Tunguska Manual 0.5

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http://www.acc.umu.se/~achtt315/tunguska/

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Chapter 1

Introduction

1.1 The fine print

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Unless otherwise stated, any code examples in this document are exempt from this license, and released into the public domain.

1.2 Foreword

This is a multi-part document covering the use of the Tunguska Emulator, the Tunguska Assembler, the Tunguska C compiler 3CC, a brief introduction to Ternary Computing, and the Specifications of Tunguska.

Tunguska is by no means affiliated with any organization, religion, political movement, nationality, sports team, text editor or pizza topping; mentioned, insinuated, or otherwise referenced. It is non-profit, non-affiliated, and largely only exists for the fun of it.

If you do find some horrible crime against mathematics or grammar in here, first make sure this is the latest version of the document by visiting the Tunguska website, and if it indeed is the latest version you’ve found the error in, feel free to send me an email with a suggested correction.
Part I

The software
Chapter 2

The emulator

2.1 Changes

From 0.0.3.x to 0.4, the most important change is the new assembler directive %INC. What this means is that instead of telling the assembler to assemble all files, you just tell it to assemble ram.asm, and it figures out where to include what automatically.

From 0.4.x to 0.5, the main change is the inclusion of 3CC, the (non-standard) C compiler for tunguska.

2.2 Getting started

To compile and install Tunguska, simply do the following

```
> cd tunguska-
> ./configure
> make
> make install
```

To be of any sort of use, Tunguska needs a memory image to load. Starting tunguska without one would be the equivalent of booting your computer without any sort of hard drive. Don’t worry, you don’t need to illegally download some proprietary image off some murky backwater website. All you need to get started ships with Tunguska. After compiling and installing Tunguska itself, you need to assemble an image, and this is how you do it.

2.2.1 The old ASM image

This memory image is old and proven, dating back to ye olden days of Tunguska’s creation. It is however written entirely in assembly, and is less accessible than the C based image described in the next section. The ASM image has more features though, and as such, serves as a nice demo of Tunguska’s functionality.

```
> tar zxvf tunguska-version/share/memory_image_asm.gz
> cd memory_image_asm
> tg_assembler -o image.ternobj ram.asm
```

You’re now ready to load the image with Tunguska

```
> tunguska image.ternobj
```

You can also assemble disk images, and load them with tunguska. To do this, you need to find the source code for some such image, I suggest you download the pong clone from Tunguska’s website http://www.acc.umu.se/~achtt315/tunguska/ and put it in the same directory as the other .asm-files. You’re now ready to assemble

```
> tg_assembler -o pong.ternobj pong.asm
```

\(^{1}\)This archive is also installed in /usr/local/share/tunguska (or someplace similar, if you changed the prefix.)
And to run it in tunguska, start with the system image

```
> tunguska image.ternobj
```

From the tunguska prompt type

```
> LOAD
ENTER IMAGE TO LOAD=pong.ternobj
DISK LOADED
```

Now, from the tunguska prompt type

```
> RUN
```

### 2.2.2 The new 3CC image

The 0.5 tunguska release and later also comes with a smaller memory image written in C, here is how to compile and run that:

```
> tar zxvf tunguska-version/share/memory_image_3cc.gz
> cd memory_image_3cc
> make
```

You load it in tunguska by running

```
> tunguska image.ternobj
```

And you’re done! That’s all there is to it. Now you’ll probably want to dive in and make your own programs. Good for you.

The most helpful tip on that (except reading this document) is to look up a 6502-assembly reference or guide on the internet. Tunguska is compatible enough for most of the stuff you’ll find there to be applicable. If something doesn’t work as expected, head over to Appendix A and check so the instruction is still there (some instructions have changed names, some have been dropped).

### 2.3 Command line arguments

Tunguska takes the following command line arguments:

- `-h` Display help message
- `-f` Full screen
- `-F` Specify floppy image
- `-Z` Don’t attempt to actually load the floppy, assume it’s zero.

### 2.4 The interface

The border around the window indicates the size of the raster window (bright) and the text/vector window (dark).

#### 2.4.1 Special keys

- **Esc** Exit
- **F9** Enable trace mode, spew the location of the program counter to standard output.
- **F10** Debug, print all registers to standard output.
- **F11** Step instruction (when in pause mode).
- **F12** Send interrupt
- **Pause** Toggle pause
2.4.2 Indicator lights

Top-left of the Tunguska window is three indicator lights, labelled R, G, AG. They correspond to:

- **R**: Running when lit, paused when not
- **G**: Graphics mode (see specifications)
- **AG**: Auxiliary graphics mode (see specifications)
Chapter 3

The C compiler, 3CC

3CC is tunguska’s c-compiler. It is not compatible with any standard of C, and never will be. It is also significantly less mature than tunguska in general, since it’s parallel development started much later than tunguska did. Caveat user.

3.1 Standard

The following is a list of portions of 3CC that differ from standard C. Some of these deviations are bugs that will be fixed in future versions, some are permanent features.

