

Interactive Performance Measurement with *VNCplay*

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Abstract

Today many system benchmarks use throughput as a measure of performance. While throughput is appropriate for benchmarking server environments, response time is a better metric for evaluating desktop performance. Currently, there is a lack of good tools to measure interactive performance; although several commercial GUI testing tools exist, they are not designed for performance measurement.

This paper presents *VNCplay*, a cross-platform tool for measuring interactive performance of GUI-based systems. *VNCplay* records a user's interactive session with a system and replays it multiple times under different system configurations; interactive response time is evaluated by comparing the times at which similar screen updates occur in each of the replayed sessions. Using *VNCplay* we studied the effect of processor speed and disk load on interactive performance of Microsoft Windows and Linux. These experiments show that the same user session can have widely varying interactive response times in different environments while maintaining the same total running time, illustrating that response time is a better measure of interactive performance than throughput. The experimental results make a case for a response time measurement tool like *VNCplay*.

1 Introduction

Most performance evaluation studies today use throughput benchmarks to quantify system performance. However, throughput is not an appropriate performance metric for user desktops. User interface studies [12] have shown that response time, rather than throughput, is the right measure of interactive performance. We believe that the lack of research studies on interactive performance is due to the lack of tools that measure response time.

In designing *VNCplay*, we came up with the following characteristics that a good tool for benchmarking interac-

tive performance should have. First, it should be able to record an interactive session and replay it multiple times under different environments, so that the same repeatable workload can be used to meaningfully compare interactive performance. Second, the tool should be able to extract a measurement of response time from replayed sessions to quantify the observed performance. Finally, it is desirable that the tool not be tied to a specific platform or GUI toolkit, so that researchers can compare the performance of various systems.

We developed a tool, called *VNCplay*, that satisfies the above criteria. This tool was developed out of a need to evaluate the interactive performance of the Collective system [10, 2]. There are several commercial GUI testing tools that provide some amount of recording and replay capability [15, 17, 14]. However, they are mainly intended for testing and do not replay reliably when the system is slow. Furthermore, they only support specific toolkits and do not have a facility for extracting measurements from the replays.

VNCplay uses the VNC remote display protocol [9] for recording and replaying sessions. Since VNC servers are available for many platforms, *VNCplay* supports a wide variety of systems. In addition, we developed an analysis technique to extract useful response time measurements from the replay sessions. We used *VNCplay* to evaluate the effect of processor speed and disk I/O on response times of interactive applications. This evaluation shows that throughput benchmarks are not sufficient in measuring interactivity and validates the need for a tool such as *VNCplay*.

The rest of the paper describes *VNCplay* in more detail. A short user's view of *VNCplay* is presented in Section 2. Section 3 explains the design and implementation of *VNCplay*. In Section 4 we demonstrate the use of *VNCplay* in evaluating the interactive performance of Microsoft PowerPoint and OpenOffice Impress over a range of CPU speeds and I/O loads, as well as evaluating the interactive performance of different Linux disk I/O schedulers. Section 5 describes some ideas for future work.

Related work is discussed in Section 6 and we conclude in Section 7.

2 User's View of *VNCplay*

Using *VNCplay* to record and replay interactive sessions is as easy as using a VNC client. To record a session, a user runs

```
$ vncplay record server:port trace.vnc
```

This command brings up a VNC client connected to the specified server. The user performs the workload to be recorded, and closes the VNC client at the end of the workload. In case of the command shown, the user's workload is saved into the file *trace.vnc*. To replay a recorded workload, the user runs

```
$ vncplay play server:port trace.vnc out.rfb
```

The workload from *trace.vnc* will be replayed against the specified VNC server, and the entire session output will be saved into a log file *out.rfb* for later review or analysis. A view-only VNC client (one that will not accept keyboard and mouse input from the user) will be displayed while the replay is taking place, to provide the user with visual feedback. To allow for unattended session replay, the password for the VNC server can be saved to a file and passed to *vncplay* by specifying the *-pwfile* option on the command line.

To obtain interactive performance metrics from replayed sessions, the user first runs an analysis stage on the session log files, which takes some time to run (on our computer it takes approximately as long as replaying each of the sessions):

```
$ vncplay analyze out1.rfb ... > analyze.out
```

The command shown above produces intermediate analysis results in *analyze.out*, which can be then used to generate graphs like the ones presented later in this paper. For example, a cumulative distribution function of response times can be generated by

```
$ vncanalyze cdf analyze.out > cdf.out
```

The resulting *cdf.out* can be plotted by a tool like *gnuplot* [5].

3 Design and Implementation

VNCplay consists of three components: a recorder, a replayer, and an analyzer. The recorder and replayer pro-

vide reliable replay of interactive sessions. The analyzer takes replayed sessions and extracts interactive performance metrics from them. All of the components are based on a modified version of the TightVNC [13] Java client. The following sections describe some details of the design and implementation of *VNCplay*.

