

**Precision Timed Machines**

by

Isaac Liu

A dissertation submitted in partial satisfaction of the  
requirements for the degree of  
Doctor of Philosophy

in

Electrical Engineering and Computer Science

in the

GRADUATE DIVISION  
of the  
UNIVERSITY OF CALIFORNIA, BERKELEY

Committee in charge:  
Professor Edward A. Lee, Chair  
Professor John Wawrzynek  
Professor Alice Agogino

Spring 2012

# **Precision Timed Machines**

Copyright 2012  
by  
Isaac Liu

**Abstract**

Precision Timed Machines

by

Isaac Liu

Doctor of Philosophy in Electrical Engineering and Computer Science

University of California, Berkeley

Professor Edward A. Lee, Chair

This is my abstract

To my wife Emily Cheung, my parents Char-Shine Liu and Shu-Jen Liu, and everyone else whom I've had the pleasure of running into for the first twenty-seven years of my life.

# Contents

<b>List of Figures</b>	<b>iii</b>
<b>List of Tables</b>	<b>iv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.2 Intro Section Header 2 . . . . .	1
<b>2 Precision Timed Machine</b>	<b>2</b>
2.1 Architecture Design (Todo: Use repeatability? predictability? analyzability?) . . . . .	2
2.1.1 Thread-Interleaved Pipelines . . . . .	4
2.1.2 Memory System . . . . .	8
2.2 Implementation . . . . .	8
2.2.1 PTARM Simulator . . . . .	8
2.2.2 PTARM VHDL Softcore . . . . .	8
2.2.3 Worst Case Execution Time Analysis . . . . .	8
<b>3 Related Work</b>	<b>9</b>
3.1 Architectural Modifications . . . . .	9
3.2 Related Section Header 2 . . . . .	9
<b>4 Programming Models</b>	<b>10</b>
4.1 PRET Programming model Section Header . . . . .	10
4.2 Pret Programming model Section Header 2 . . . . .	10
<b>5 Applications</b>	<b>11</b>
5.1 Eliminating Side-Channel-Attacks . . . . .	11
5.2 Real Time 1D Computational Fluid Dynamics Simulator . . . . .	12
<b>6 Conclusion and Future work</b>	<b>14</b>
6.1 Summary of Results . . . . .	14
6.2 Future Work . . . . .	14
<b>Bibliography</b>	<b>15</b>

# List of Figures

1.1	Image Placeholder . . . . .	1
2.1	Simple Multithreaded Pipeline . . . . .	3
2.2	Sample execution sequence of a thread-interleaved pipeline with 5 threads and 5 pipeline stages . . . . .	4
2.3	Sample code segments that cause data dependencies in typical pipelines . . . . .	5
2.4	Handling of conditional branches in single threaded pipelines . . . . .	6
2.5	Handling of data dependencies in single threaded pipelines . . . . .	7
2.6	Illustrative example showing the replay mechanism . . . . .	7
2.7	None Pipelined Floating Unit . . . . .	8
3.1	Image Placeholder . . . . .	9
4.1	Image Placeholder . . . . .	10
5.1	Image Placeholder . . . . .	13

## List of Tables

## Acknowledgments

I want to thank my wife

I want to thank my parents

I want to thank my advisor, Edward A. Lee

I want to thank the committee members

I want to thank Hiren Patel

I want to thank Jan Rieneke

I would also like to thank the ptolemy group especially Christopher and Mary, Jia for providing me the template

I would like to thank everyone else that made this possible



# Chapter 1

## Introduction

Outline

### 1.1 Background

- Discuss the problem
- show the difficulty in execution time analysis as background

Fig. 1.1 shows an image

### 1.2 Intro Section Header 2

Here is another header

The remaining chapters are organized as follows. Chapter 3 surveys the related research that has been done on architectures to make them more analyzable. Chapter 2 explains the architecture of PRET including the thread-interleaved pipeline and memory hierarchy, Chapter ??, Chapter 5, Chapter 6,

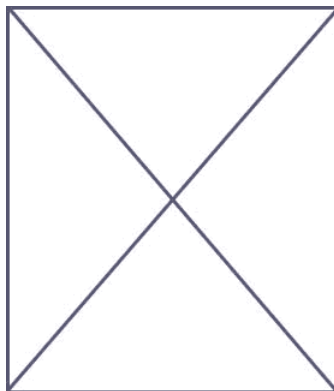


Figure 1.1: Image Placeholder

## Chapter 2

# Precision Timed Machine

In this chapter we present the PREcision Timed (PRET) Machine. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nam eu est neque. Suspendisse mollis gravida mi in blandit. Vivamus porta libero at massa sagittis pellentesque. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed nibh magna, facilisis ac dapibus vitae, tincidunt nec magna. Morbi ac neque in est porta placerat. Duis viverra blandit ante, ut scelerisque arcu sodales vel. Aenean sapien erat, tincidunt malesuada accumsan a, eleifend feugiat leo. Maecenas auctor nulla non purus fringilla nec hendrerit massa facilisis. Donec vel diam nibh. Maecenas sed massa non mauris faucibus condimentum et et metus. Fusce placerat, dolor et adipiscing suscipit, orci lectus fringilla mauris, a tincidunt dolor mauris id ligula. Vestibulum luctus, dolor in bibendum accumsan, leo turpis suscipit enim, et hendrerit odio metus eget dolor. Morbi in lectus massa.