3.1.1 Datatypes

3CC has only two basic datatypes: char and int, and they are both signed. In fact, unsigned datatypes do not exist due to the base of tunguska. There are no long or short types or modifiers. Only integral types are supported, there is no float or double types or modifiers. structs are in, and work as should be expected. Arrays almost work properly, though the array code is somewhat unstable bug. Array declarations mostly work as expected in regular C. Global variables can be extern, but not functions. The whole notion is redundant since there is no intermediate object stage. In 3CC, compiling multiple files is indistinguishable from tacking all of the code together into a single file. The following construct does not work:

type a, b[ , c , . . . ];

3.1.2 Constants

Analogous to the 0x-notation in binary C, 3CC allows you to specify balanced nonary number with 0n. Furthermore, it allows ternary numbers to be specified with 0t.

int a = 0nABD410; // This is a full 12 trit integer
char b = 0tPPNPP0; // This is a 6 trit character
char c = 0n412; // This is also 6 trit character

It should be mentioned that some constant expressions do not fold properly in the current version of 3CC, and are hence evaluated at runtime.

3.1.3 Dynamic vs. static variables

3CC uses a 729 tryte variable stack. This imposes significant limits on how many dynamic variables can be allocated, before data is corrupted due to stack overflow. In general, it is a bad idea to allocate arrays and structs dynamically. Deeply recursive functions are also dangerous. If the number of recursions ever

Table 3.2: List of datatypes

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>1</td>
<td>364</td>
<td>-364</td>
</tr>
<tr>
<td>int</td>
<td>2</td>
<td>265,720</td>
<td>-265,720</td>
</tr>
<tr>
<td>type*</td>
<td>2</td>
<td>265,720</td>
<td>-265,720</td>
</tr>
</tbody>
</table>
risk coming close to \(729 / (\text{stack frame size}^1)\), you should seriously consider finding another approach. 3CC currently does not support tail recursion.

Speed is another good reason reason to consider using static variables. They assign faster, evaluate faster, increment faster, pretty much anything about them is faster. The only downside is that recursion is out the window, as is calling the same functions from the interrupt service routine\(^2\) and userland.

### 3.1.4 Arithmetics and operators

3CC has most of C’s standard operators. It does not have a digit-shift operator (\(<<\, or\, >>\)), however a nice thing to keep in mind is that due to the base Tunguska operates in, there is no difference between arithmetic shifts and logical shifts – so you might as well use multiplication and division by powers of 3.

Pointer arithmetic does not work as expected (it works like integer arithmetic)\(^{bug}\).

#### 3.1.4.1 N-value operator \(<<N>>\>

3CC has the ability to take advantage of ternary logic’s many different operators, and gives the programmer the ability to use any given commutative ternary operator (tritwise) on two ints or chars. The name of this operator is absolutely terrifying: “arbitrary commutative ternary tritwise operator operator”, so let’s just call it N-value operator instead. It has the following syntax:

\[
a <<\!N\!>> b
\]

This specific command will execute the operator with FFUUTT-code \(N\) with parameters \(a\) and \(b\). See section 6.2.3 for the meaning of FFUUTT codes and arbitrary ternary operators. Needless to say, this operator is very powerful once mastered.

#### 3.1.4.2 The sign operator \(^{-}\)

Since logical inversion is identical to arithmetic inversion, the \(^{-}\)-operator has been given the new function of returning the sign of a value in a single trit. Use the minus operator - to invert a number / flip it’s trits. There are several useful tricks involving \(^{-}\):

- \(^{-}X\) is the value of the most significant trit of \(X\).
- \(X^*^{-}X = \text{abs}(X)\)

#### 3.1.4.3 Comparisons

Some of the comparing operators of 3CC–greater than and less than–behave slightly different from regular C. If the values are differet, they return true or false, but if they are the same, they return 0.

\[
a < b = \begin{cases} 
1 & a < b \\
0 & a = b \\
-1 & a > b 
\end{cases} \\
a \leq b = \begin{cases} 
1 & a < b \\
0 & a = b \\
-1 & a > b 
\end{cases} \\
a = b = \begin{cases} 
1 & a = b \\
0 & a \neq b 
\end{cases} \\
a > b = \begin{cases} 
-1 & a < b \\
1 & a = b \\
1 & a > b 
\end{cases}
\]

#### 3.1.5 Operator precedence

Most operators in 3CC work as expected, but for reference, this is how they precede:

1. Incrementers, decrementers
2. Tritwise operations and the sign operator
3. Multiplication, division and modulo
4. Addition and subtraction
5. Comparisons (e.g. \(>\))
6. Logical operations (i.e. \&\& and \(||\))
7. Assignments

---

1Total size of all dynamic variables of the function, including arguments.
2See the By Example section below.
3.1.6 Missing features

Among other features that are missing are

- Gotos
- The ternary operator (i.e. foo?bar:baz)
- Function pointers
- Variadic functions
- Switch-case statements
- Do-while statements – Use for (;;) { loop_code_here; if (!condition) break; } for now.
- Unions
- Enums
- Typedefs

Will be implemented in the future. * Will probably not be implemented in the foreseeable future.