3.1 Recording and Playback

Based on our past experience with interactive session replay tools, such as [15, 7, 19, 1], we observed that one of the biggest problems that all of the tools have in common is correctly replaying mouse clicks. Most tools replay each input event, such as a mouse click, at exactly the same time that it occurred during recording. When replaying a session on a slower system, such an approach is not appropriate, as it can easily lead to mouse clicks being delivered to the wrong application. For example, suppose that during recording, the user brings up a window and clicks on a button in that window. During replay on a slower system, the window might take a few more seconds to appear. A purely time-based replay tool would click on the background image, where the button should have been, without waiting for the window and button to appear, resulting in different behavior in the replay than in the recorded session. This is not acceptable; therefore *VNCplay*'s recorder and replayer focus largely on reliable delivery of mouse events. Section 5 discusses reliable replay of sessions with both keyboard and mouse input.

The VNC recorder acts like a normal VNC client, except that it records the user's activity into a VNC replay log, such as the one shown in Figure 1. The log contains input events (mouse clicks and movements, and key presses) along with timestamps of when these events occurred. For each mouse click event, a snapshot of the screen is taken by the recorder and written to the replay log. These screen snapshots will enable the VNC replayer to reliably deliver the associated mouse click events.

During playback, the replayer connects to a VNC server as a client, and reads events from the VNC replay log. Events from the replay log are processed according to their timestamps; input events such as key presses and mouse movements are sent to the VNC server directly. For mouse clicks, the VNC replayer waits for the screen image to match the corresponding screen snapshot in the replay log before sending the mouse click event. The screen snapshot captures the visual state of the system when the user clicked the mouse during recording. By waiting for the screen image to match the snapshot, we ensure that the system has reached the same state during replay as during recording, at which time the mouse click can be safely delivered.

The replayer records all of the screen updates received from the server during replay into a log file [8] for later



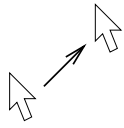
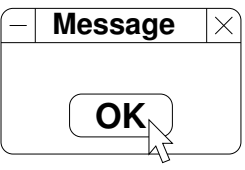

Event	 Keypress	 Keypress	 Mouse Motion	 Screen Snapshot	 Mouse Click	• • •
Time	0 msec	100 msec	200 msec	500 msec	800 msec	• • •

Figure 1: Example of a replay log used to record and play back VNC sessions. Keys "A" and "B" were pressed at 0 and 100 msec respectively, the mouse cursor was moved at 200 msec, a screen snapshot was taken at 500 msec, and a mouse click happened at 800 msec.

analysis or debugging. This allows the analysis of the replayed session to be performed at a later time offline, as it can be computationally intensive.

3.2 Reliable Playback

To reliably replay the same session multiple times, the system must behave repeatably – that is, at each replay, it should start from the same state, and given the same input, it should provide the same output. In working with *VNCplay*, we have found that complex desktop environments, such as Windows or Linux, are not fully deterministic from the point of view of VNC. This section describes some of the problems we encountered in achieving reliable session playback, and workarounds we have implemented to address them.

We found that a snapshot of the entire screen is often difficult to match during replay; non-deterministic elements like the system clock or tooltips are usually different between recording and replay, and get in the way of perfect reproducibility. *VNCplay* uses screen snapshots to ensure that mouse clicks are delivered to the same UI element during replay as during recording. For this purpose, we have found that it suffices to take a snapshot of just the screen area around the mouse cursor. For example, if during recording the user clicks on an "OK" button, we only need to take a snapshot of the button to ensure that we click on it correctly during replay. In our current implementation, we use a square area of about 10 pixels by 10 pixels around the cursor for screen snapshots. This significantly improves *VNCplay*'s ability to reliably replay sessions, by avoiding non-deterministic tooltips and other changing screen elements.

VNCplay attempts to deliver mouse click events reliably during playback, but other events, such as mouse motion, are simply replayed at the pace at which they were recorded. This resulted in some surprising behavior in a situation where mouse motion does matter. Some GUI elements, such as menus, change appearance when the

mouse is located over them – for example, the menu item that the mouse is pointing to might be highlighted. When a menu is slow to open, *VNCplay* will move the mouse cursor to where it expects the menu item to appear, before the menu item actually appears on the screen. As it turns out, in Windows, menu items "notice" that the mouse is pointing to them and highlight themselves only when the mouse moves. Thus, if the mouse is already pointing to a menu item by the time the menu item is drawn, the menu item will fail to notice that it should be highlighted. In turn, *VNCplay* will be unable to match the screen snapshot taken during recording, which shows a highlighted menu item, and replay will stall. To fix this problem, the replayer wiggles the mouse cursor by one pixel while waiting for a screen snapshot to match. This triggers "on-mouse-motion" callbacks in such GUI elements, allowing *VNCplay* to proceed with playback.

