

CPU Trace Recompilation

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Abstract

We propose a $O(n \log n)$ time complexity algorithm to recompile long sequences C of assembly instructions into a novel code called SECODE. When C is encountered again, SECODE is run, producing the same effects as C . SECODE also matches with trace code with the same non-pointer register values as C . Thus a key property of SECODE is that it matches with trace codes that use different memory locations. If C uses s non-transient heap space and t non-transient stack operations, then the size of SECODE is $O(s + t)$, and it runs in time $O(s \log s + t)$, with small constants. This is without any programmer annotations.

1 Introduction

CPU designers have focused away from increasing the clock speed because the processors cannot be cooled fast enough. More heat is created from faster clock speed and a point has been reached where the amount of energy it takes to cool increasingly fast processors is prohibitively expensive. CPU manufacturers have turned to parallelism for clock speedups. For example, Intel has released the *Intel Parallel Studio*, which is a software development project to facilitate parallel programming to take advantage of multi-core processors. However, this complicates the coding process, eliminating coding abstractions that isolate the programmer from the underlying details of the computer running the code.

This obstacle invites new approaches to increasing the speed of CPU's. With the Programming Smart Machine Lab (PSML)[[AWE+14](#), [WAS12](#), [App14](#)], a new model is proposed. It is noted that traces of CPUs are very non-random. This implies there's redundancy in the trace streams, which implies there exists so-called hot paths, which are long pieces of code with minimal side-effects that are repeatedly executed by the computer. PSML proposes a form of *Memoization* of the hot paths, originally proposed by [[Mic68](#)]:

““It would be useful if computers could learn from experience and thus automatically improve the efficiency of their own programs during execution... When I write a clumsy program for a contemporary

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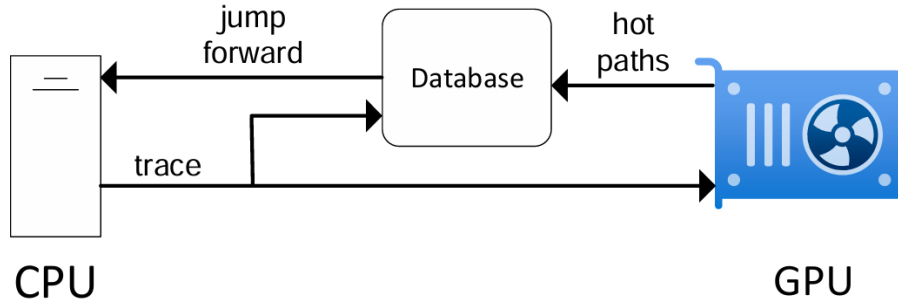


Figure 1: The proposed setup for exploiting hot paths.

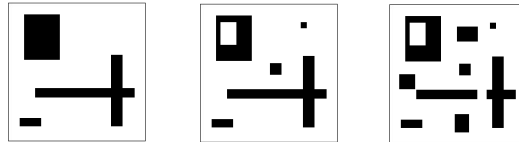


Figure 2: The evolution of the state of the computer, represented as a binary image.

computer a thousand runs on the machine do not re-educate my handiwork. On every execution, each time-wasting blemish and crudity, each needless test and redundant evaluation, is meticulously reproduced.”

Mitchie further noted that functions can be *memoized* and either calculated directly (rote) or through a lookup table (rule).

“On each given occasion proceed either by rule, or by rote, or by a blend of the two, solely as dictated by the expediency of the moment ... rule versus rote decisions shall be handled by the machine behind the scenes.”

With memoization in mind, the proposed setup (with some minor changes) can be seen in Figure 1. The CPU sends its operating trace to a GPU, which uses machine learning to identify hot paths. The hot paths are sent to a database. This database, upon receiving the same trace as the GPU, will periodically indicate a jump forward in the state of the computer. To the author’s knowledge, PSML was the first team to propose this configuration.

This paper proposes a solution to the database component in Figure 1. This database is called the SEDATABASE, short for side effect database. The machine learning portion is out of the scope of this paper, but some discussion on this topic is included. We introduce a new method to directly compile, in $O(n \log n)$

time, large streams of assembler trace C into new code that contains a minimal set of conditions and side effects of C . This new compiled code is called SECODE, short for side effect code. SECODE contains conditions, called SECONDITIONS and changes, called SECHANGES. If C uses s non-transient heap space and performs t non-transient stack operations, then the size of SECONDITIONS is $O(s + t)$ and it runs in time $O(s \log s + t)$. The running time of *SEChanges* is $O(s + t)$. e SECHANGES is highly optimized. The following components of C are removed:

- Redundant memory operations.
- Math operations.
- Transient register operations.
- Transient memory operations.
- Transient stack operations.

