An Assembly Language I.D.E. To Engage Students Of All Levels
** A Tutorial **
2007 CCSC: Central Plains Conference

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MARS is a software simulator for the MIPS assembly language intended for educational use. We will explore the capabilities of MARS release 3.2.1 in this three part tutorial.

MARS may be downloaded from `www.cs.missouristate.edu/MARS`.

Part 1 : Basic MARS Use

The example program is **`Fibonacci.asm`** to compute everyone's favorite number sequence.

1. Start MARS from the Start menu or desktop icon.

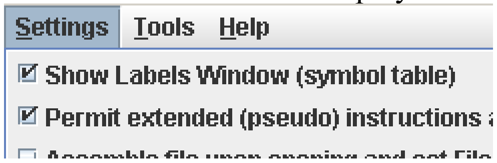
2. Use the menubar File…Open or the Open icon to open Fibonacci.asm in the default folder. *(All icons have menubar equivalents; the remainder of these steps will use the icon whenever possible.)*

3. The provided assembly program is complete. Assemble the program using the icon

4. Identify the location and values of the program's initialized data. Use the checkbox to toggle the display format between decimal and hexadecimal ☐ Hexadecimal Values.
   - The nineteen-element array **`fibs`** is initialized to zero, at addresses 0x10010000 … 0x10010048.
   - The data location **`size`** has value 19_{ten} at 0x1001004c.
   - The addresses 0x10010050 … 0x1001006c contain null-terminated ASCII strings.

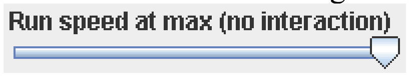
Use the checkbox to toggle the display format between decimal and hexadecimal, ☐ Hexadecimal Values.

5. Use the Settings menu to configure the MARS displays. The settings will be retained for the next MARS session.

- The Labels display contains the addresses of the assembly code statements with a label, but the default is to *not* show this display. Select the checkbox from the Settings menu. 

☑ Show Labels Window (symbol table)
☑ Permit extended (pseudo) instructions
- Select your preference for allowing pseudo-instructions (programmer-friendly instruction substitutions and shorthand).
- Select your preference for assembling *only one* file, or *many* files together (all the files in the current folder). This feature is useful for subroutines contained in separate files, etc.
- Select the startup display format of addresses and values (decimal or hexadecimal).

6. Locate the Registers display, which shows the 32 common MIPS registers. Other tabs in the Registers display show the floating-point registers (Coproc 1) and status codes (Coproc 0).

7. Use the slider bar to change the run speed to about 10 instructions per second. 

This allows us to "watch the action" instead of the assembly program finishing directly.

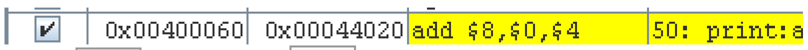
8. Choose how you will execute the program:

   - The icon runs the program to completion. Using this icon, you should observe the yellow highlight showing the program's progress and the values of the Fibonacci sequence appearing in the Data Segment display.
   - The icon resets the program and simulator to initial values. Memory contents are those specified within the program, and register contents are generally zero.
   - The icon is "single-step." Its complement is , "single-step backwards" (undoes each operation).

9. Observe the output of the program in the Run I/O display window:

```
The Fibonacci numbers are:
1 1 2 3 5 8 13 21 34 55 89 144 233 377 610 987 1597 2584 4181
-- program is finished running --
```

10. Modify the contents of memory. (Modifying a register value is exactly the same.)
    - Set a breakpoint at the first instruction of the subroutine which prints results. Use the checkbox at the left of the instruction whose address is 0x00400060 = 4194400_{ten}.



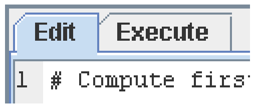
```
✓ 0x00400060 0x00044020 add $8,$0,$4    50: print:a
```

- Reset and re-run the program, which stops at the breakpoint.
- Double-click in one of the memory locations containing the computed Fibonacci numbers. The cell will be highlighted and will accept keyboard entry, similar to a spreadsheet. Enter some noticeably different value, and use the Enter key or click outside the cell to indicate that the change is complete. *Example: Memory address 0x10010020 = 268501024 $_{ten}$ presently contains data 0x00000022 = 34 $_{ten}$.*
- Click to continue from the breakpoint. The program output includes your entered value instead of the computed Fibonacci number.

11. Open the Help for information on MIPS instructions, pseudoinstructions, directives, and syscalls.

12. Modify the program so that it prompts the user for the Fibonacci sequence length.

- Select the Edit tab in the upper right to return to the program editor.



```
1 # Compute firs
```

- The MIPS comment symbol is #. All characters on the line after the character # are ignored.
- Un-comment lines 12-19. The newly exposed program fragment will prompt the user for the length of the Fibonacci sequence to generate, in the range $2 \le x \le 19$. (The length of the sequence must be limited to the size of the declared space for result storage.)
- Determine the correct **`syscall`** parameter to perform "read integer" from the user, and insert the parameter at line The correct **`syscall`** parameter may be found at Help … Syscall tab…read integer service. The completed line will have the form **`li $v0, 42`** (where in this case 42 is not the right answer).
- Reset and re-run the program. The program will stop at the breakpoint you inserted previously. Continue and finish with .