VNC is a very simple remote frame buffer protocol, in which the server provides periodic screen updates to the client at arbitrary intervals; it is up to the server to decide when a screen update should be sent to the client. The VNC protocol provides a kind of "eventual consistency" guarantee: when an image appears on the server's screen and stays there, a screen update containing that image will eventually be sent to the client. In particular, consider the effect of this remote frame buffer model on the updates seen by a VNC client during the rendering of a complex user interface. A VNC client might receive a screen update for every intermediate step of rendering the screen image, such as the steps shown in Figure 2, or it might only see one screen update representing the final state – such as step 3 in the figure.

This behavior of VNC screen updates complicates the process of taking a screen snapshot in *VNCplay*, because a screen snapshot is something that we expect to see each and every time we replay the recorded session. If the recorder takes a snapshot using an intermediate screen update, during replay the VNC server might not send us

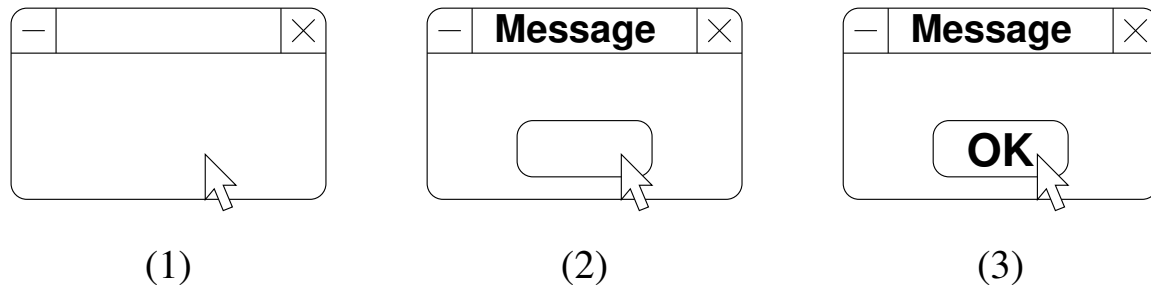


Figure 2: Three consecutive screen updates, as a dialog box is being rendered, that could be combined by the VNC server. VNC quiescing ensures that only the last screen update in such a sequence is used for a screen snapshot.

the same intermediate screen update, instead choosing to send only the final state and thereby preventing the replayer from matching the screen snapshot. For example, if we take a screen snapshot using step 1 or 2 in Figure 2 during recording, the server may choose to only send us the third screen update from the figure, preventing the replayer from successfully matching the screen snapshot. This means that if replay is to be reliable, screen snapshots taken by the VNC recorder should not be intermediate screen states.

To get around the problem of intermediate screen states, we implement VNC *protocol quiescing* during recording. When the recorder decides to take a screen snapshot, it temporarily blocks input events from being sent to the VNC server, and waits a short period of time for the system to process all prior user input and come to some final state; in other words, quiesce. After the screen has quiesced, the recorder takes a screen snapshot, and any blocked input events are sent to the VNC server. This technique produces screen snapshots which can be reliably observed during playback, and allows for robust replay of sessions. We have measured the time required for the operating system and the VNC server to quiesce under workloads such as a user using Microsoft PowerPoint or Word. On a 100 Mbps local area network, the VNC screen image quiesces within 100 milliseconds; *VNCplay* conservatively waits for 150 milliseconds before taking a screen snapshot.

3.3 Performance Analysis

The main metric that we wish to obtain from the interactive replay experiments is the response time for each input event. We implemented an analyzer that compares a set of replayed sessions and extracts interactive response times for various input events.

The analyzer looks for similar screen updates between the replayed sessions; for example, if the user opens a menu in the recorded session, the analyzer would find the times at which the menu opened in the different replays.

For each matching screen update, it finds the nearest preceding input event in all of the sessions, and assumes that this input event caused the screen update. The time difference between the screen update and the input event in each session is taken as the interactive response time for that input event in that session.

To make the analyzer run in acceptable space and time, we had to make a few optimizations. First, the resolution of all screen updates is scaled down (currently by a factor of four in each dimension). This reduces the size of each screen update by a factor of 16, without impacting the accuracy of screen matching – the features we want to match are larger than 4 pixels. Next, screen updates that happen at the same time are coalesced, reducing the number of screen updates that need to be scanned. Lastly, only significant screen updates are analyzed to find corresponding matches – currently the threshold we use is at least 2% pixel difference from the previous analyzed update. This optimization prevents the analyzer from analyzing periods of little or no activity (for example, only mouse movement). As a result of these optimizations, the analyzer can compare two typical interactive sessions on a 2.4GHz Pentium IV computer with 1GB of memory in about the same time it takes to replay the sessions.