Very large FOR loops are handled by compiling together the SECONDITIONS of the most common paths taken. SECODE is compiled without any programmer annotation. This method can also handle floating point registers with approximate programming. However this requires explicit markup in the code by the programmer.

In [AWE⁺14], the state of the computer was represented as a $1 \times n$ binary picture which evolves over time, as seen in Figure 2 (seen as an $n \times n$ picture). They described the evolution of the computer as a very long video. Partial states of the image are queried into the database and if a matching rule is found, the state of the computer is updated with a new partial picture.

However, this approach has some difficulties. Take, for example, the following code. It starts with an input of two integer variables n and m and a pointer $head$. It constructs a m sized linked list starting at $head$ and at node i it stores $func(n, i)$, for some complicated math function $func$. It then terminates. Because the $head$ pointer is different at every run, one cannot use the method described in [AWE⁺14]. One would like the recompiled code to be pointer agnostic. Indeed, in this paper, SECODE treats pointers as variables, so it can create the linked list as well as memoize $func(n, i)$ for every node. The following criterion is used to distinguish pointers¹ from regular variables:

Pointers only are added to and subtracted from, and compared with other pointers or zero.

An example is trace assembler code C that sorts a doubly linked list, with starting values (5, 3, 2, 4, 1). If C is compiled into SECODE and sent to the SEDATABASE, then the next time C is reached and a match (5, 3, 2, 4, 1) is made, then SEDATABASE will automatically jump to the list being sorted, (1, 2, 3, 4, 5).

¹This paper doesn't deal with the case of testing the difference between two pointers, but this can be handled readily.

Figure 3: The original code is compiled into SEDIAGRAMS which are, in turn, reduced and recompiled into SECODE.

This will happen each time C is reached and matched to $(5, 3, 2, 4, 1)$, regardless of the particular pointer values of each run.

There are two phases in the overall setup, the SECODE construction phase and the execution phase.

The construction process starts when the machine learning component selects a region of trace assembler code to be compiled. Discussion of this component can be found in Section 6. Once the trace code is identified, it is recompiled into SECODE. To do this, the original code is compiled into an annotated directed graph. This graph is represented visually with SEDIAGRAMS. We will use the term graph and SEDIAGRAMS interchangeably. SEDIAGRAMS can be reduced to a minimal set of conditions and side effects of the original code. Then the SEDIAGRAMS is recompiled into SECODE, in particular the SECONDITIONS and the SECHANGES. The entire process can be completed in $O(n \log n)$ time. This configuration can be found in Figure 3.

The execution of the SEDATABASE IS AS FOLLOWS. Say the computation uses s non-transient heap space and t non-transient stack operations. For each compiled SECODE the SECONDITIONS checks whether there is a match in $O(s \log s + t)$ time. Multiple SECONDITIONS can be compiled together into a conditional tree structure. If, during the course of operation, a SECONDITION is satisfied, then the output is an array of pointers. Using this array, the side effects of the compiled code are computed with its corresponding SECHANGES code in $O(s + t)$ time. After that, normal operation resumes.

2 Related Work

In [GTM99], sequences of assembler instructions are jumped over using a lookup table. Memoization has been implemented on functional languages, [ABH11]. A program to dynamically identify areas of code that represent good candidates for memoization was introduced in [TPG15]. In [ACV05], lossy memoization for multimedia floating-point applications was proposed.

There is a lot of work on combining pattern recognition and computing when the results only need to be approximately correct [Mit16]. Machine learning has been incorporated at the operating system level with regard to learning configurations, learning policies, learning mechanism, and process scheduling [KK20]. Machine learning has also been suggested as a tool for managing the configuration of operating systems [ZH19]. A machine learning library for kernel space has been developed [UAZ20]. However, to the author's knowledge, there is nothing in the literature (aside from PSML) which suggests applying machine learning directly to CPU traces with the intention of leveraging hot paths.