Part 2 : MARS Tools

You may have noticed that MARS has a **Tools** menu. The capabilities provided through this menu really catapult MARS into a different league of computer science educational software.

We call each of the items in the Tools menu a MARS Tool. A MARS Tool is best described as a pop-up application that observes MIPS memory and/or register activity during MIPS program execution then communicates that activity to the tool user to serve a particular purpose. This is best seen by example.

MARS Tools Activity 1 : Running the Data Cache Simulator tool

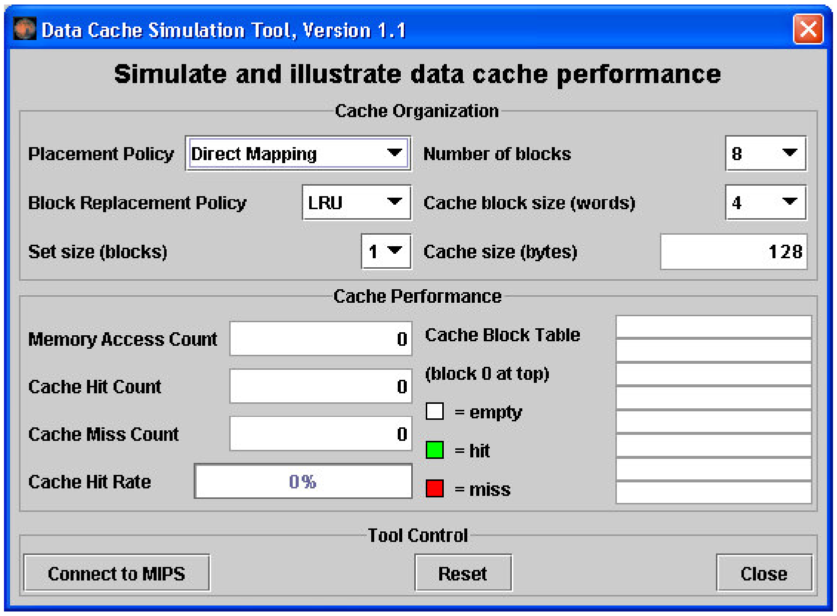
1. Close any MIPS programs you are currently using.

2. Open the program **`row-major.asm`** from the `Examples` folder. This program will traverse a 16 by 16 element integer matrix in row-major order, assigning elements the values 0 through 255 in order. It performs the following algorithm:

```
for (row = 0; row < 16; row++)
   for (col = 0; col < 16; col++)
      data[row][col] = value++;
```

3. Assemble the program.

4. From the **Tools** menu, select **Data Cache Simulator**. A new frame will appear in the middle of the screen.



Simulate and illustrate data cache performance

Cache Organization

Placement Policy: Direct Mapping
Number of blocks: 8
Block Replacement Policy: LRU
Cache block size (words): 4
Set size (blocks): 1
Cache size (bytes): 128

Cache Performance

Memory Access Count: 0
Cache Hit Count: 0
Cache Miss Count: 0
Cache Hit Rate: 0%

Cache Block Table (block 0 at top)
☐ = empty
🟩 = hit
🟥 = miss

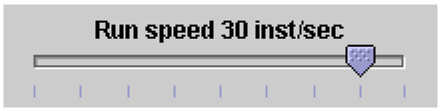
Tool Control

This is a MARS Tool that will simulate the use and performance of cache memory when the underlying MIPS program executes. Notice its three major sections:

- *Cache Organization:* You can use the combo boxes to specify how the cache will be configured for this run. Feel free to explore the different settings, but the default is fine for now.
- *Cache Performance:* With each memory access during program execution, the simulator will determine whether or not that access can be satisfied from cache and update the performance display accordingly.
- *Tool Control:* These buttons perform generic control functions as described by their labels.

5. Click the tool's **Connect to MIPS** button. This causes the tool to register as an observer of MIPS memory and thus respond during program execution.

6. Back in MARS, adjust the **Run Speed slider** to 30 instructions per second. It is located at the right side of the toolbar. This slows execution so you can watch the Cache Performance animation.



7. In MARS, run the program using the **Run** toolbar button , the menu item or keyboard shortcut. Watch the Cache Performance animate as it is updated with every access to MIPS memory.

8. *What was the final cache hit rate?* _____________. With each miss, a block of 4 words are written into the cache. In a row-major traversal, matrix elements are accessed in the same order they are stored in memory. Thus each cache miss is followed by 3 hits as the next 3 elements are found in the same cache block. This is followed by another miss when Direct Mapping maps to the next cache block, and the patterns repeats itself. So 3 of every 4 memory accesses will be resolved in cache.

9. Given that explanation, *what do you predict the hit rate will be if the block size is increased from 4 words to 8 words?* ______________. *Decreased from 4 words to 2 words?* ___________.

10. Verify your predictions by modifying the block size and re-running the program from step 7.
    NOTE: when you modify the Cache Organization, the performance values are automatically reset (you can always use the tool's **Reset** button).

    NOTE: You have to **reset** the MIPS program before you can re-run it.
    NOTE: Feel free to adjust the **Run Speed slider** to maximum speed anytime you want.