4 Evaluation

This section describes our experience using *VNCplay* to evaluate interactive performance of Microsoft Windows and Linux. We subject these systems to various workloads and compare the interactive performance under these scenarios.

We performed four sets of experiments. The first two experiments measure effect of processor speed and disk I/O on interactive performance. The third experiment demonstrates that *VNCplay* can reliably replay interactive sessions over a wide range of system response times by running workloads on a system with an extremely slow disk, which increases the total runtime by a factor of 10. Finally, the fourth experiment shows that we can measure

interactive performance of a conventional Linux machine without the use of VMware, by evaluating the interactive performance effects of different disk I/O schedulers in Linux 2.6.

For the first three experiments, we used VMware's GSX Server [16] to run the system to be measured. VMware simplifies the task of making an identically-configured system for each experimental run. It also provides an efficient and platform-independent VNC server that is connected to the virtual machine's console. These experiments were done on a Thinkpad T42p laptop with a 2.0 GHz Pentium M processor, 1GB of memory and a 7200rpm 60GB hard drive.

For experiments with VMware virtual machines, we used the VNC recorder to record a user session in a virtual machine containing Microsoft Windows XP and Microsoft Office 2003, and another virtual machine containing Fedora Core 1 Linux and OpenOffice. Both sessions lasted about 6 minutes and consisted of a user creating a presentation, either in PowerPoint or OpenOffice Impress. These sessions were replayed in a variety of environments and the resulting session logs analyzed for interactive performance.

4.1 Effect of Processor Speed

We used the Enhanced Speedstep capabilities of the Pentium M processor to vary the processor speed from 300 MHz to 2.0 GHz and replayed both the PowerPoint and OpenOffice sessions in each of these scenarios. A point to note here is that the Pentium M processor running at a reduced speed does not accurately simulate the performance of an older processor that normally runs at that speed. This is because other characteristics of the processor, such as cache size and memory bus speed, remain unchanged.

Figures 3 and 4 show the total running time of the PowerPoint and OpenOffice sessions for various processor speeds. The running time stays more or less the same, with the difference between fastest and slowest times being less than 1%.

However, the interactive response times of individual events are very different for different processor speeds. Figures 5 and 6 show a CDF plot of the response times for sessions replayed under two different configurations: a simulated 300 MHz system and a 2.0 GHz system. The CDF plot shows the fraction of time that the system's response to user input was within a given value. For instance, a point with an x-axis value of 1 second and y-axis value of 90% would indicate that 90% of the time, the interactive response time was within 1 second.

These figures clearly show that both PowerPoint and OpenOffice running at 300 MHz respond much slower than running at 2.0 GHz, and a user would find it to be sig-

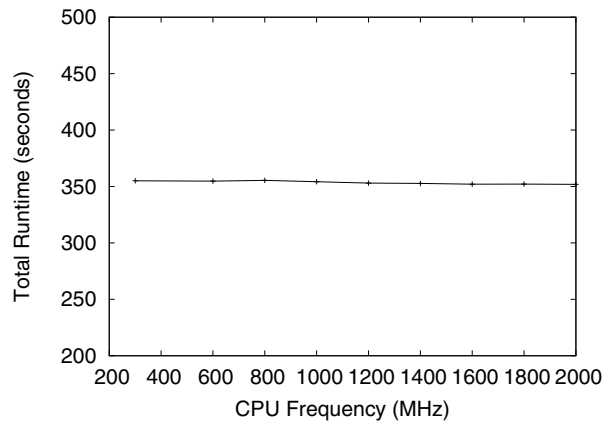


Figure 3: Total running time of a Microsoft PowerPoint session at various processor speeds

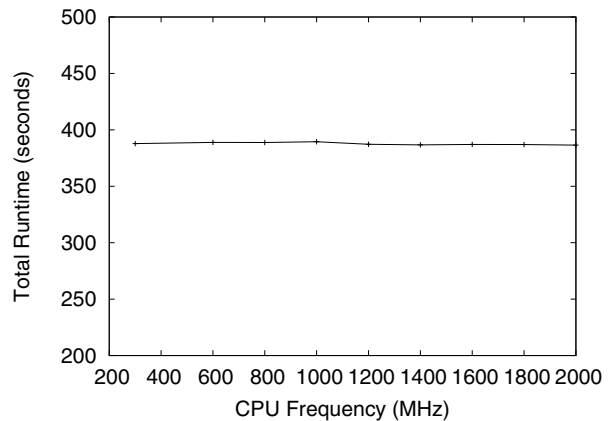


Figure 4: Total running time of a Linux OpenOffice session at various processor speeds

nificantly sluggish. For example, in the Linux OpenOffice environment the response time at the 40th percentile when running at 300 MHz is about five times the response time as when running at 2.0 GHz. The slowdown is further illustrated by Figures 7 and 8. These figures show the ratio of response times of events in OpenOffice and PowerPoint running at 300 MHz, to the response times of the same events while running at 2.0 GHz. The OpenOffice plot shows that most of the events are slowed down by a factor of two to factor of five, while for PowerPoint the slowdown is much more modest. This shows that OpenOffice running under Linux requires more CPU resources than PowerPoint under Windows XP.