3.1.7 #pragma directives

3CC has a few pragma directives, all relating to where in memory the code is being written.

**SCL** Store Current Location.

**RCL** Restore Current Location.

**ORIGIN** Set current location.

To understand these instructions you need to understand what a ternobj file is. It is essentially a memory snapshot of the entire system memory, that is injected directly into the memory of tunguska. Naturally, writing code for all of the memory in sequence would be very hard, so what SCL, RCL and ORIGIN does is allow you to jump between memory locations, and back. There are various reasons why you might want to do this, but the most useful one is defining global variables in the same location Tunguska has it’s memory registers. Example:

```c
#pragma SCL // Store current location
#pragma ORIGIN 0nDDDDDD // Jump to 0nDDDDDD
struct {
    char number;
    char data;
} irq;
#pragma RCL // Jump back to the previous location
```

This can be inserted virtually anywhere outside of a function, and will allow you to access IRQ data like any old global variable! See the tunguska specifications for a map of reserved memory addresses and their functionality.

3.2 Running

Running 3CC is simple, though you probably want to manually preprocess your files using some third party tool (GNU CPP works fine) before you pass them to 3cc, since that allows you to use preprocessor macros to include arious useful metaprogramming. It is somewhat important to specify origin (-O parameter to 3cc), but 3CC will warn if you choose a disastrous value. A simple build process might look like the following:

1. Preprocess all individual files, save the output to filename.ppc
2. Pass all .ppc-files to 3cc in one go: 3cc -o myprogram.asm *.ppc
3. Assemble the source file: `tg_assembler -O someplace -o myprogram.ternobj myprogram.asm`

4. Run the built program: `tunguska myprogram.ternobj`

A working and easy to modify makefile (for GNU make) is supplied:

```bash
# GNU style makefile for building sources with
# GNU CPP, 3CC and tg_assembler.
#
# This code is public domain.

SOURCES=file.c anotherfile.c yetanotherfile.c # These are the sources you are building
OUTPUT=myprogram.ternobj # This is the output file

# If you store your tunguska assembler or 3cc in some funky place, you may want to alter these:
ASSEMBLER=tg_assembler
TRICC=3cc
CPP=cpp
ORIGIN=0n100000 # Specify origin

# Don't modify any code beneath this line

PP_SOURCES=$(SOURCES:.c=.ppc)

# Main build sequence
all: image clean mini

# Compile image
image: $(PP_SOURCES)
  $(TRICC) -o out.asm $(PP_SOURCES)
  $(ASSEMBLER) -O$(ORIGIN) -o $(OUTPUT) out.asm

# Remove preprocessed sources
clean mini:
  rm -rf *.ppc

# Remove all output
clean: clean mini
  rm -rf out.asm $(OUTPUT)

# Tell make to use suffix rules for targets ending in .ppc
.SUFFIXES: .ppc

# Tell make how to preprocess sources
.c.ppc: $(CPP) $(CPP) $< -o $@
```

---

3.3 By example

The following section is dedicated to some examples of code illustrating key to essential functionality of Tunguska. They are code that require a lot of low level direct memory manipulation, inline assembly

---

3 On400000 is a good choice, just make sure you write a bootstrap function at 0n000000.
or other arcane tricks that need a deep level of understanding of the underlying architecture I can’t ask people to get right away.

### 3.3.1 Interrupt Service Routine (ISR)

This is how to build an interrupt service routine, to handle input and various exceptions. The default ISR is simply the instruction to return back to the code – leaving the interrupt unhandled, but dropped from the queue. If you want access to peripherals like they keyboard or the mouse in your program, you will need an ISR.

```c
#pragma SCL /* Save current location, we’re going to define some code at magic locations */
#pragma ORIGIN 0nDDDDDD
struct { /* The IRQ registers are located at 0nDDDDDD and 0nDDDDDC */
    char number;
    char data;
} irq;
#pragma ORIGIN 0 /* Make sure the bootstrap ends up at origin, it must */
void bootstrap() { /* Stop interrupts */
    *(void**)&(0n444442) = isr; /* Set interrupt handler */
    *(char*)(0n444441) = 0n444;
    asm("CLI"); /* Resume interrupts */
    main(); /* Run code */
    asm("PAUSE"); /* Pause if main returns, to avoid screenfulls of garbled nonsense */
}
void main() { /* Your code goes here */
    static int counter;
    set_random(data);
    if(counter++ > 1000) repaint(); /* See the next example on text output */
}
void clock_cycle(char data) { /* Something like this: */
    if(irq.number == 0) /* Key interrupt */
        got_key_input(irq.data);
    else if(irq.number == 1) /* Clock interrupt */
        clock_cycle(irq.data);
    else if(irq.number == 5) /* Mouse motion */
        mouse_motion(irq.data / 27, irq.data ^ 0000NNN);
    else if(irq.number == 6) /* Mouse click */
        mouse_click(irq.data);
    else unhandled_interrupt();
    /* End of handler, restore tmp (note the reversed order) */
    asm("PLL tmp+1", "PLL tmp");
}
/* The following is especially important in an ISR, */
```
the compiler will attempt to return with the RST instruction, but that causes catastrophical failures in an interrupt handler, so it is necessary to manually inject an RTI (ReTurn from Interrupt)

```
asm("RTI");
```
Chapter 4

