risso and L. Degioanni. An architecture for high performance network analysis. In *Proc. 6th IEEE Symposium on Computers and Communications*, pages 686–693, July 2001.
- [20] Transaction Processing Performance Council. *TPC Benchmark C (On-line Transaction Processing) Specification*. <http://www.tpc.org/tpcc/>.
- [21] Transaction Processing Performance Council. *TPC Benchmark W (Web Commerce) Specification*. <http://www.tpc.org/tpcw/>.
- [22] K. Yaghmour and M. R. Dagenais. Measuring and characterizing system behavior using kernel-level event logging. In *Proc. USENIX Annual Technical Conference*, June 2000.