11. Repeat steps 2 through 10 for program **`column-major.asm`** from the `Examples` folder. This program will traverse a 16 by 16 element integer matrix in column-major order, assigning elements the values 0 through 255 in order. It performs the following algorithm:

    ```
    for (col = 0; col < 16; col++)
       for (row = 0; row < 16; row++)
          data[row][col] = value++;
    ```

    NOTE: You can leave the Cache Simulator in place, move it out of the way, or close it. It will not interfere with the actions needed to open, assemble, or run this new program and will remain connected to MIPS memory. If you do not close the tool, then skip steps 4 and 5.

12. *What was the cache performance for this program?* ____________. The problem is the memory locations are now accessed not sequentially as before, but each access is 16 words beyond the previous one (circularly). With the settings we've used, no two consecutive memory accesses occur in the same block so every access is a miss.

13. Change the block size to 16. Note this will reset the tool.

14. Create a second instance of the Cache Simulator by once again selecting **Data Cache Simulator** from the **Tools** menu. Adjust the two frames so you can view both at the same time. Connect the new tool instance to MIPS, change its block size to 16 and change its number of blocks to 16.

15. Re-run the program. *What is the cache performance of the original tool instance?* ____________. Block size 16 didn't help because there was still only one access to each block, the initial miss, before that block was replaced with a new one. *What is the cache performance of the second tool instance?* ____________. At this point, the entire matrix will fit into cache and so once a block is read in it is never replaced. Only the first access to a block results in a miss.

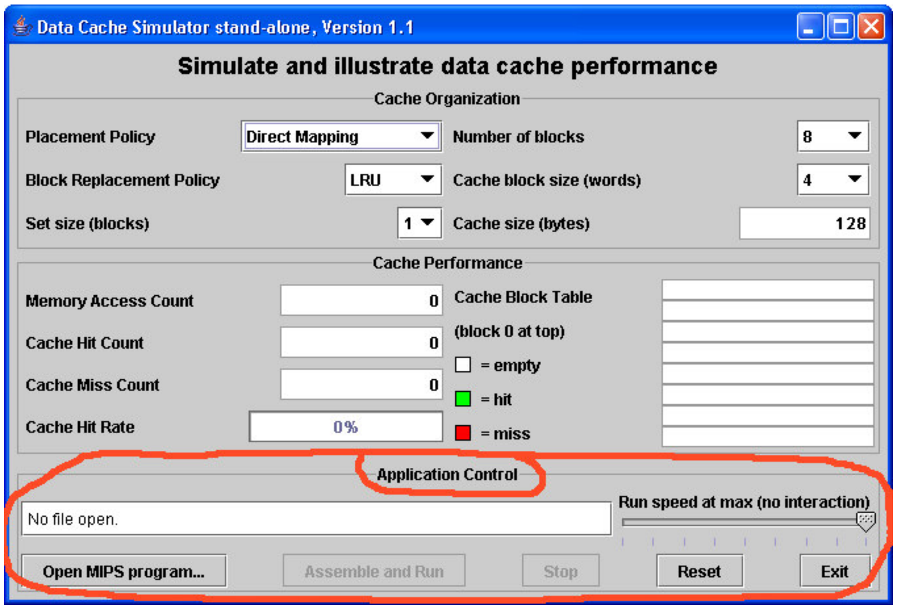
In what courses might an exercise like this one be useful for your students? I have used a variation on this exercise as a student exercise in Operating Systems, and for a lecture illustration of the cache concept in Otterbein's CS 0 course, "The Scope of Computer Science".

MARS Tools Activity 2 : Running the Cache Simulator as a stand-alone

1. In command mode, traverse to the directory containing Mars.jar and enter the command:

   ```
   java  -classpath  Mars.jar  mars.tools.CacheSimulator
   ```

2. The cache simulator tool is launched. Its Tool Control section is replaced by Application Control, which contains additional controls for loading, assembling and running MIPS programs. It uses MARS' MIPS assembler and runtime simulator in the background to control MIPS execution.


Data Cache Simulator stand-alone, Version 1.1

Simulate and illustrate data cache performance

Cache Organization

Placement Policy	Direct Mapping	Number of blocks	8
Block Replacement Policy	LRU	Cache block size (words)	4
Set size (blocks)	1	Cache size (bytes)	128

Cache Performance

Memory Access Count	0
Cache Hit Count	0
Cache Miss Count	0
Cache Hit Rate	0%

Cache Block Table (block 0 at top)
☐ = empty
🟩 = hit
🟥 = miss

Application Control

No file open.

3. Click the **Open MIPS program** button and a File Open dialog will pop up. Browse to and select a MIPS program to run. Select **`row_major.asm`** again if you wish.

4. The **Assemble and Run** button is now enabled. Click it to assemble and run the program. The animation will be very rapid.

5. Use the **Run Speed slider** to adjust the running speed, click the **Reset** button then click **Assemble and Run** again. While the program is running, the **Stop** button is enabled. Program status is updated in the single line text field.