The assembler

4.1 Conventions

The following document uses the following conventions, anything inside hard brackets [like this] is optional. Anything inside braces and separated by pipes {like|this} is a situation where you must select one of the options (in the example, either like or this). ‘n’ means any numeral, ‘s’ means any string, ‘a’ means any address or label name, ‘l’ means explicitly any label name.

4.2 Command line arguments

The assembler takes the following command line arguments:

- -v Verbose mode
- -o Specify output
- -h Display help message

4.3 Numerical constants

There are two main numeral classes in the Tunguska assembler, trytes and words. Trytes have trit-width 6, and words have trit-width 12. A tryte can generally be used in place of a word, but a word can not be used in place of a tryte. There are two special operators, ‘LOW’ and ‘HIGH’ that allow you to extract the individual trytes of a word, and use that as a tryte.

In the strictest sense, it is sometimes possible to use a word in place of a tryte without the assembler complaining, but it isn’t recommended.

There are two allowed numeral bases, decimal and balanced nonary. Balanced nonary allows numbers in the range -4,...,4; but since there is no symbols for negative numbers, the letters A,...,D are used to symbolize -1,...,-4. Balanced nonary is to ternary roughly what octal is to binary.

31 Regular decimal. No prefix required. Since it is within +-364, both a word and a tryte.
1000 Regular decimal. No prefix required. Only a word, not a tryte.
%0DA Nonary triplet. Always a tryte long.
%0DA114 Nonary sextet. Always a word long.
%000000 Nonary sextet. Always a word long, even if it is smaller than 364.
LOW %0DA114 Lower tryte of nonary sextet. Equivalent to %114.
4.4 Instructions and addressing modes

In general, there is no forbidden instructions in Tunguska. Even if you try to pass an unexpected addressing mode to an operator, the whole machine shouldn’t crash and burn. There can be unexpected behavior though, so don’t do it on purpose. For a complete list of Tunguska instructions, see the machine specifications.

The tunguska assembler expects all instructions to be uppercase, any lower case instructions will be interpeted as labels or variables, and the assembler will complain.

4.4.1 Addressing modes

OP Implicit addressing. No argument.
OP A Accumulator. Whatever operation is done with the accumulator as argument. Strictly speaking, this is the same as implicit addressing.
OP #n Immediate addressing. Whatever operation is done with the directly specified numeral as argument.
OP a Absolute addressing. Whatever operation is done on the memory at address a.
OP a,X Absolute addressing with X offset. Whatever operation is done on the memory at address a+X.
OP a,Y Absolute addressing with Y offset. Whatever operation is done on the memory at address a+Y.
OP (a) Indirect addressing. Whatever operation is done on the memory pointed to by the memory at address a.
OP (a,X) Indirect addressing with X offset. Whatever operation is done on the memory pointed to by the memory at address (a+X).
OP (a),Y Indirect addressing with Y offset. Whatever operation is done on (the memory pointed to by the memory at address a) + Y.
OP X,Y XY-addressing. Whatever operation is done on the memory pointed to by X:Y.

4.5 Assembler macros

The Tunguska assembler supports a series of pseudo-instructions, or macros that do not affect the machinecode itself, but allows the assembler to enter non-generated data, or perform other operations.

As a rule of thumb, all macros begin with an @, and are all uppercase.

@DT {n|s}, {n|s}, ...
Define tryte. Accepts a comma separated list of numerals and strings. These are entered into the assembled memory output as-is.

@DW {n|s|a}, {n|s|a}, ...
Define word. Accepts a comma separated list of numerals, strings or memory addresses (labels).

@REST {n|s} [{n|s} = 0]
Reserve argument1 number of trytes into memory, set them to argument2.

@EQU 1 {n|s|a}
Set variable argument1 to argument2. For most intents and purposes, this is identical to jumping to argument 2 and declaring a label there.
@ORG {n|a}
Jumps instruction counter to address or label specified. Interpret as "this is where I want the following code to go into memory."

@INC {s}
Include file argument1 at this position.

4.6 Inline arithmetics

The Tunguska assembler has support of inline arithmetics, that is, it can calculate pretty much any algebraic function based on values available to it at assembly-time. A magic $$ token is available, resolving to the address of this (the current) memory position. It works pretty much like you’d expect it to, with regular infix syntax. The only quirk is that you can’t use paranthesis for precedence override, instead you must use braces.