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nam eu est neque. Suspendisse mollis gravida mi in blandit. Vivamus porta libero at massa sagittis pellentesque. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed nibh magna, facilisis ac dapibus vitae, tincidunt nec magna. Morbi ac neque in est porta placerat. Duis viverra blandit ante, ut scelerisque arcu sodales vel. Aenean sapien erat, tincidunt malesuada accumsan a, eleifend feugiat leo. Maecenas auctor nulla non purus fringilla nec hendrerit massa facilisis. Donec vel diam nibh. Maecenas sed massa non mauris faucibus condimentum et et metus. Fusce placerat, dolor et adipiscing suscipit, orci lectus fringilla mauris, a tincidunt dolor mauris id ligula. Vestibulum luctus, dolor in bibendum accumsan, leo turpis suscipit enim, et hendrerit odio metus eget dolor. Morbi in lectus massa.

### 2.1 Architecture Design (Todo: Use repeatability? predictability? analyzability?)

Multithreaded architectures were introduced to improve instruction throughput over instruction latency. The architecture optimizes thread-level parallelism over instruction-level parallelism to improve performance. Multiple hardware threads are introduced into the pipeline to fully utilize thread-level parallelism. When one hardware thread is stalled, another hardware thread can be fetched into the pipeline for execution to avoid stalling the whole pipeline. To lower the context switching overhead, the pipeline contains physically separate copies of hardware thread states, such as registers files and program counters etc, for each hardware thread. Figure 2.1 shows a architectural level view of a simple multithreaded pipeline. It contains 5 hardware threads, so it has 5

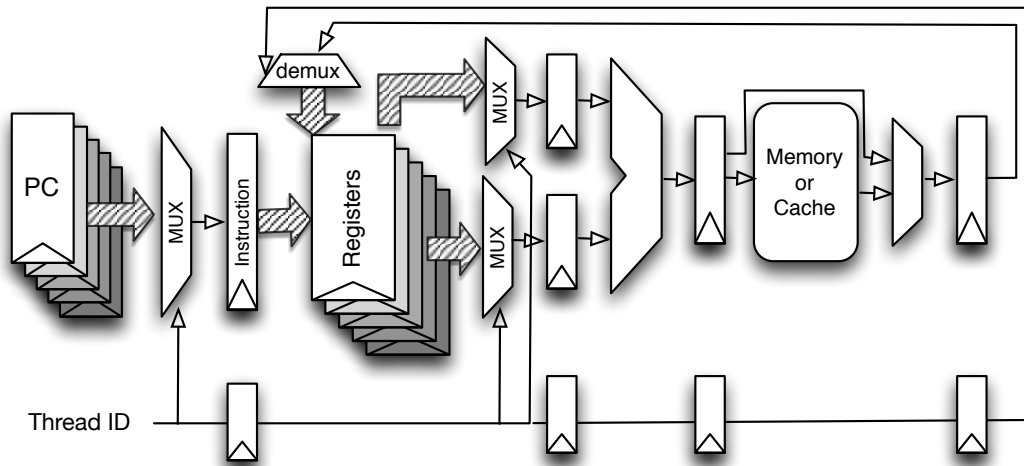


Figure 2.1: Simple Multithreaded Pipeline

copies of the Program Counter (PC) and Register files. Once a hardware thread is executing in the pipeline, its corresponding thread state can be selected by signaling the correct selection bits to the multiplexers. The rest of the pipeline remains similar to a traditional 5 stage pipeline as introduced in Hennessy and Patterson (Todo: citation). The extra copies of the thread state and the multiplexers used to select them thus contribute to most of the hardware additions needed to implement hardware multithreading.