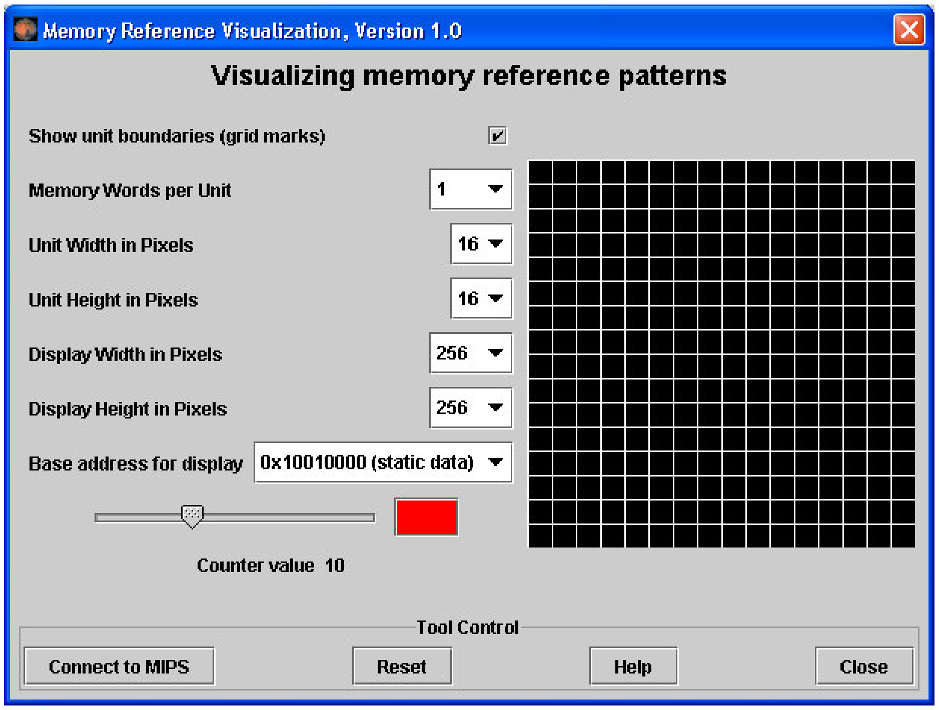
We plan to implement a small MARS Tool Suite application to simplify the selection and launching of tools such as the Cache Simulator that are capable of running outside the MARS integrated development environment.

MARS Tools Activity 3 : The Memory Reference Visualization tool

1. Open the program **`row-major.asm`** from the `Examples` folder if it is not already open.

2. Assemble the program.

3. From the **Tools** menu, select **Memory Reference Visualization**. A new frame will appear in the middle of the screen.



Visualizing memory reference patterns

Show unit boundaries (grid marks) ✓
Memory Words per Unit 1
Unit Width in Pixels 16
Unit Height in Pixels 16
Display Width in Pixels 256
Display Height in Pixels 256
Base address for display 0x10010000 (static data)
Counter value 10

This tool will paint a grid unit each time the corresponding MIPS memory word is referenced. The base address, the first static data segment (`.data` directive) word, corresponds to the upper-left grid unit. Address correspondence continues in row-major order (left to right, then next row down).

The color depends on the number of times the word has been referenced. Black is 0, blue is 1, green is 2, yellow is 3 and 4, orange is 5 through 9, red is 10 or higher. View the scale using the tool's slider control. You can change the color (but not the reference count) by clicking on the color patch.

4. Click the tool's **Connect to MIPS** button. This causes the tool to register as an observer of MIPS memory and thus respond during program execution.

5. Back in MARS, adjust the **Run Speed slider** to 30 instructions per second.

6. Run the program. Watch the tool animate as it is updated with every access to MIPS memory. *Feel free to stop the program at any time.*

7. Hopefully you observed that the animation sequence corresponded to the expected memory access sequence of the row-major.asm program. *If you have trouble seeing the blue,* reset the tool, move the slider to position 1, change the color to something brighter, and re-run.

8. Repeat steps 2 through 7, for **`column-major.asm`**. You should observe that the animation sequence corresponded to the expected memory access sequence of this program.

9. Repeat again for **`fibonacci.asm`** to observe the animated pattern of memory references. Adjust the run speed and re-run if necessary.

10. *(Optional)* Create a new instance of the Data Cache Simulator. Move the two frames around so you can see both. Connect the cache simulator to MIPS and reset the Memory Reference Visualization. Re-run the program. This exercise illustrates that two different tools can be used simultaneously.

The Memory Reference Visualization tool could be useful in an operating systems course to illustrate spatial and temporal locality and memory reference patterns in general.

Part 3 : Extending MARS Capabilities

Our session today is not long enough for interactive activities in this area, but we'll provide you with enough detail that you can pursue them on your own if you desire.

Abstract

MARS can be customized and extended in four different ways: (1) writing new MARS Tools, (2) writing new MIPS system calls, (3) writing new MIPS pseudo-instructions, and (4) writing new MIPS basic instructions. Techniques for all four are described here.

You have the ability to extend and customize certain MARS capabilities to make it more useful in your courses. This document describes four different techniques for extending MARS capabilities:

1. Ability to write MARS Tools for inclusion in the Tools menu and stand-alone use.

2. Ability to define and add new system calls for subsequent use by MIPS programs.

3. Ability to customize the instruction set by adding, removing or modifying pseudo (macro) instruction specifications.

4. Ability to customize the basic instruction set by adding, removing or modifying basic instruction specifications.

These procedures apply to MARS 3.2.1, released January 2007. Some may be streamlined in future releases.