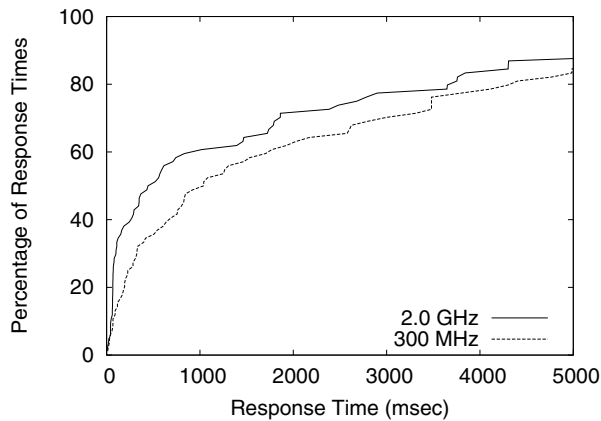


Figure 5: CDF plot of interactive response times for Microsoft PowerPoint under different conditions: on a 2.0 GHz machine and on a simulated 300 MHz machine. Each line shows the fraction of interactive response times (vertical axis) that are within a certain value (horizontal axis).

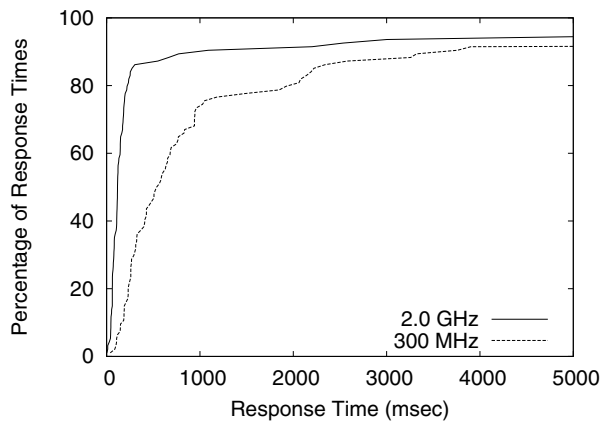


Figure 6: CDF plot of interactive response times for Linux OpenOffice under different conditions: on a 2.0 GHz machine and on a simulated 300 MHz machine. Each line shows the fraction of interactive response times (vertical axis) that are within a certain value (horizontal axis).

Note that in spite of the significant differences in response times between the 300 MHz and the 2.0 GHz runs, the total run time is the same in both OpenOffice and PowerPoint. This is because the interactive sessions consist of considerable amount of idle time between events (i.e., user think time). The extra latency in the 300 MHz ses-

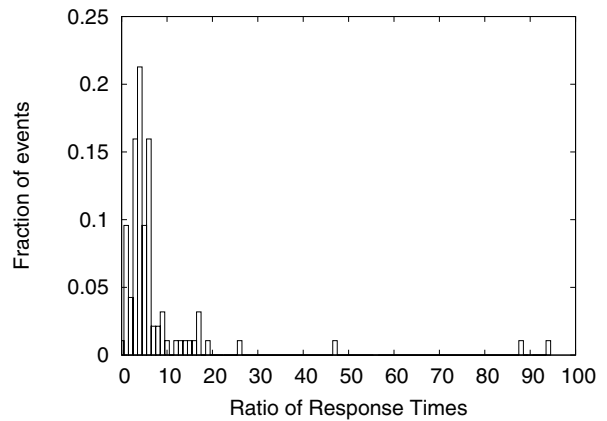


Figure 7: Histogram of the ratio of interactive response times for Linux OpenOffice on a simulated 300 MHz machine and a 2.0 GHz machine.

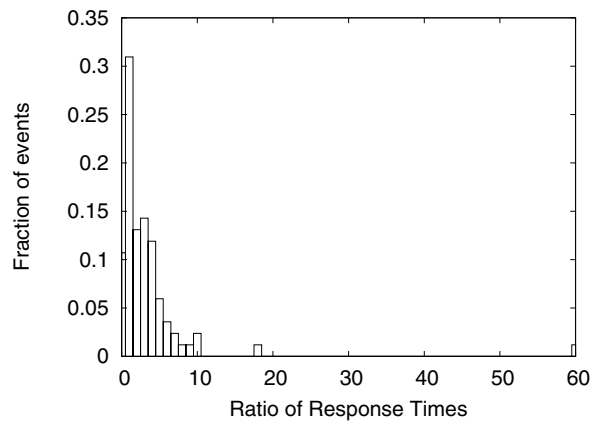


Figure 8: Histogram of the ratio of interactive response times for Microsoft PowerPoint on a simulated 300 MHz machine and a 2.0 GHz machine.

sions is absorbed by this idle time, leaving the total running time unchanged. This clearly demonstrates that total run time (and hence throughput benchmarks) are not appropriate for studying interactive responsiveness of systems and makes a case for tools like *VNCplay*.