This works: \{1+2\} * 3 - 5 + $$ - somelabel*2
This doesn’t: (1+2) * 3 - 5 + $$ - somelabel*2

4.7 Labels and assembler variables

While labels and assembler variables are in many ways interchangable, there are a few differences. Labels can have local child labels and child variables that, from within the label are accessible through .localname and from outside the label through label.localname, but a variable can not.

A label is declared through labelname: in the beginning of a line, and accessed through substituting labelname where-ever an address is requested.

A variable is declared through @EQU variable value, and is accessible in much the same way a label is. Furthermore, it is possible to store not only words, but trytes in variables, which can be accessed for an instance in immediate addressing mode like this: OP #variable.

A very powerful combination is the $$ -token and variables. For an instance, if you want to determine the length of a string automatically for use later, you can use a construct like this:

mysting: @DT ‘Hello world!’, 2, ‘How are you doing?’
@EQU .length $$ - mystring

The length of mystring (which reads: 'Hello world![new line]How are you doing?') will be stored in mystring.length at no cost of machine memory.
Part II

Introduction to Ternary Computing
Notes

This is more or less original research, and on some parts it might be downright erroneous. See it as a crash course into the relevant parts of Ternary computing to Tunguska. It’s unfortunately a bit esoteric in it’s fairly heavy use of mathematical and logical symbols and conventions.

Non-mathematical introduction

Before I go into the mathematical stuff, I’m going to list a few of the benefits of balanced ternary numeral systems and ternary logic.

There are many neat features of this base, for an example, it is very simple to round off. What you do to round a balanced number is to drop the least significant digits (as many as you want), and replace them with zeros; and that’s all there is to it, you’ll never get an error in the same way rounding the decimal number 199 to 100 will.

Another benefit is the representation of negative numbers. In a binary computer, you need to keep a separate bit to keep track of the sign of your number. This is redundant in a computer with a balanced base. There is no possibility of “minus zero”, and no need for ugly fixes like two’s complement.

Negative numbers in general make a lot more sense in a balanced base. A lot of everyday mathematics regarding negative numbers is downright strange, from the separate minus operation (which is just adding a negative number), to the minus prefix to negative numbers. It resembles some sort of cargo cult, struggling to keep a hold of the confused conventions of the ancestors without really considering what they do.

More resources

There is a multitude of resources on Ternary Computing available on the Internet, though they can be difficult to find. Here are some of them:


http://jeff.tk/wiki/Trinary Trinary - Jeff.tk (Some sort of project to build a ternary computer? Has a lot of useful links, not very clear on what the purpose of the page is.)

http://www.ternary.info/ Ternary.info - special interest group on balanced ternary numeral system and ternary logic (Ternary site mostly in Russian, has helpful people in it’s forum.)

http://en.wikipedia.org/wiki/ Lots of information under they keywords “Balanced ternary”, “Ternary logic”, “Ternary numeral system”, ...

http://www.trinary.cc/ Mostly hardware-oriented trinary computer site.
Chapter 5

Numerical representation

5.1 Conventions

I will use subscript to indicate numeral base. \( n_{10} \) is decimal, \( n_3 \) is ternary, \( n_{3b} \) is balanced ternary, \( n_{9b} \) is balanced nonary. When nothing else is indicated, assume decimal.

I will use vector form to represent a number, in this fashion:

\[
\mathbf{n} = < a_{N-1}, a_{N-2}, \ldots, a_1, a_0 >
\]

\( \mathbf{n} \) will mean arbitrary number, \( N \) the number of digits in a number, \( a \) will mean a digit in given number.

5.2 Ternary numeral base

The regular ternary numeral system uses base 3, that is, it has three digits: 0, 1 and 2. The value of a ternary number is formally defined as

\[
V = \sum_{i=0}^{N} 3^i a_i
\]

(5.1)

Where \( a_i \) is the i:th digit (and \( a_0 \) is the least significant digit). More practically, this means that the ternary number 201, in decimal is

\[
210_3 = 2 \cdot 3^2 + 0 \cdot 3 + 1 = 19_{10}
\]

There really isn’t anything special or spectacular with this numeral base, it works much like you’d expect any old base to do. Much like any conventional base, it’s range is

\[
0 \leq X < 3^N
\]

(5.2)

where \( N \) is the number of digits. At a fixed word size, addition with consideration to spillover is defined by

\[
T_0 + T_1 = (T_0 + T_1) \mod 3^N
\]

(5.3)

5.2.1 Balanced ternary

The balanced ternary numeral system is a non-standard base. It still follows equation (4.1), but the digits are shifted one step down. That is, it’s digits are -1, 0, 1; but since there is no symbol for the digit -1, it’s conventional to call the digits N, 0 and P. Again, to supply an example:

\[
PN0_{3b} = 1 \cdot 3^2 + (-1) \cdot 3 + 0 = 6_{10}
\]

An important thing to note is it’s range. Note the extreme difference between the range of regular ternary in equation (4.2), and the range of balanced ternary:

\[
-\left\lfloor \frac{3^N}{2} \right\rfloor \leq X \leq \left\lceil \frac{3^N}{2} \right\rceil
\]

(5.4)
Addition with consideration to spillover is defined by

\[ T_0 + T_1 = (T_0 + T_1 + \left\lfloor \frac{3^N}{2} \right\rfloor) \mod 3^N - \left\lfloor \frac{3^N}{2} \right\rfloor \]  

(5.5)

Where \( T_1 \) is positive. Do note the difference between equations (4.5) and (4.3).