The ability to define and plug in new MARS Tools will be used to develop new learning aids for students in a variety of computer science courses and provide micro-worlds for assembly language students to target in their projects. Through those tools it is possible to deeply engage students in both settings.

The ability to modify the set of system calls, basic instructions, and pseudo-instructions can be used to define a complete instruction set for an alternative RISC architecture. MARS was not designed with this in mind however, so support is uneven. For example, instruction syntax analysis and code generation is driven by the example and template provided with each instruction, whereas lexical analysis such as the recognition of register names is embedded in program logic and cannot easily be modified. A customized instruction set has to use MIPS conventions for labeling, register naming, and so forth. Hopefully MARS can be refactored in future releases to facilitate its use for alternative instruction sets.

1. Writing your own MARS Tool and plugging it into MARS

Abstract

If you think MARS Tools like the Cache Simulator are cool then why not develop your own? There are two different ways to do so: (1) write a class that implements the MarsTool interface and is launched from the Tools menu in MARS, or (2) write a class that extends the AbstractMarsToolAndApplication class and runs either from the Tools menu or as a free-standing application. You can also write a free-standing application that uses the Mars API.

This section describes two different techniques for developing your own MARS Tool.

1. Write a class that implements the **`mars.tools.MarsTool`** interface and keep it in the **`mars.tools`** package. It will automatically be added to the **Tools** menu the next time MARS is run and launched when its menu item is selected.

2. Write a class that extends **`mars.tools.AbstractMarsToolAndApplication`** and keep it in the **`mars.tools`** package. It will automatically be added to the **Tools** menu the next time MARS is run and launched when its menu item is selected. It can also be launched from outside MARS as a free-standing Java application that uses the Mars API to control the assembly and execution of MIPS programs.

It is also possible to write your own application from scratch using the Mars API. This should be considered only for very specialized applications and should be undertaken with great care. The `AbstractMarsToolAndApplication` class provides full support for assembling and running MIPS programs in the background and is the preferred approach.

`MyTool implements MarsTool approach`

1. Extract the MARS distribution from its JAR file. The JAR file does not have an outermost folder to contain everything, so you'll want to create one and extract it into that folder.

2. Develop your class in the **`mars.tools`** package (`mars/tools` folder).

3. Your class must implement the **`MarsTool`** interface, which is in that package. This has only two methods: `String getName()` to return the name to be displayed in

its Tools menu item, and `void action()` which is invoked when that menu item is selected by the MARS user. These will assure its inclusion in the Tools menu when MARS is launched.

4. The user interface should be based on the **`javax.swing.JDialog`** class. The tool interacts with simulated MIPS memory and registers through the **`mars.mips.hardware.Memory`** and **`mars.mips.hardware.Register`** classes, both of which extend **`java.util.Observable`**. The Memory class provides several addObserver() methods that permit an Observer to register for selected memory addresses or ranges. Javadoc-produced documentation is available in the `doc` folder of the MARS distribution.

5. After successful compilation, MARS will automatically include the new tool in its Tools menu.

`MyTool extends AbstractMarsToolAndApplication` approach

A better alternative is to extend the **`AbstractMarsToolAndApplication`** class, which is also in the mars.tools package. By doing so, you get the following elements:

- ability to run either from the Tools menu or as a free-standing application
- basic user interface JDialog with Tool Control section (for tools)
- basic user interface JFrame with Application Control section (for applications)
- basic user interface layout (BorderLayout) and rendering algorithm
- basic MIPS memory and register observer capabilities

1. Extract the MARS distribution from its JAR file if you have not already done so.

2. Develop your class in the **`mars.tools`** package (`mars/tools` folder).

3. Your class must extend the **`AbstractMarsToolAndApplication`** abstract class, which is in that package. Nineteen of the 21 methods in this class have default implementations.

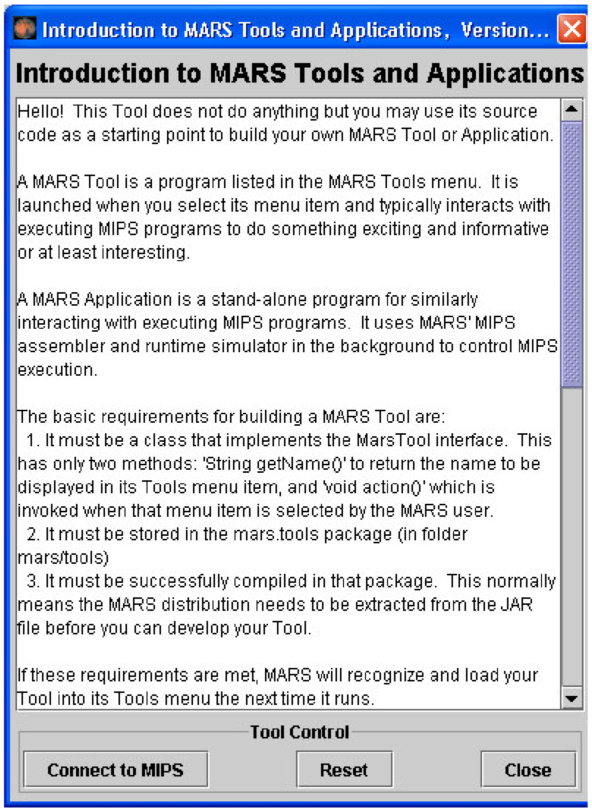
4. Define at least the two abstract methods: `String getName()` to return the tool's display name, and `JComponent buildMainDisplayArea()` to construct the central area of the tool's graphical user interface. It will automatically be placed in the CENTER of a BorderLayout, with title information to its NORTH and tool control buttons to its SOUTH. Several addAsObserver() methods are available for registering as a memory and/or register observer.