3 MIPS Instruction Set

In this paper, a subset of MIPS instruction set is used for the traces. With some redundancy, the entire instruction set can be used. The majority of this paper assumes the operations are over integers. Section 6 addresses how the SEDATABASE handles floating point numbers. We assume the reader is familiar with operations of registers and the stack. All registers are denoted by \$n, for some number n . The stack pointer register is represented \$sp. We assume a small, but unspecified, number of registers. The following MIPS operations will be used in this paper.

Load Immediate

```
1 li $1, 300
```

The load immediate operation puts the constant second argument into the register specified in the first argument.

Move

```
1 move $1, $2
```

The move operations puts the contents of register \$2 into register \$1.

Add Immediate

```
1 addi $1, $2, 200
```

The contents of register \$1 is set to the contents of register \$2 plus the absolute number (in this case 200).

Add

```
1 add $1, $2, $3
```

The contents of register \$1 is set to the contents of register \$2 plus register \$3.

Subtract

```
1 sub $1, $2, $3
```

The contents of register \$1 is set to the contents of register \$2 minus register \$3.

Multiply

```
1 mul $1, $2, $3
```

The contents of register \$1 is set to the contents of register \$2 times register \$3. The way SEDATABASE handles MUL is the same way it handles all mathematical operations other than addition and subtraction. This includes OR, AND, DIV, an SHIFT. Therefore, we exclude these operations from the scope of the paper.

Branch on Equal

```
1 beq $1, $2, 100
```

If register \$1 is equal to register \$2, then goto the program counter + 4 + offset (in this case, 100). SEDATABASE handles branch on equal exactly how it handles branch on not equal, BNE, so this operation is not included.

Branch on Less Than

```
1 blt $1, $2, 100
```

If register \$1 is less than register \$2, then goto the program counter + 4 + offset (in this case, 100). SEDATABASE handles branch on less than as it handles branch on less than or equal, greater than, and greater than or equal, so these operations are not included in this paper.

Load Word

```
1 lw $1, 100($2)
```

Register \$1 is set to the contents of the memory at the location specified by register \$2 plus the offset (in this case 100).

Store Word

```
1 sw $1, 100($2)
```

The contents of register \$1 is saved into memory at location in register \$2 plus the offset (in this case 100).

New

To allocate memory, MIPS specifies placing the memory size a register and returns the address location in another. However, for simplification purposes, we will use the following notion to allocate memory.

```
1 new $1, $2
```

This operation creates memory of size equal to the contents of register \$2 and places its location in register \$1.

Free

The MIPS instruction set does not include a method for freeing memory. We create a new operation of the following form.

```
1 free $1
```

This operation frees the memory location at the address in register \$1.

Trace Code

When the assembler code is run, the registers will have values associated with them. In order to represent them, numbers are point in the comments section.

```
1 add $1 $2 $3 # 5 4 1
```

This indicates register \$1 results in a value of 5 and registers \$2 and \$3 are 4 and 1, respectively. Depending on the operation, the first argument equals either the current register value or a new assigned value. An example is the LW and SW operations.

```
1 lw $1, 100($2) # 200 14352
2 sw $1, 400($2) # 300 45902
```

The LW operation indicates register \$1 results in a value of 200 and \$2 contains the address 14352+200 that was referenced. The SW indicates 300 is in register \$1, which is stored in address 45902+400.

4 SEDIAGRAMS

SEDIAGRAMS are linearly constructed from large swaths of assembler trace code. SEDIAGRAMNS consists of two types of constructs: nodes and lines. Nodes are represented by gray rectangles and the lines have arrows at the end. The diagram is a directed acyclic graph that flows downward. An abstract SEDIAGRAM can be seen in Figure 4. For each operation in the trace code, zero, one or two nodes are created at the bottom of the SEDIAGRAM. New lines going into the node are constructed, connecting to previous created nodes higher up in the SEDIAGRAM. After the SEDIAGRAM has been constructed, it can be used to create the SECONDITIONS and SECHANGES. The SECONDITIONS construct is an annotated directed graph representing pointers and constant values. The SECHANGES is assembler code to be run on the SEDATABASE that will implement the side effects of the original code. The construction of the SECONDITIONS and SECHANGES from the SEDIAGRAM occurs with algorithms starting at the top of the diagram and then working its way down.