Ungerer et al. [22] surveyed different multithreaded architectures and categorized them based upon the (Todo: thread selection?) policy and the execution width of the pipeline. The thread selection policy is the context switching scheme used to determine which threads are executing, and how often a context switch occurs. Coarse-grain policies manage hardware threads similar to the way operation systems manage software threads. A hardware thread gain access to the pipeline and continues to execute until a context switch is triggered. Context switches occur less frequently via this policy, so less hardware threads are required to fully utilize the processor. Different coarse-grain policies trigger context switches with different events. Some trigger on dynamic events, such as cache miss or interrupts, and some trigger on static events, such as specialized instructions. Fine-grain policies switch context much more frequently – usually every processor cycle. Both coarse-grain and fine-grain policies can also have different hardware thread scheduling algorithms that are implemented in a hardware thread scheduling controller to determine which hardware thread is switched into execution. The width of the pipeline refers to the number of instructions that can be fetched into execution in one cycle. For example, superscalar architectures have redundant functional units, such as multipliers and ALUs, and can dispatch multiple instructions into execution in a single cycle. Multithreaded architectures with pipeline widths of more than one, such as Simultaneous Multithreaded (SMT) architectures, can fetch and execute instructions from several hardware threads in the same cycle.

Multithreaded architectures typically bring additional challenges to execution time analysis of software running on them. Any timing analysis for code running on a particular hardware thread needs to take into account not only the code itself, but also the thread selection policy of the

architecture and sometimes even the execution context of code running on other hardware threads. For example, if dynamic coarse-grain multithreading is used, then a context switch could occur at any point when a hardware thread is executing in the pipeline. This not only has an effect on the control flow of execution, but also the state of any hardware that is shared, such as caches or branch predictors. Thus, it becomes nearly impossible to estimate execution time without knowing the exact execution state of other hardware threads and the state of the thread scheduling controller. However, it is possible for multithreaded architectures to fully utilize thread-level parallelism while still maintaining timing predictability. Thread-interleaved pipelines use a fine-grain thread switching policy with round robin thread scheduling to achieve high instruction throughput while still allowing precise timing analysis for code running on its hardware threads. Below, its architecture and trade-offs are described and discussed in detail along with examples and explanation of how timing predictability is maintained. Through the remainder of this chapter, we will use the term “thread” to refer to explicit hardware threads that have physically separate register files, program counters, and other thread states. This is not to be confused the common notion of “threads”, which is assumed to be software threads that is managed by operating systems with thread states stored in memory.

### 2.1.1 Thread-Interleaved Pipelines

Thread-interleaved pipelines use fine-grain multithreading; every cycle a context switch occurs and a different hardware thread is fetched into execution. The threads are scheduled in a deterministic round robin fashion. This also reduces the context switch overhead down to nearly zero, as no time is needed to determine which thread to fetch next, and barely any hardware is required to implement round robin thread scheduling; a simple  $\log(n)$  bit up counter (for  $n$  threads) would suffice. Figure 2.2 shows an example execution sequence from a 5 stage thread-interleaved pipeline with 5 threads. The thread-interleaved pipelines shown and presented in this thesis are all of single width. In the figure, time progresses horizontally towards the right, each time step, or column, represents a processor cycle. Each row

represents an instruction that is fetched and executed within the pipeline. Each block represents the instruction entering the different stages of the pipeline – fetch (F), decode (D), execute (E), memory (M) and writeback (W). Each color represents instructions from different hardware threads. We can observe from the figure that each time step an instruction from a different hardware thread is fetched into execution and the hardware threads are fetched in a round robin order. At time step 4, the processor is completely filled, and each pipeline stage is occupied by a different hardware thread. This remains the same for time step 5, 6, 7 and so on. The fine-grained thread interleaving and the round robin scheduling combine to form this unique property of thread-interleaved pipelines, which

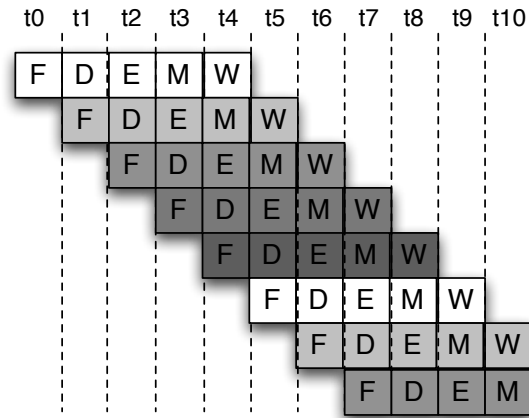


Figure 2.2: Sample execution sequence of a thread-interleaved pipeline with 5 threads and 5 pipeline stages