To compare across a range of processor speeds, we plot the 25th, 50th, and 75th percentile response time latencies at various processor speeds in Figures 9 and 10. From these figures, we see that there is a minimum processor speed (between 300 MHz and 600 MHz) below which the interactive performance of office workloads de-

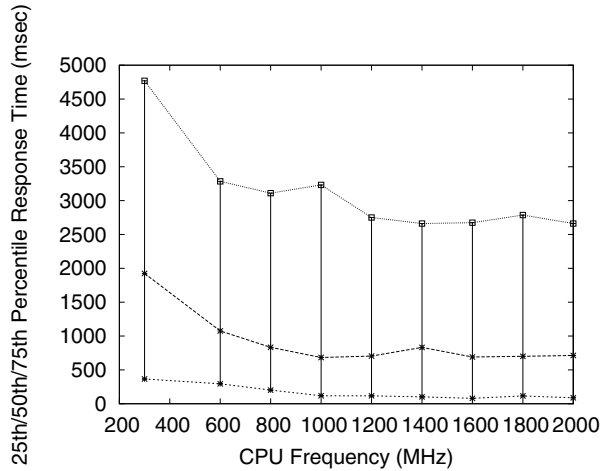


Figure 9: 25th/50th/75th percentiles of the interactive event latencies for Microsoft PowerPoint at various processor speeds

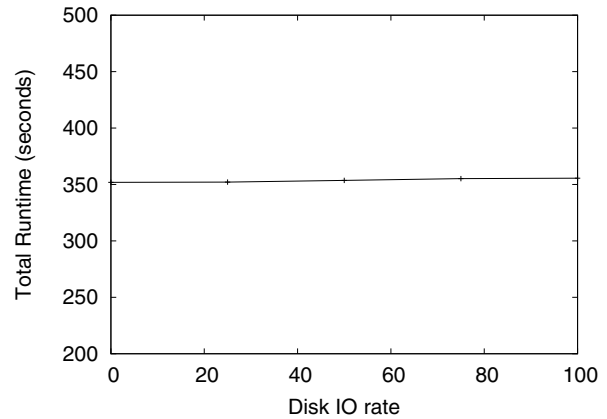


Figure 11: Total running time of the PowerPoint session at various disk I/O rates

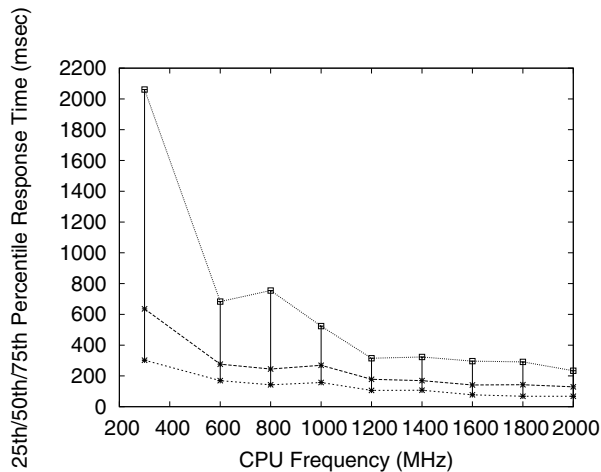


Figure 10: 25th/50th/75th percentiles of the interactive event latencies for Linux OpenOffice at various processor speeds

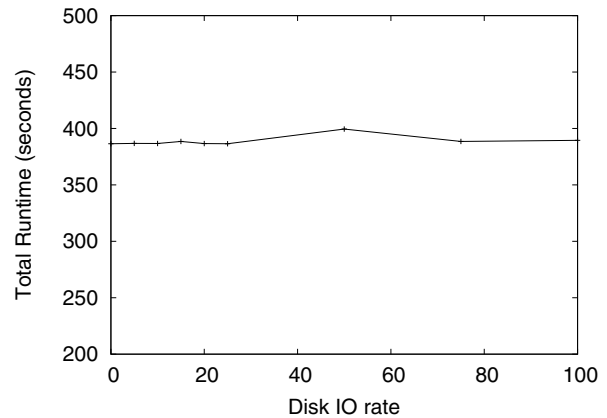


Figure 12: Total running time of the OpenOffice session at various disk I/O rates

grades rapidly. Increases in processor speed beyond this point provide a gradually diminishing increase in returns, as is to be expected.