5. Override additional methods as desired. Some do nothing by default.

6. After successful compilation, MARS will automatically include the new tool in its Tools menu.

7. To run it as a stand-alone application, you either need to add a `main()` to create the tool object and call its `go()` method or write a short external application to do the same.

For a better idea of the GUI elements that come with this abstract class, launch MARS and select **Introduction to Tools** from the Tools menu.


Introduction to MARS Tools and Applications, Version...
Introduction to MARS Tools and Applications

Hello! This Tool does not do anything but you may use its source code as a starting point to build your own MARS Tool or Application.

A MARS Tool is a program listed in the MARS Tools menu. It is launched when you select its menu item and typically interacts with executing MIPS programs to do something exciting and informative or at least interesting.

A MARS Application is a stand-alone program for similarly interacting with executing MIPS programs. It uses MARS' MIPS assembler and runtime simulator in the background to control MIPS execution.

The basic requirements for building a MARS Tool are:
 1. It must be a class that implements the MarsTool interface. This has only two methods: 'String getName()' to return the name to be displayed in its Tools menu item, and 'void action()' which is invoked when that menu item is selected by the MARS user.
 2. It must be stored in the mars.tools package (in folder mars/tools)
 3. It must be successfully compiled in that package. This normally means the MARS distribution needs to be extracted from the JAR file before you can develop your Tool.

If these requirements are met, MARS will recognize and load your Tool into its Tools menu the next time it runs.

By extending the provided abstract class `AbstractMarsToolAndApplication`, you get everything in this figure except the scrolled `JTextArea` displayed in the center.

You build the main user interface of your tool by defining the inherited abstract `buildMainDisplayArea()` method. This method returns a `JComponent` that will automatically be displayed in the center of the default BorderLayout.

Javadoc-produced documentation of the `AbstractMarsToolAndApplication` class is available in the `doc` folder of the MARS distribution.

Source code files for the MARS Tools are included together with their bytecode files in the `mars/tools` folder. Feel free to refer to them. All MARS source files, including tools, are included in the `src` folder.

If you develop a nifty MARS Tool, feel free to send it to us and with your permission we'll post it on the MARS web site for others to use!

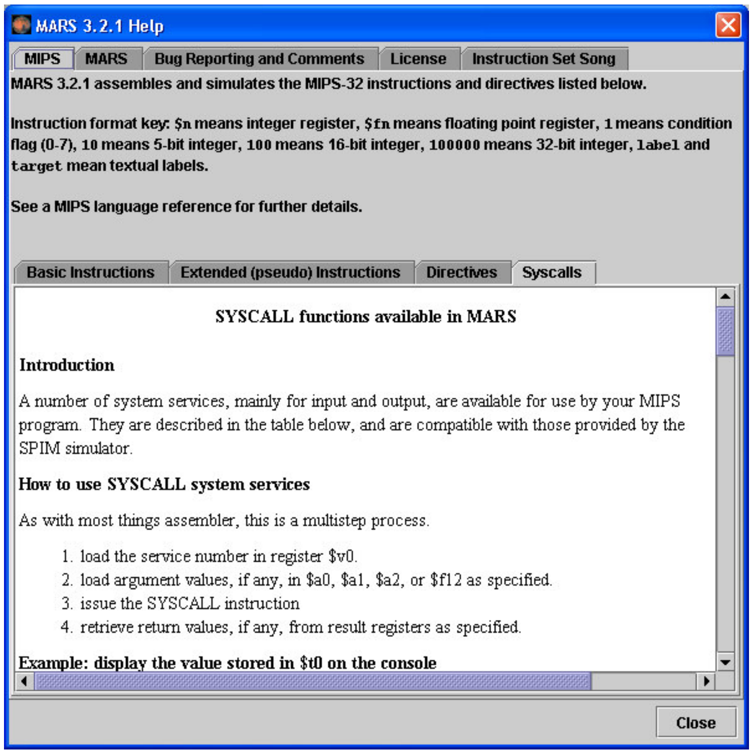
2. Writing a system call (syscall) and plugging it into MARS

Abstract

MIPS System calls are functions that interface with the operating system to perform I/O and related operations. They are accessible to MIPS assembly programs through service numbers and the **`syscall`** instruction. MARS provides the 17 system calls documented in *Computer Organization and Design Third Edition*, but you can develop and add your own by writing a class that implements the Syscall interface or extends the AbstractSyscall class.

MIPS system calls perform operating system functions and input/output operations in particular. A system call is used in MIPS assembly by loading its identifier (an integer) into register $v0, loading any required arguments into registers as specified by the call's protocol, then issuing the **`syscall`** instruction.