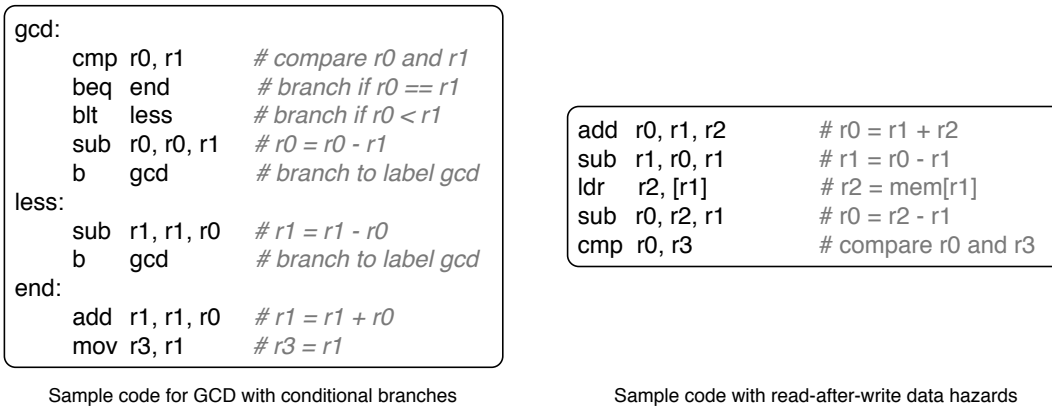


Figure 2.3: Sample code segments that cause data dependencies in typical pipelines

provides the basis for a timing predictable architecture design.

For thread-interleaved pipelines, if there are, at a minimum, the same number of threads as there are pipeline stages, then the data-dependencies that were caused from pipelining no longer exist. We will use the term “full” thread-interleaved pipelines if there exists at least the same number of threads in the pipeline as pipeline stages. Data-dependencies arise when an instruction needs data from another instruction that is currently executing in the pipeline and has not yet completed its execution. As illustrated in figure 2.2, instructions in a full thread-interleaved pipeline can never be dependent upon any other instruction that’s currently in executing in the pipeline, because at stage of the pipeline is occupied by an instruction from a separate thread. In other words, an instruction will always commit before the next instruction from the same thread is fetched, thus no data-dependency within instructions can occur. To further illustrate this point, we will use the two code segments shown in figure 2.3 and show how data and control hazards no longer exist in thread-interleaved pipelines. Both code segments shown in figure 2.3 consists of assembly instructions from the ARMv4 ISA([Todo: citation](#)). The code on the left shows an implementation of Greatest Common Divisor (GCD) using conditional branch instructions *beq* (branch equal) and *blt* (branch less than). The code on the right shows an arbitrarily constructed computation code where each instruction is dependent on the results of the previous instruction.

Conditional branch instructions in the ARM instruction set architecture (ISA) branch based on conditional flags that are set with special compare instructions([Todo: citation](#)). The *cmp* instruction is one such compare instruction that subtracts two registers and updates the conditional flags according to the results. The GCD implementation shown on the left of of figure 2.3 uses this mechanism to determine whether to continue or end the algorithm. Conditional branches cause control-flow hazards in the pipeline; the instruction after the branch, which should be fetched the next cycle, is unknown until after the branch is resolved. Figure 2.4 show two ways conditional branches are commonly handled in a single-threaded pipeline. A simple but effective way of handling control-flow hazards is by simply stalling the pipeline until the conditional branch is resolved. This is shown on the left of the figure, as 2 pipeline delays (or bubbles) are inserted in the decode stage for the instruction *beq*, until the *cmp* instruction is completed in the write back stage. The dependencies between instructions are also drawn out to make clear why the pipeline bubbles are

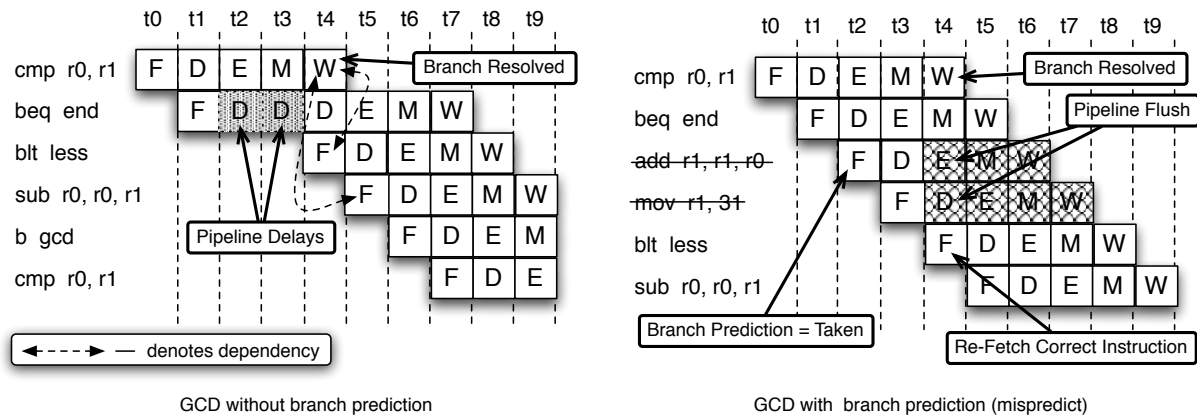


Figure 2.4: Handling of conditional branches in single threaded pipelines

necessary.