4.2 Effect of Disk I/O

We measure the effect of disk I/O on the interactive performance of Microsoft Windows and Linux systems by injecting background disk activity and replaying the PowerPoint and OpenOffice sessions. We wrote a small utility that performs background disk I/O at a specified rate.

Each disk I/O is a 32 KB read from the disk.

Figures 11 and 12 show the total run times for various disk I/O rates. As in the previous experiment, the differences in total run times are very small. In Figures 13 and 14 we can see the distribution of interactive response times in two sessions: one with no extra background disk activity and the other with a rate of 100 disk I/Os per second. The response times for the latter session are higher than the ones in the former session. Although the interactive response times of the system are noticeably different in the two cases, the total runtime remains the same, underscoring the need for an interactive performance measurement tool like *VNCplay*.

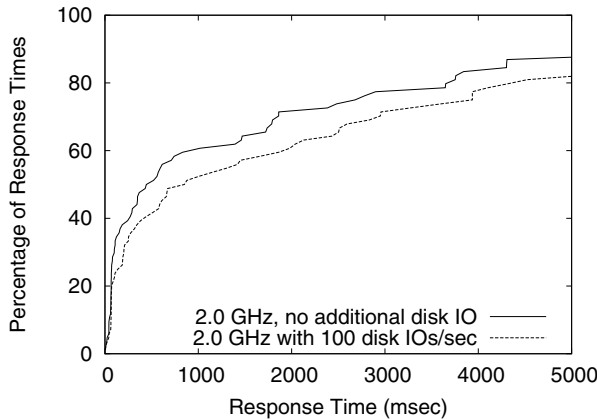


Figure 13: CDF plot of interactive response times for Microsoft PowerPoint under different conditions: on a 2.0 GHz machine with no additional disk IO and on the same machine experiencing 100 additional disk IOs per second. Each line shows the fraction of interactive response times (vertical axis) that are within a certain value (horizontal axis).

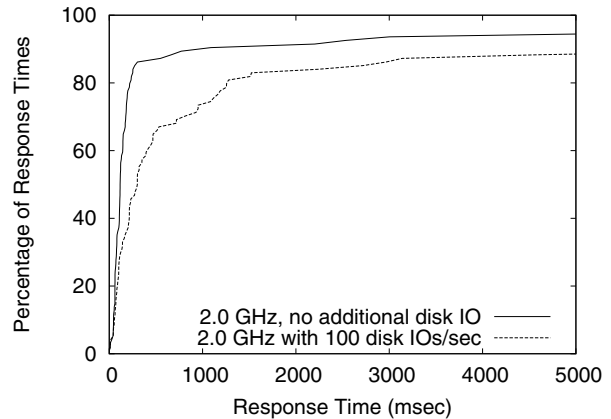


Figure 14: CDF plot of interactive response times for Linux OpenOffice under different conditions: on a 2.0 GHz machine with no additional disk IO and on the same machine experiencing 100 additional disk IOs per second. Each line shows the fraction of interactive response times (vertical axis) that are within a certain value (horizontal axis).

4.3 Reliable Session Playback

To verify that our tools can replay interactive sessions in extreme environments, we simulated an environment with an extremely slow disk subsystem. In particular, we moved the virtual disks of our experimental virtual machine onto an NFS file server connected by a simulated 1.5 Mbps down / 384 Kbps up DSL network link with 40ms round-trip latency. We then replayed a PowerPoint session and a similar Word session on this virtual machine. Although the total running time of the sessions increased from 6 minutes to approximately an hour, the sessions nonetheless completed successfully. This suggests that our replay mechanism is robust against large variations in system response time.

4.4 Replay without VMware

In the above experiments, we used VMware to run the system to be measured. In some experiments this might not be appropriate and the system might need to run on physical hardware. In this section, we demonstrate the use of *VNCplay* in one such scenario: measurement of the effect of different linux disk I/O schedulers on interactive performance. This experiment needs to be performed on physical hardware since VMware's high overhead for disk I/O can bias the experimental results.

The test machine in this case was a 2.2GHz Xeon ma-

chine with 4GB of memory, running Fedora Core 3. The system was configured to run a standard graphical login session on a VNC server for the purpose of this experiment. For each replay session, a test user account was created from scratch and the machine was rebooted to clear the buffer cache. This ensures that the test machine is brought back to the same state at the beginning of each experimental run.

For this experiment, we recorded a user session lasting about 8 minutes. This consisted of a user creating a simple presentation in OpenOffice Impress, developing a small program in the KDevelop integrated development environment, and changing his desktop background. The Linux system was configured with a different I/O scheduler on each experiment run, and we injected heavy background disk activity. The session was replayed to analyze interactive performance. We tested the anticipatory, deadline, cfq, and noop schedulers that are present in the Linux 2.6 kernel.