MARS supports the MIPS system call specifications given in Appendix A of Patterson and Hennessy's *Computer Organization and Design Third Edition*. This appendix is freely available on the web at **`http://www.cs.wisc.edu/~larus/HP_AppA.pdf`**. MARS provides all 17 of the system calls specified there.



MARS 3.2.1 assembles and simulates the MIPS-32 instructions and directives listed below.

Instruction format key: `$n` means integer register, `$fn` means floating point register, `1` means condition flag (0-7), `10` means 5-bit integer, `100` means 16-bit integer, `100000` means 32-bit integer, `label` and `target` mean textual labels.

See a MIPS language reference for further details.

SYSCALL functions available in MARS

Introduction

A number of system services, mainly for input and output, are available for use by your MIPS program. They are described in the table below, and are compatible with those provided by the SPIM simulator.

How to use SYSCALL system services

As with most things assembler, this is a multistep process.

1. load the service number in register $v0.
2. load argument values, if any, in $a0, $a1, $a2, or $f12 as specified.
3. issue the SYSCALL instruction
4. retrieve return values, if any, from result registers as specified.

Example: display the value stored in $t0 on the console

`MySystemCall implements Syscall` approach

1. Extract the MARS distribution from its JAR file, if you have not done so.

2. Develop your class in the **`mars.mips.instructions.syscalls`** package (`mars/mips/instructions/syscalls` folder).

3. Your class must implement the **`Syscall`** interface, which is in that package. This has four methods: `String getName()` to return an assigned name for this service, `setNumber()` and `getNumber()` to set and get its associated service number, and `simulate()` to simulate the execution of the system call at MIPS runtime.

4. After your class compiles successfully, it will be automatically plugged in and available to MIPS programs the next time you launch MARS.

`MySystemCall extends AbstractSyscall` approach

1. Extract the MARS distribution from its JAR file, if you have not done so.

2. Develop your class in the **`mars.mips.instructions.syscalls`** package (`mars/mips/instructions/syscalls` folder).

3. Your class must extend the **`AbstractSyscall`** class, which is in that package. It provides a constructor and defines the three `Syscall` getter and setter methods. The `simulate()` method is abstract so you must define that yourself.

4. After your class compiles successfully, it will be automatically plugged in and available to MIPS programs the next time you launch MARS.

Additional Information

Implementation of the `simulate()` method may require access to one or more simulated MIPS memory and register objects. The pertinent classes are `mars.mips.hardware.Memory` and `mars.mips.hardware.RegisterFile`. Also study the source code of existing system calls. Source code files for the 17 MARS system calls are located in the `src` folder. Follow the folder hierarchy `mars/mips/instructions/syscalls`.

The MARS distribution includes a text file `Syscall.properties` which you can edit to override any system service number assigned in a constructor. This allows you to change number assignments without re-compiling any Java source files.

The **Syscalls** help page is static at this time so it will not reflect any additional system calls or renumbering.

If you develop a nifty system call, please send it to us and with your permission we'll post it on the MARS web site for others to access!

We have had philosophical discussions concerning the development of additional system calls and so far have resisted doing so. On one hand, it would be very useful to have a small library of handy functions such as random number generators available through the syscall mechanism. On the other hand, such functions are not considered operating system operations that would be performed in kernel mode and it would be misleading to infer such status. Let us know what you think!

3. Modifying the set of pseudo (extended, macro) instructions

Abstract

To define a new pseudo-instruction, edit the `PseudoOps.txt` file included in the MARS distribution. The instruction specification is one line long and consists of a tab-separated list containing an example usage of the instruction followed by the one or more basic instructions that the assembler will expand it to. Use specification language symbols to control the substitution of program statement operands into the generated basic instruction(s).

The MIPS instruction set includes a large number of pseudo-instructions. These are instructions that follow MIPS instruction syntax specifications but are not directly supported by the MIPS architecture. They are instead expanded into a sequence of one or more basic instructions by the assembler. For this reason they are sometimes called macro instructions.

The classic example of a pseudo-instruction is `la`, or load address. Here's an example:

```
la   $t0, number
```

where `number` is the label for a data item. A corresponding MIPS machine instruction would have to include the operation code, the 5 bit register number and the 32 bit address. But since machine instructions are only 32 bits long, this is not possible. It requires two instructions.

Pseudo-instructions are provided entirely for the programmer's convenience, and MARS includes an assembler setting that will disallow their use.

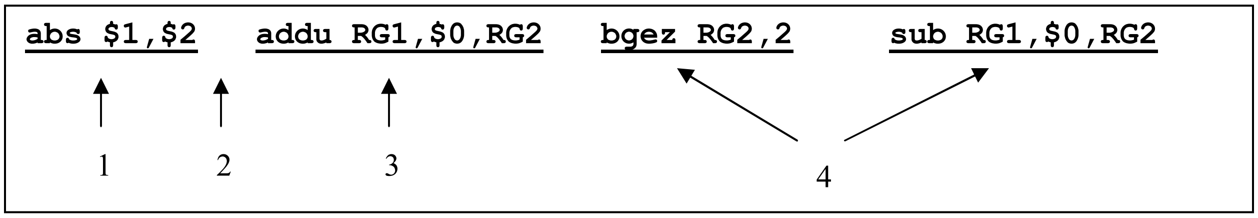
To modify the pseudo-instruction set, follow this process:

1. Extract the MARS distribution from its JAR file if you have not already done so.

2. Edit `PseudoOps.txt` appropriately. Each pseudo-instruction and its macro expansion are specified on one line in this file. Details below.