For instructions that take multiple cycles, a replay mechanism is used so the round robin thread scheduling is preserved and no interference is introduced between the threads. When a multi-cycle instruction is fetched into the pipeline from a thread, it executes as any instruction. As the instruction goes through the pipeline, no results are committed, but instead its state is saved in a hardware thread control block and does not increment the program counter for this thread. When an instruction fetch from this thread occurs, the same instruction is dispatched into the pipeline to continue its execution. If it still has not completed its execution, then the program counter for this thread is again not incremented and the same instruction is dispatched, until it is completed. Figure 2.6 illustrates this mechanism.

For instructions that take multiple cycles due to limitations of the pipeline design, this mechanism makes sense. Instructions that do 64-bit operations on a 32-bit pipeline datapath for example falls into this category. In order to abide to the round-robin thread scheduling, the thread simply saves the instruction state and continues execution when it gains access to the pipeline. However, for other multi-cycle instructions, such as memory operations, this mechanism might seem counter intuitive. These instructions require multiple cycles because data is required from other hardware components that have longer access latencies. Memory operations or floating point operations are categorized into such instructions because they are waiting for data from main memory access or computation results from floating point units. Often times multithreaded architectures mark these threads inactive and the thread is not rescheduled until the data is ready. This is done to maximize the throughput of the pipeline, since threads waiting for data from other hardware components cannot make any progress until the data is returned. However, this leads to unpredictable timing behaviors in the threads. When threads are scheduled and unscheduled dynamically, the other threads in the pipeline would dynamically execute more or less frequently depending on which threads are active and inactive. This greatly complicates any timing analysis on the software running on each thread as the execution frequency of the threads would depend on the execution of other threads. Thus, our thread-interleaved pipeline does not mark threads inactive, but simply replays the instruction from the thread. The effects of latency hiding is still present, as other threads continue to progress while

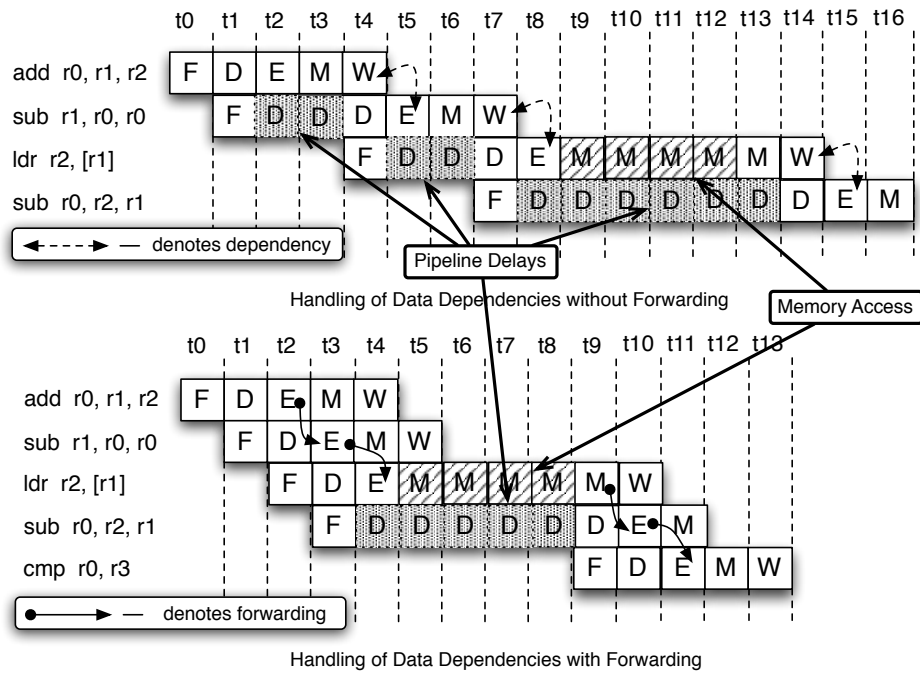


Figure 2.5: Handling of data dependencies in single threaded pipelines

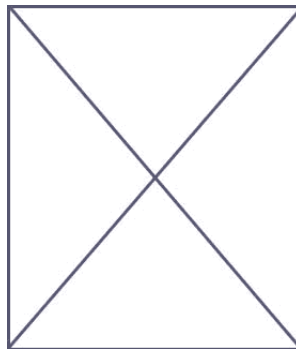


Figure 2.6: Illustrative example showing the replay mechanism

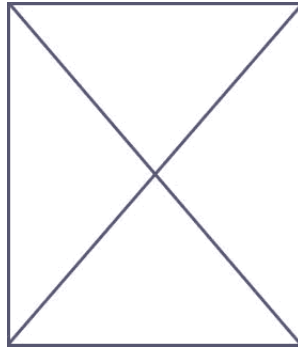


Figure 2.7: None Pipelined Floating Unit

one thread is replaying its multi-cycle instruction.