If, during the course of the operation of the computer, there is a match with a SECONDITIONS construct, then the current state of the computer matches the state of the computer when the original trace code was compiled. Thus, there is a match between values accessed during the running of the trace and a bijection between pointers of interest. This means that the control flow of the

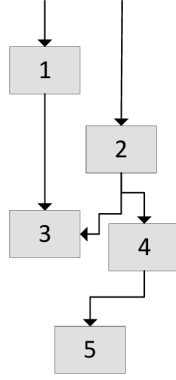


Figure 4: An abstract SEDIAGRAM. The nodes of the SEDIAGRAM are compiled into SECODE from top to bottom, in the order specified.

two states are the same. Due to this match, math and branching operations do not need to be recomputed.

The SECODE distinguishes between two different types of data, pointers and numbers. The key difference between these two datatypes is that pointers can only perform one of the following operations.

- Added by a number.
- Subtracted by a number.
- Compared to 0.
- Compared to another pointer.

Using this criteria, the construction of the SEDIAGRAM determines which information is a regular number or a pointer. The set of node types of SEDIAGRAMS can be seen in Figure 5.

4.1 Lines

Lines contain three pieces of information: a val, a register number, and a type. There are three different types of lines: *Const*, *Var*, and *SP*. The *Const* lines represent values in the computation which are not pointer values. The val of a *Const* line is the value of the constant. For example, if the trace code is the sorting of a linked list, then the *Const* lines represent the integer values accessed and modified in the linked list nodes. The *Var* lines represent the pointer values used in the original trace code. The val of a *Var* line is the raw pointer value. The *Var* lines have the restriction that the only operations that can be applied to them is addition or subtraction by a constant, or testing equality with other *Var* lines or NULL. The *SP* lines, short for Stack Pointer, contains the value of



Figure 5: The eight different node types of the SEDIAGRAM.

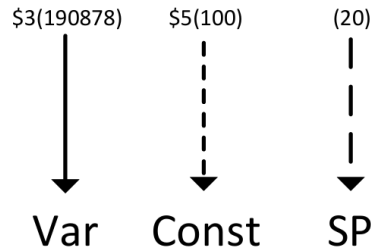


Figure 6: The three different type of lines. The *Var* line is on register \$3 with val 190878. The *Const* line is on register \$5 with val 100. The *SP* line has offset equal to 20.

the \$sp register. Thus the register of the *SP* is always \$sp. The *SP* line always starts with a value of 0, representing an offset from the original \$sp value. Thus if the *SP* line contains val of 100, then this means the stack pointer is 100 more than its original value. Other than the *SP* line, all lines are initiated with the *Var* type.

A line is active if there is no line further down with the same register. When a operation occurs, it may create a node. Some of the arguments of this operation are registers. If there are active lines with these registers, then they are connected to the input of these nodes. Otherwise, a new line is created with an indication that its starting point is the register at the starting point of the trace code. The end state of registers can be simply calculated from the active ser of lines at the bottom of the SEDIAGRAM.

Figure 6 shows how the lines are displayed graphically, with their information shown on top. The register number and/or the value can be omitted to not overly clutter the diagram.

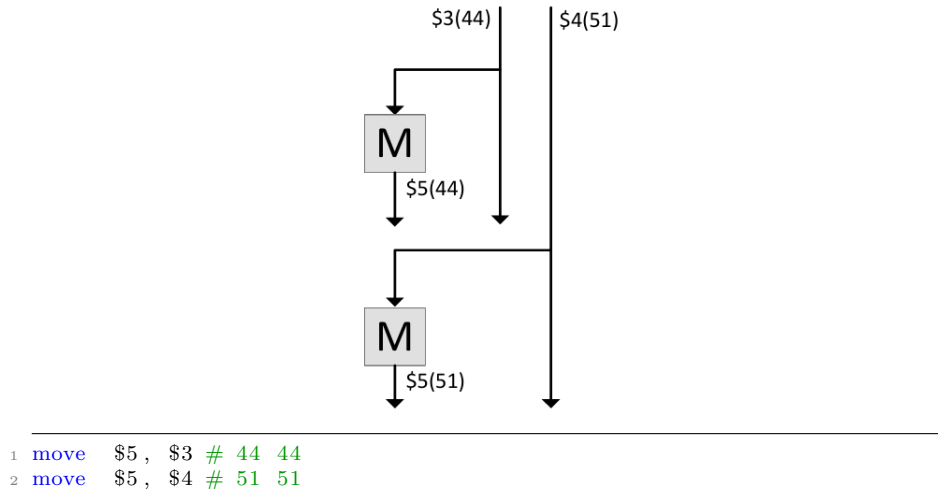


Figure 7: The move operation is represented by the M node. The value 44 is passed from register \$3 to register \$5. Then this line becomes inactive when 51 is passed from register \$4 into register \$5.