Scheduler	Total Runtime (min)
anticipatory	14.1
cfq	7.7
deadline	7.5
noop	7.4

Figure 15: Total running time of the user session with various I/O schedulers

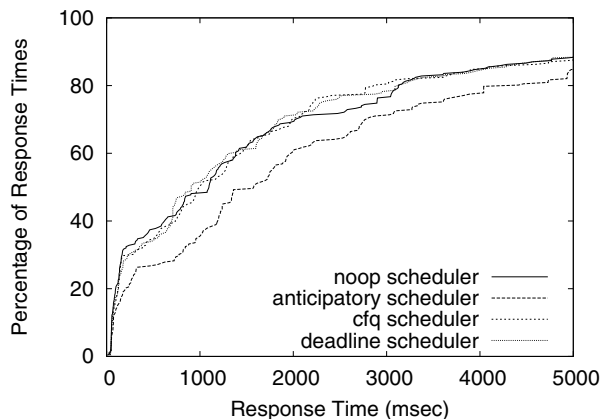


Figure 16: CDF plot of interactive response times for a desktop Linux workload using different disk I/O schedulers and a heavy background disk I/O load.

Figure 15 shows the total runtime, and Figure 16 shows the CDF plot of response times for sessions replayed under the various schedulers. As these figures illustrate, the anticipatory disk scheduler has the worst interactive performance under heavy disk load. This can be easily explained by the anticipatory scheduling algorithm. After having serviced a disk request from a process, the anticipatory scheduler waits for a short period of time for subsequent requests from the same process; any disk requests so received are given high priority. Thus this algorithm favors disk requests from background process with heavy disk activity, and hurts the performance of interactive processes.

From the results of our evaluation, we observe that latency measurements rather than total runtime are an appropriate metric of interactive performance. We also see that *VNCplay* can robustly measure interactive latency over a wide range of scenarios, including various platforms such as Microsoft Windows and Linux, and wide variations in system response time.

5 Future Work

There are a few areas in which our current recorder and replayer fall short. Our current implementation does not attempt to properly synchronize keyboard input events. To make session replay robust across a wide range of workloads, we have worked around the problem by explicitly inserting screen snapshots before keyboard input. This is done by making additional mouse clicks in the application before any keyboard input is sent.

Time-sensitive UI elements are another shortcoming of

our system we hope to address in the future. For instance, Windows makes use of sub-menus that automatically expand when the mouse cursor hovers over a menu item for some period of time. The VNC replayer does not wait for the sub-menu item to appear before proceeding with the replay, and thus can sometimes go astray when replaying in a slow environment. In the current system, we explicitly click on each menu item, even if it has already expanded automatically, to ensure that session can be replayed reliably.

We are exploring the following idea to learn dependencies between input events (both keyboard and mouse) and output events from many replay sessions. After recording an interactive session on a baseline system, we replay the same workload on the baseline system with slight timing variations in the input. Using the runs that were successful, *VNCplay* learns which output events must always happen before an input event is sent, and which ones are irrelevant for the purpose of dependencies. We believe that this information can be used to make replay very robust.

An alternative approach to handling keyboard input is to use a mouse-driven keyboard input tool like the Character Map in Windows.

6 Related Work

Industry benchmarks such as Winbench and Winstone [18] measure the time to complete a fixed workload, but do not indicate how responsive the system is to user input.

Several tools available today for replaying interactive workloads are toolkit-specific [15, 17, 19, 14, 1]. In contrast, *VNCplay* is toolkit- and platform-agnostic. Most of the above tools are intended for GUI testing and require the user to manually insert delay statements for correct replay on slower systems. In addition, to the best of our knowledge, none of them provide response time measurements for the replayed sessions. *VNCplay* provides such measurements and can also be used to perform GUI testing and task automation similar to the tools mentioned above.

Interest in the research community on quantifying interactive performance has been relatively recent. Endo et al. [4, 3] make a case for using latency as a measure for interactive performance. Recent work on measuring thin client systems [11, 6] uses response time as a measure of performance of thin client systems. However, there is no general toolkit for measuring interactive response times, and we developed *VNCplay* to fill this need.

7 Conclusions

This paper presents a tool for reliably replaying interactive user sessions by correlating screen updates with user input while recording and obeying this ordering during replay. The interactive performance of the system in each of the replayed sessions is analyzed by comparing the timestamps of matching screen updates across sessions. Our evaluation of the tool suggests that it is useful for measuring interactive performance of real systems.

8 Availability

The toolkit described in this paper is available for download at:

<http://suif.stanford.edu/vncplay/>

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