Care must also be taken when adding datapaths that take multiple cycles, or else the interference introduced could easily disrupt the timing analysis of threads. If the added datapath isn't able to support pipelined or simultaneous operations, then it will introduce contention amongst the threads. For example, in figure 2.7 we show the effects of adding a non-pipelined floating point divider that takes 20 cycles to execute. As one thread executes a floating-point division instruction, any other thread that also executes a floating-point division must now wait until the first instruction finishes. If other threads also execute the same instruction, then queuing mechanisms must be introduced, for threads that are contending for the floating-point divider. This would greatly complicate the timing analysis, as the execution time of floating-point division instructions now depend on the execution context of other threads. Pipelining the floating-point divider would increase the throughput at the cost of area and latency. However, by pipelining the floating-point divider unit, each thread that executes a floating-point division can now access it without contention. The replay mechanism also hides the long latency of the instruction, and benefits from the improved latency. Because there is no contention, the timing analysis of floating-point operations are now trivial and predictable.

In summary, blah blah blah...

### 2.1.2 Memory System

## 2.2 Implementation

### 2.2.1 PTARM Simulator

### 2.2.2 PTARM VHDL Softcore

### 2.2.3 Worst Case Execution Time Analysis



## Chapter 3

# Related Work

### 3.1 Architectural Modifications

Fig. 3.1 shows an image

### 3.2 Related Section Header 2

Here is another header

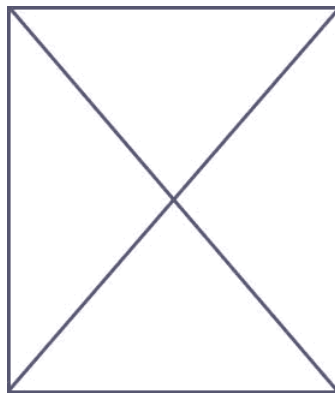


Figure 3.1: Image Placeholder

## Chapter 4

# Programming Models

Intro text here

### 4.1 PRET Programming model Section Header

Fig. 4.1 shows an image

### 4.2 Pret Programming model Section Header 2

Here is another header

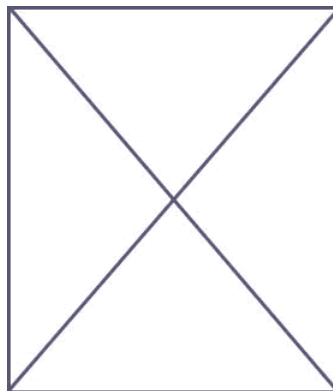


Figure 4.1: Image Placeholder

## Chapter 5

# Applications

### 5.1 Eliminating Side-Channel-Attacks

Encryption algorithms are based on strong mathematical properties to prevent attackers from deciphering the encrypted content. However, their implementations in software naturally introduce varying run times because of data-dependent control flow paths. Timing attacks [14] exploit this variability in cryptosystems and extract additional information from executions of the cipher. These can lead to deciphering the secret key. Kocher describes a timing attack as a basic signal detection problem [14]. The “signal” is the timing variation caused by the key’s bits when running the cipher, while “noise” is the measurement inaccuracy and timing variations from other factors such as architecture unpredictability and multitasking. This signal to noise ratio determines the number of samples required for the attack – the greater the “noise,” the more difficult the attack. It was generally conceived that this “noise” effectively masked the “signal,” thereby shielding encryption systems from timing attacks. However, practical implementations of the attack have since been presented [6, 9, 25] that clearly indicate the “noise” by itself is insufficient protection. In fact, the architectural unpredictability that was initially believed to prevent timing attacks was discovered to enable even more attacks. For example, computer architects use caches, branch predictors and complex pipelines to improve the average-case performance while keeping these optimizations invisible to the programmer. These enhancements, however, result in unpredictable and uncontrollable timing behaviors, which were all shown to be vulnerabilities that led to side-channel attacks [3, 20, 2, 8].

In order to not be confused with Kocher’s [14] terminology of *timing attacks* on algorithmic timing differences, we classify all above attacks that exploit the timing variability of software implementation *or* hardware architectures as *time-exploiting attacks*. In our case, a *timing attack* is only one possible *time-exploiting attack*. Other time-exploiting attacks include branch predictor, and cache attacks. Examples of other side-channel attacks are power attacks [17, 13], fault injection attacks [4, 10], and many others [25].