4.2 Move

The move operation transports the contents of one register into another register. It corresponds to the “M” node in the SEDIAGRAM, which is shown in Figure 7.

4.3 Const

The input to a Const node is zero, one, or two lines and the output is zero or one line. When a Const node is created, if an input line is of type *Var* then it will be changed to type *Const*. An example of a Const node with zero input lines can be seen with the LI command, which loads a constant into a register. Its corresponding SEDIAGRAM can be found in Figure 8.

The multiply operator MUL (as well as the OR, AND, DIV, and SHIFT operations) will create a Const node. This is because we assume that the computation does not perform these operations on pointers. An example of multiple Const nodes in tandem can be found in Figure 9.

4.4 Add and Subtract

The ADD and SUB instructions will create Add and Sub nodes, respectively. Both nodes take two inputs and one output. They can be seen in Figure 11.

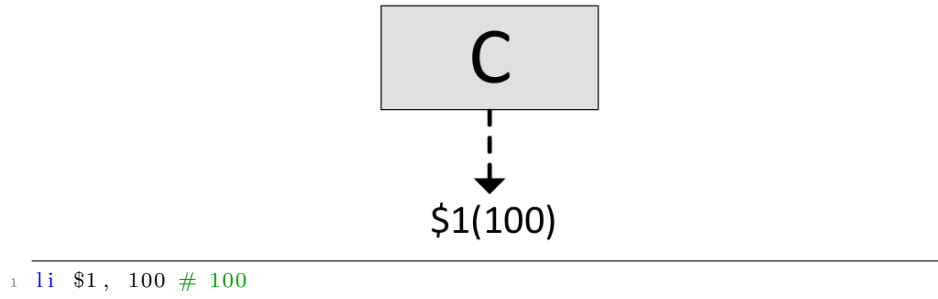


Figure 8: The SEDIAGRAM constructed from one LI operation.

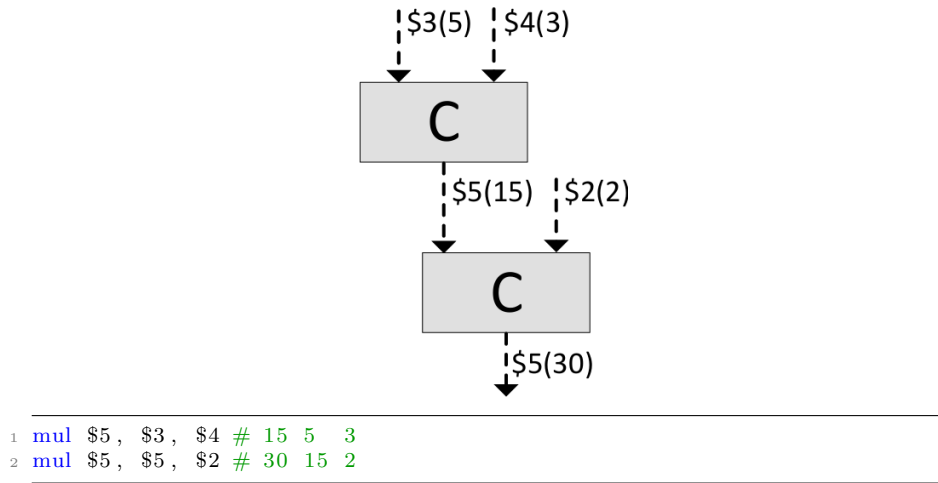


Figure 9: The SEDIAGRAM constructed from two MUL operations. Note that the diagram would be the same for DIV, AND, or OR operations. Note that that, to remove clutter, the active lines are not extended to the bottom of the diagram, though technically they should be.

4.5 Add Immediate

The ADDI operation adds a constant number to a register. The corresponding SEDIAGRAM produces two nodes, a Const node and an Add node. The Const node has no input and produces one output, which is the constant to be added to. The output of the Const node is sent to the second input of the Add node. this line does not have a register. An example can be seen in Figure 8.