The biggest difference between balanced bases and non-balanced “regular” bases is how negative numbers are handled. There is no neat way of handling negative numbers in non-balanced bases, so you have to invent work-arounds. These work-arounds are generally eyesores, either because they allow illegal states (negative zero in one’s complement), or because they generate asymmetric ranges (two’s complement).

This issue is non-existent in balanced bases, since negative numbers are inherently supported. All you need to do to invert a balanced number is invert all the digits (4.6).

\[-n = -< a_{N-1}, a_{N-2}, ..., a_1, a_0 > = < -a_{N-1}, -a_N, ..., -a_1, -a_0 >\]  

(5.6)

An important thing to note is that the sign of a balanced number is the sign of the most significant digit.

While there is nothing wrong with holding on to the minus prefix commonly used in balanced numbers, it really is quite redundant.

5.2.2 Compact representation

There are two major ways of representing ternary numbers in a more manageable way: Nonary (Base 9) and Septemvigesimal (Base 27). Septemvigesimal is very unpractical, since it requires symbols for 17 additional digits beyond our decimal 0…9.

Nonary is much more manageable. It is very close to decimal in data density and therefore easy to “intuit” the value of. Nonary should be easier to wrap your mind around than say hexadecimal which is more alien to decimal, data-density-wise.

In this document, we’re interested specifically balanced nonary. It has nine digits, -4, -3, -2, -1, 0, 1, 2, 3, 4. Again, we lack symbols for negative digits, and for this reason, I will introduce the letters A…D to represent -1…-4.

It’s value is governed by the following formula:

\[ V = \sum_{i=0}^{N} 9^i a_i \]  

(5.7)

Example:

\[ 3AD_{9b} = 9^2 \cdot 3 + 9 \cdot (-1) + (-4) = 230_{10} \]

Each balanced nonary digit represents two balanced nonary digits.

5.3 Ternary representation on binary computers

There is no such binary word size \( b \) that it’s possible to represent a ternary word of size \( t \) without superfluous states. This follows from the prime uniqueness theorem, which simplified to fit this case states that

\[ 3^b \neq 2^t \forall b, t \neq 0 \]

So the quest is not to find a lossless representation of ternary values on binary computer, but minimizing loss while maximizing usability and speed. Assume ternary word size 6, 729 states. The smallest number of binary bits that can represent that many states is 10, 1024 states. That’s 295 meaningless states. Furthermore, there is no real obvious connection between individual bits in the binary representation of the ternary word, and the digits of the ternary word.

Obviously, this is not a good representation. It is small, but quite useless. Instead, if one represents a ternary digit with two bits. This representation squanders states pretty carelessly, but it is by far the most easily used one. There is a clear tie between bits and ternary digits, and it is quite fast.

It is also worth mentioning that it is possible to implement ternary logic with memory pointers, where the value is represented by a pointer to a memory location containing a true-false value, but this
memory location can also be some invalid value (typically NULL), meaning the third state. However, this is even worse from a state point of view. On a 32 bit computer, \(2^{32} = 4,294,967,296\) states (the size of a memory address) are used to store one state, and the other two states are stored in hopefully one bit, but more likely 8. So, worst case scenario, that’s using \(2^{32} + 2^8 = 4,294,967,552\) states to store 3 states. Needless to say, this is not something you’ll want to use for speed or size. No matter how you twist and turn this, it will never be an effective solution.\(^1\)

### 5.3.1 Hexadecimal Packed Balanced Nonary

A convenient trick to outputing balanced nonary data in binary computers is to pack them in hexadecimal numbers. What you do is simply to map 0,...,4 to 0,...,4; and -1,...,-4 to 10,...,14. Conversion is a bit tricky, but the benefits is to be able to use native printf-like functions that understand hexadecimal numbers to print nonary numbers without having to mess around with strings.

---

\(^1\)For creating a ternary computer, emulated or in hardware. There is probably some cases where this sort of construction can be useful in other fields.
Chapter 6

Ternary logic

6.1 Conventions

In this part, I will abbreviate TRUE to T, UNKNOWN to U, FALSE to F; furthermore, I will use standard logic symbols

- $\land =$ AND
- $\lor =$ OR
- $\oplus =$ XOR
- ...