In recent years, we have seen a tremendous effort to discover and counteract side-channel attacks on encryption systems [4, 8, 15, 11, 1, 12, 7, 24, 23]. However, it is difficult to be fully assured that all possible vulnerabilities have been discovered. The plethora of research on side-channel exploits [8, 4, 15, 11, 1, 12, 7, 24, 23] indicates that we do not have the complete set of solutions as more and more vulnerabilities are still being discovered and exploited. Just recently, Coppens et al. [8] discovered two previously unknown time-exploiting attacks on modern x86 pro-

cessors caused by the out-of-order execution and the variable latency instructions. This suggests that while current prevention methods are effective at *defending* against their particular attacks, they do not *prevent* other attacks from occurring. This, we believe, is because they do not address the root cause of time-exploiting attacks, which is that run time variability *cannot be controlled* by the programmer.

It is important to understand that the main reason for time-exploiting attacks is *not* that the program runs in a varying amount of time, but that this variability *cannot be controlled* by the programmer. The subtle difference is that if timing variability is introduced in a controlled manner, then it is still possible to control the timing information that is leaked during execution, which can be effective against time-exploiting attacks. However, because of the programmer’s *lack of control* over these timing information leaks in modern architectures, noise injection techniques are widely adopted in attempt to make the attack infeasible. These include adding random delays [14] or blinding signatures [14, 7]. Other techniques such as branch equalization [18, 25] use software techniques to rewrite algorithms such that they take equal time to execute during each conditional branch. We take a different approach, and directly address the crux of the problem, which is the *lack of control* over timing behaviors in software. We propose the use of an embedded computer architecture that is designed to allow predictable and controllable timing behaviors.

At first it may seem that a predictable architecture makes the attacker’s task simpler, because it reduces the amount of “noise” emitted from the underlying architecture. However, we contend that in order for timing behaviors to be controllable, the underlying architecture *must* be predictable. This is because it is meaningless to specify any timing semantics in software if the underlying architecture is unable to honor them. And in order to guarantee the execution of the timing specifications, the architecture must be predictable. Our approach does not attempt to increase the difficulty in performing time-exploiting attacks, but to eliminate them completely.

In this paper, we present the PREcision Timed (PRET) architecture [16] in the context of embedded cryptosystems, and show that an architecture designed for predictability and controllability effectively eliminates all time-exploiting attacks. Originally proposed by Lickly et al [16], PRET provides instruction-set architecture (ISA) extensions that allow programmers to control an algorithm’s temporal properties at the software level. To guarantee that the timing specifications are honored, PRET provides a predictable architecture that replaces complex pipelines and speculation units with multithread-interleaved pipelines, and replaces caches with software-managed fast access memories. This allows PRET to maintain predictability without sacrificing performance. We target embedded applications such as smartcard readers [15], key-card gates [5], set-top boxes [15], and thumbpods [21], which are a good fit for PRET’s embedded nature. We demonstrate the effectiveness of our approach by running both the RSA and DSA [19] encryption algorithms on PRET, and show its immunity against time-exploiting attacks. This work shows that a disciplined defense against time-exploiting attacks requires a combination of software and hardware techniques that ensure controllability and predictability.