3. Launch MARS and test your instruction.

Here's an example specification, for the **absolute value** instruction **`abs`**



```
abs $1,$2	addu RG1,$0,RG2	bgez RG2,2	sub RG1,$0,RG2
```

1. Example instruction use. This instruction takes two register operands. The $1 and $2 represent generic registers and are used only to generate a token sequence for syntax analysis. *There is no relationship between register references in the example instruction (item 1) and register references in the macro expansions (items 3 and 4)!*

2. Each item in the specification must be separated by a single TAB character. Only the first one is pointed out but there is also a TAB between each of the remaining items.

3. The first instruction of the macro expansion. RG1 is a formal parameter that will be replaced by the actual first register operand of the statement being assembled. RG2 is similarly replaced by the actual second register operand of the statement being assembled.

4. Second and third instructions of the macro expansion. Perform similar substitutions.

Statement to assemble	*Macro expansion*

`abs  $t3, $t4`	`addu  $t3, $0, $t4`
	`bgez  $t4, 2`
	`sub   $t3, $0, $t4`

This example uses the simple substitutions RG1 and RG2. Other macro substitution symbols are more complex, such as `VL2P3` which means to substitute the low order 16 bits of the 32 bit value in source operand 2 after adding 3 to it (used in the expansion of certain unaligned loads and stores).

The macro substitution language is described in detail in the file itself.

If you add any pseudo-instructions, they will automatically be included in the instruction list produced by the Help feature's **Extended (pseudo) Instructions** subtab. If the instruction specification ends with a comment on the same line (# is the comment marker, just like in MIPS), that comment will be included in the list along with the example instruction use.

4. Modifying the set of Basic Instructions

Abstract

It is possible to modify the basic instruction set recognized by MARS. This requires you to edit and re-compile the `mars.mips.instructions.InstructionSet` class. The specification of a basic instruction includes four components: (1) an example of instruction use, (2) the instruction format – R, I, or J, (3) a template for generating the 32 bit machine code from a program statement, and (4) a method to simulate the execution of that program statement.

This is the one type of MARS extension that requires re-compilation of a standard MARS source file. Specifications for the MIPS basic instruction set are contained in the `mars.mips.instructions.InstructionSet` class. Each specification follows the same format. Here is an example, for the **and** instruction that performs logical AND.

```
instructionList.add(new BasicInstruction(
   "and $1,$2,$3",                         ← 1. example use
   BasicInstructionFormat.R_FORMAT,        ← 2. instruction format
   "000000ssssstttttfffff00000100100",     ← 3. machine code template
   new SimulationCode()                    ← 4. execution simulator
   {
       public void simulate(ProgramStatement statement)
       {
           int[] operands = statement.getOperands();
           RegisterFile.updateRegister(
                  operands[0],
                  RegisterFile.getValue(operands[1]) &
                  RegisterFile.getValue(operands[2])   );
       }
   }
   ));
```

The `BasicInstruction` constructor takes four parameters, annotated on the example:

1. Example instruction use. This instruction takes three register operands. The $1, $2 and $3 represent generic registers and are used only to generate a token sequence for syntax analysis.

2. MIPS instruction format. MIPS defines the R-format (works with registers), I-format (works with immediate value), and J-format (jump instruction). MARS defines a second version of the I-format called I-branch-format when the immediate value is used in a branch instruction.

3. Machine code template. This String of length 32 consists of the characters `0`, `1`, `f`, `s`, and `t`. When the MIPS program statement syntactically matches this instruction, the 32 bit machine code instruction is constructed by substituting low order bits from the **f**irst operand for `f`, low order bits from the **s**econd operand for `s` and low order bits from the **t**hird operand for `t`. The result is converted to 32 bit binary. This example has register numbers which are 5 bits because MIPS32 defines 32 integer registers.

4. Constructs the object whose `simulate()` method will be called to simulate the execution of the program statement at MIPS runtime. The object is constructed from an anonymous subclass of the `SimulationCode` class defined right here. The `simulate()` method receives information about the program statement as a parameter and manipulates MIPS registers and/or memory to carry out the instruction.

To modify the basic instruction set, follow this process:

1. Extract the MARS distribution from its JAR file if you have not already done so.

2. Copy `InstructionSet.java` from the `src/mars/mips/instructions` folder into the `mars/mips/instructions` folder.

3. Make a backup copy of `InstructionSet.java` for safe keeping.

4. Edit `InstructionSet.java` appropriately. Implementation of the `simulate()` method will likely require access to one or more simulated MIPS memory and/or register objects. The pertinent classes are `mars.mips.hardware.Memory` and `mars.mips.hardware.RegisterFile`. Javadoc-generated documentation for all MARS classes is provided in the distribution's `doc` folder. Also study the source code of existing instructions.

5. Compile `InstructionSet.java` and test your instruction.

NOTE: This technique applies to MARS release 3.2.1. It is possible that the technique for specifying basic instructions will change in a future release of MARS. If so, it would be converted to a technique similar to that now used for system calls.