6.2 True, Unknown, False

Boolean logic, TRUE or FALSE-logic, while immensely powerful, is limited due to the fact that it only deals in absolutes. Answer the question “Was it raining in western Beijing 4:39 PM, March 13 1839?” in boolean logic. Unless you’re an archeometeorologist, are exceptionally old, or own a time machine; you won’t know the answer, and therefore, you will be unable to answer either true or false.

But, note well how your head is not spinning and sparking and you how you are not shrieking “DOES NOT COMPUTE!” repeatedly, because unlike robots in science fiction films from the 1950’s, you understand ternary logic.

Ternary logic isn’t something new and scary, it’s something old and mundane. It’s, just as boolean logic, a formalization of human logic. Only difference is that ternary logic introduces a third state. There are multiple ideas of what this third state should be; unknown, both, neither, a zen non-answer. None of them are inherently wrong, they are all ternary logic systems. I will be primarily describing true-unknown-false logic.

It’s important to realize that this is just one possible interpretation of ternary logic. Even though I will be using “proof”-like devices to to derive the output of the functions, this is merely so that the system of logic formulated is self-consistent, and compatible with boolean logic. This also means the proofs can be more lax, and call on common sense more often than otherwise merited.

6.2.1 Logical conditionals

What does this mean for logical conditionals? Let’s take a look at them.

6.2.1.1 Material conditional

Material conditionals don’t need that much modification. Assume you have a rule “If P, then Q”, or in logical symbols $P \rightarrow Q$, then since modifying existing boolean rules is undesirable, it is necessary to make a rule for the case P is Unknown. It is not hard to convince yourself that if P is unknown, and P implies Q, then Q must also be unknown. We can also protect ourselves against the logical fallacy of affirming the consequent by introducing a rule that states that if P implies Q, and Q is true, then P is unknown.
6.2.1.2 Logical biconditional

Logical biconditionals are also pretty much the same. Assume you have the rule “P if and only if Q”, or in logical symbols \( P \leftrightarrow Q \), then the case of concern is when P is unknown. Since all cases involving true or false, for both P and Q, are already taken by boolean logic, then a logical biconditional with either P or Q unknown must imply that the other is also unknown.

6.2.2 Ternary operators

Boolean logic isn’t wrong, it works and it arrives at the correct results, so whatever extensions are made to it must preserve backward compatibility with boolean logic, so all standard boolean operators with exclusively true or false values must result in the same values you would expect them to with conventional boolean logic.

6.2.2.1 \( \wedge \) (AND)

The AND operator can pretty much be intuited from what we know of its boolean counterpart. We know AND is commutative, so the only cases we need to deal with are:

- \( T \wedge U = U \); Since \( T \wedge F \neq T \wedge T \), the result must be \( U \).
- \( F \wedge U = F \); Since \( F \wedge F = F \wedge T = F \), the result must be \( F \).
- \( U \wedge U = U \); Since both arguments are unknown, nothing is known about the result.

6.2.2.2 \( \vee \) (OR)

The same logic used to deduce the results of the AND operator can be used to deduce the results of the OR operator. It also is commutative, so the cases are the same:

- \( T \vee U = T \); Since \( T \vee F = T \vee T = T \), the result must be \( T \).
- \( F \vee U = U \); Since \( F \vee F \neq F \vee T \), the result must be \( U \).
- \( U \vee U = U \); Since both arguments are unknown, nothing is known about the result.

6.2.2.3 \( \oplus \) (XOR)

The same logic used to deduce the results of AND and OR also works for XOR. XOR is also commutative, so these are the cases we must consider:

- \( T \oplus U = U \); Since \( T \oplus F \neq T \oplus T \), \( T \oplus U = U \).
- \( F \oplus U = U \); Since \( F \oplus F \neq F \oplus T \), \( T \oplus U = U \).
- \( U \oplus U = U \); Both arguments are unknown, nothing can be said about the result.

A small point of interest, if ternary logic is represented with balanced ternary, so that \( T=1, U=0, F=-1 \), then \( P \oplus Q = -(P \cdot Q) \), which makes \( \oplus \) very useful in ternary computing, since it both does masking and inversion.

6.2.2.4 \( \neg \) (NOT)

If nothing is known about a variable, then nothing can be known about the inverted variable. Therefore, \( \neg U = U \).
6.2.3 Formalization with Set Theory

It is possible to generalize the method used above to go from boolean logic to ternary true-unknown-false logic with set theory.

First define the set \( R = \{ \text{True}, \text{False} \} \), furthermore, the subsets \( T = \{ \text{True} \} \), \( F = \{ \text{False} \} \), \( U = \{ \text{True}, \text{False} \} \).