## 5.2 Real Time 1D Computational Fluid Dynamics Simulator

Here is another header

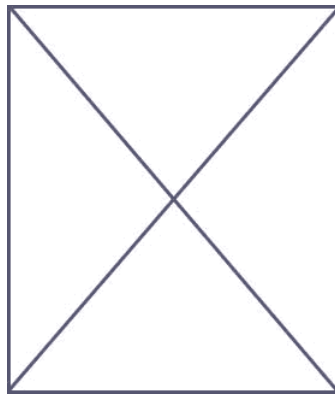


Figure 5.1: Image Placeholder

## **Chapter 6**

# **Conclusion and Future work**

### **6.1 Summary of Results**

This is my summary

### **6.2 Future Work**

Here is what you can keep doing

# Bibliography

- [1] O. Aciicmez, Çetin Kaya Koç, and J.-P. Seifert. On the Power of Simple Branch Prediction Analysis. In *ASIACCS '07: Proceedings of the 2nd ACM symposium on Information, computer and communications security*, pages 312–320, New York, NY, USA, 2007. ACM.
- [2] O. Aclicmez, J. pierre Seifert, and C. K. Koc. Predicting secret keys via branch prediction. In *in Cryptology CT-RSA 2007, The Cryptographers Track at the RSA Conference 2007*, pages 225–242. Springer-Verlag, 2007.
- [3] D. J. Bernstein. Cache-timing Attacks on AES, 2004.
- [4] E. Biham and A. Shamir. Differential Fault Analysis of Secret Key Cryptosystems. *Lecture Notes in Computer Science*, 1294:513–525, 1997.
- [5] S. C. Bono, M. Green, A. Stubblefield, A. Juels, A. D. Rubin, and M. Szydlo. Security analysis of a cryptographically-enabled rfid device. In *SSYM'05: Proceedings of the 14th conference on USENIX Security Symposium*, pages 1–1, Berkeley, CA, USA, 2005. USENIX Association.
- [6] D. Brumley and D. Boneh. Remote timing attacks are practical. In *SSYM'03: Proceedings of the 12th conference on USENIX Security Symposium*, pages 1–1, Berkeley, CA, USA, 2003. USENIX Association.
- [7] D. Chaum. Blind Signatures for Untraceable Payments. In *Advances in Cryptology: Proceedings of Crypto 82*, pages 199–203. Plenu Press, 1983.
- [8] B. Coppens, I. Verbauwhede, K. De Bosschere, and B. De Sutter. Practical Mitigations for Timing-Based Side-Channel Attacks on Modern x86 Processors, 2009.
- [9] J.-F. Dhem, F. Koeune, P.-A. Leroux, P. Mestre, J.-J. Quisquater, and J.-L. Willems. A Practical Implementation of the Timing Attack. In J.-J. Quisquater and B. Schneier, editors, *Proceedings of the Third Working Conference on Smart Card Research and Advanced Applications (CARDIS 1998)*. Springer-Verlag, 1998.
- [10] M. Feng, B. B. Zhu, M. Xu, S. Li, B. B. Zhu, M. Feng, B. B. Zhu, M. Xu, and S. Li. Efficient Comb Elliptic Curve Multiplication Methods Resistant to Power Analysis, 2005.
- [11] R. Karri, K. Wu, P. Mishra, and Y. Kim. Fault-Based Side-Channel Cryptanalysis Tolerant Rijndael Symmetric Block Cipher Architecture. In *DFT '01: Proceedings of the IEEE International Symposium on Defect and Fault Tolerance in VLSI Systems*, page 427, Washington, DC, USA, 2001. IEEE Computer Society.

- [12] J. Kelsey, B. Schneier, D. Wagner, and C. Hall. Side Channel Cryptanalysis of Product Ciphers. In *Journal of Computer Security*, pages 97–110. Springer-Verlag, 1998.
- [13] P. Kocher, J. J. E. and B. Jun. Differential Power Analysis. In *Lecture Notes in Computer Science*, pages 388–397. Springer-Verlag, 1999.
- [14] P. C. Kocher. Timing attacks on implementations of Diffie-Hellman, RSA, DSS, and other systems. In *Lecture Notes in Computer Science*, pages 104–113. Springer-Verlag, 1996.
- [15] O. Kömmerling and M. G. Kuhn. Design Principles for Tamper-Resistant Smartcard Processors. In *USENIX Workshop on Smartcard Technology proceedings*, pages 9–20, 1999.
- [16] B. Lickly, I. Liu, S. Kim, H. D. Patel, S. A. Edwards, and E. A. Lee. Predictable Programming on a Precision Timed Architecture. In *CASES '08: Proceedings of the 2008 international conference on Compilers, architectures and synthesis for embedded systems*, pages 137–146, New York, NY, USA, 2008. ACM.
- [17] T. S. Messerges, E. A. Dabbish, and R. H. Sloan. Investigations of Power Analysis Attacks on Smartcards. In *In USENIX Workshop on Smartcard Technology*, pages 151–162, 1999.
- [18] D. Molnar, M. Piotrowski, D. Schultz, and D. Wagner. The Program Counter Security Model: Automatic Detection and Removal of Control-Flow Side Channel Attacks. In *In Cryptology ePrint Archive, Report 2005/368*, 2005.
- [19] National Institute of Standards and Technology. "Digital Signature Standard". Federal Information Processing Standards Publication 186, 1994.
- [20] C. Percival. Cache missing for fun and profit. In *Proc. of BSDCan 2005*, page 05, 2005.
- [21] P. Schaumont, K. Sakiyama, Y. Fan, D. Hwang, S. Yang, A. Hodjat, B. Lai, and I. Verbauwhede. Testing ThumbPod: Softcore bugs are hard to find. In *Eighth IEEE International High-Level Design Validation and Test Workshop, 2003*, pages 77–82, 2003.
- [22] T. Ungerer, B. Robič, and J. Šilc. A survey of processors with explicit multithreading. *ACM Comput. Surv.*, 35:29–63, March 2003.
- [23] Z. Wang and R. B. Lee. Covert and Side Channels Due to Processor Architecture. In *ACSAC '06: Proceedings of the 22nd Annual Computer Security Applications Conference*, pages 473–482, Washington, DC, USA, 2006. IEEE Computer Society.
- [24] Z. Wang and R. B. Lee. New cache designs for thwarting software cache-based side channel attacks. In *Proceedings of the 34th annual international symposium on Computer architecture*, pages 494 – 505, San Diego, CA, June 2007 2007.
- [25] Yongbin. Side-channel attacks: Ten years after its publication and the impacts on cryptographic module security testing.