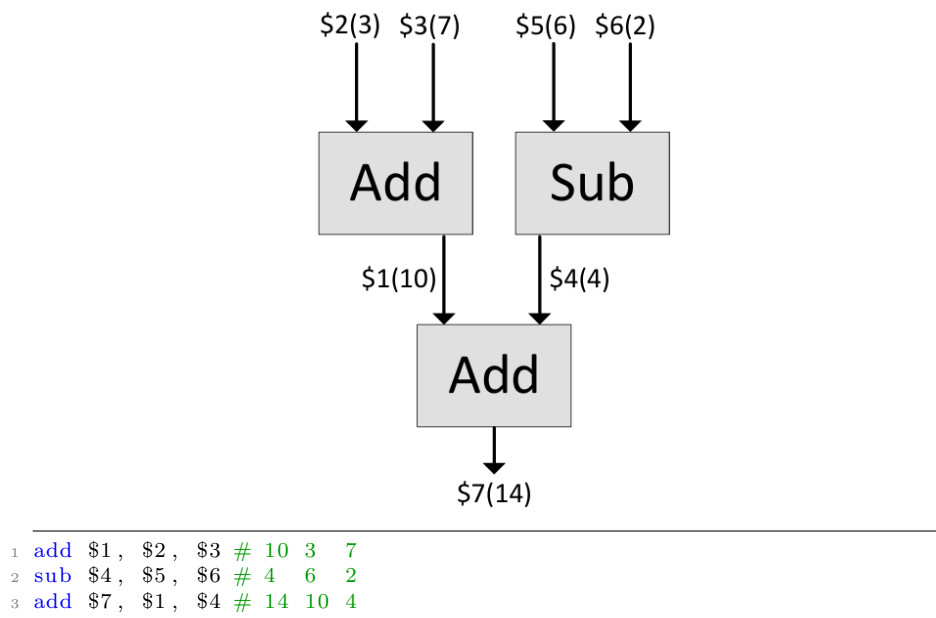


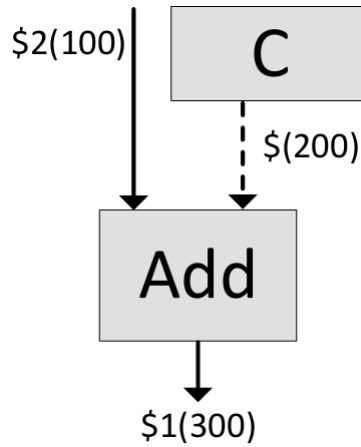
Figure 10: The SEDIAGRAM constructed from two ADD operations and one SUB operation.

4.6 Branch on Equal

The BEQ command branches if the two register arguments are equal. If the corresponding lines of the two arguments are of type *Const*, then the branch will always occur or not occur, because all computer states that match the SECONDITIONS will have the same const values. Thus the current computation will take the same branch choice as the original compiled trace code. Similarly, if the arguments are two pointers, as we will see later in the paper, all computer states that match the SECONDITION will result in an identical branch outcome. This is also true for matching a pointer with 0. Therefore when a BEQ operation is encountered, it is ignored, and the SEDIAGRAM remains unchanged.

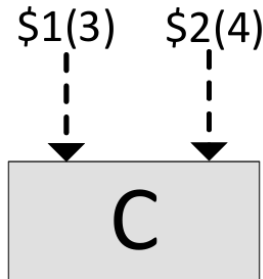
4.7 Branch on Less Than

We assume that two pointers are not compared to each other by the less than operation (or the other inequalities). Thus only numbers are compared to. The BLT operation creates a Const node with two *Const* input lines and no output lines. If the input line is initially of type *Var*, then it is changed to type *Const*. An example of the BLT command can be found in Figure 12



```
1 addi $1, $2, 200 # 300 100
```

Figure 11: The SEDiagram constructed from an ADDI operation. There are two nodes created. The first node is of type Const, and outputs the constant parameter of the ADDI command. The second node is of type Add, and it sums the constant with the first register parameter. The const line that is outputted from the Const node has no register associated with it.



```
1 blt $1, $2, 100 # 3 4
```

Figure 12: The BLT operation produces a Const node with two input *Const* lines. There is no output lines.

4.8 Load Word

The LW operation loads the contents of the memory with the address of the second register parameter into the first parameter. The address is offset by a

constant number. The address line cannot be of type *Const*. This operation creates a single LW node as shown in Figure 13.

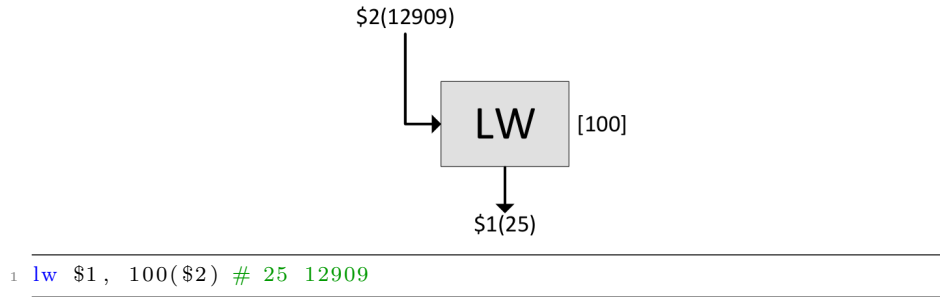


Figure 13: The LW operation produces a LW node with on input *Const* line and one output line. The address is on the left side of the node and the data that was loaded is outputted at the bottom. The address offset is on the left.

4.9 Store Word

The SW operation stores data in the memory at the address specified by the second register argument. The address is offseted by a constant. The SW operation results in a single SW node. The node takes in an address on its left side and information from the top.

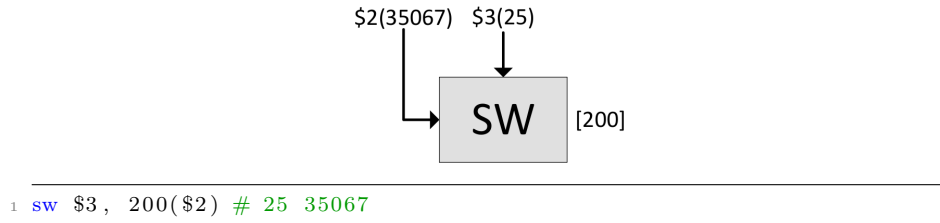


Figure 14: The SW operation produces a SW node with two inputs and no outputs. The address is fed into the node on the left. The data to be stored reaches the node from the top. The address offset is on the left.

4.10 New and Free

The NEW operation takes in an argument specifying the amount of memory to allocate and returns a pointer to the memory allocated. The FREE operation takes in a single argument specifying a pointer to memory to be freed. The

New and Free nodes of the SEDIAGRAM are created. An example can be seen in Figure 15

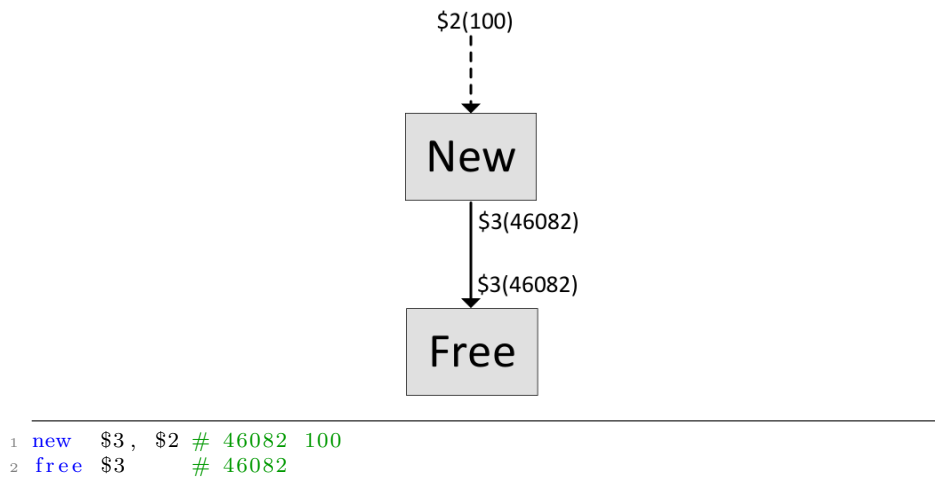


Figure 15: Following code creates and frees memory. The NEW operation creates a New node, which takes in a *Const* line argument specifying the amount of memory to allocate. The output of the New node is sent to the input of the Free node, which is created from the FREE operation.

5 Floating Point Numbers

6 Machine Learning

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