Furthermore, define the following axioms

\[
O(T, U) = O(T, T) \cup O(T, F)
\] (6.1)

\[
O(F, U) = O(F, T) \cup O(F, F)
\] (6.2)

\[
O(U, T) = O(T, T) \cup O(F, T)
\] (6.3)

\[
O(F, U) = O(T, F) \cup O(F, F)
\] (6.4)

\[
O(U, U) = O(U, T) \cup O(U, F) \cup O(T, U) \cup O(F, U)
\] (6.5)

Given you know the truth values for any given boolean value, you can use these five axioms to determine the remaining truth values in the true-unknown-false logic described herein. This is a method of deriving a ternary extension of a boolean function, so it can’t be proven or disproven (indeed, it can not be true or false).

An interesting extension to this formalism is the introduction of Neither \( N = \{ \} \) as the empty set, allowing for a description of a quaternary true-unknown-false-neither system. A possible rule set for this could look something along the line of

\[
O(X, N) = \{ T, F \} \setminus (O(X, T) \cup O(X, F))
\]

6.2.4 Non-boolean operations and FFUUTT-notation

There are 19,683 possible ternary operations (stemming from the 9 degrees of freedom available). Most of these are headache inducing, non-commutative and just plain unpleasant to work with. Now, sifting through just south of 20,000 operations is a lot of work, so it would be nice to find some sort of subset that is guaranteed to be more easy to work with. I’ve already mentioned commutativity. \( A \) op \( B \) should, in a nice operation, be the same as \( B \) op \( A \).

Since commutative operators removes three degrees of freedom, there are 729 of them. Unlike boolean logic, which has 16 operations (all with a name), no one can be expected to remember 729 names. Therefore, I introduce FFUUTT-numbers. Each operation is given a number from -364 through 364, that describes it’s operation in a quite eloquent way.

The number is simply the result of the operation when the arguments are arranged in a specific, and easy to remember order. Just insert the results into a table like the one to the right. And then interpret the list of numbers as digits in a balanced nonary number \( N \), which is the FFUUTT-code for the given operation.

\[
N_{OP} = 3^5X_5 + 3^4X_4 + 3^3X_3 + 3^2X_2 + 3X_1 + X_0
\]
6.2.4.1 Shift (N=168)

The shift operator is an operator of convenience. It doesn’t correspond to any particular logical relationship. What it does is essentially addition with wrap around. With balanced ternary, the function is defined as

\[
S(P, Q) = \begin{cases} 
1 & P + Q = -2 \\
-1 & P + Q = -1 \\
0 & P + Q = 0 \\
1 & P + Q = 1 \\
-1 & P + Q = 2
\end{cases}
\]

6.2.4.2 Shift w/o rollover (N=-312)

The shift without rollover operator (called permute in Tunguska, from it’s ability to permute values) is like shift, without the wrap-around.

\[
S|(P, Q) = \begin{cases} 
-1 & P + Q < 0 \\
0 & P + Q = 0 \\
1 & P + Q > 0
\end{cases}
\]

6.2.4.3 BUT (N=-241)

The BUT operator is a complement to AND and OR. It does not correspond to any semantic operator. It is part of the same family of operators as AND and OR, with a 5:3:1 distribution of values. AND has 5F:3U:1T, OR has 5T:3U:1F; while BUT has 5U:3F:1T.

There are many other 5:3:1-operators, truth to be told, BUT is only implemented in Tunguska because it is in TriINTERCAL, so not to hang any TriINTERCAL-users out to dry without their favorite operator.

6.3 Other systems

Other systems I’m not going to spend any more paper (or screen) deducing, but roughly outline because of their importance is true/neither/false (TNF) and boolean-conservative (BC).

True/neither/false is another human-logic translation where the third state is set to mean neither instead of unknown.

Boolean-conservative is another step towards that direction, it treats the third state as false. As an outcome of this, it’s return values are always compatible with boolean logic.

The C++ library “Boost” implements yet another ternary logical system in “tribool”\(^1\), that is not consistent with regular boolean logic.

I’m bringing them up because they are good food for thought, and pondering them, and even more exotic, non-boolean systems are a great way of getting a more intimate understanding of ternary logic.

For an example, consider the XOR operation, it is notable that this is not the only meaningful extension of XOR. A pattern that emerges in binary XOR is that the operation answers the question “are these values different?” – but the above interpretation answers it in a more abstract way than one might like: Looking at the meaning of the symbols, U and U represent all possible permutations of true and false, but looking at the symbols themselves, they are the same and only the same.

So, which one is XOR? Both are. The only real requirement to be XOR is to be compatible with boolean XOR. The true/unknown/false XOR I started out with is one variant of XOR, the symbol-level XOR is another. For any given commutative boolean operation, there are three degrees of freedom, and consequently 27 ternary siblings (ranging from sensible to nonsensical.)

6.4 Truth tables

Here are truth tables for the hitherto mentioned logical operations.

\(^1\)See "http://www.boost.org/doc/libs/1.36.0/doc/html/tribool.html"
### Table 6.3: Truth tables

<table>
<thead>
<tr>
<th>A</th>
<th>T</th>
<th>T</th>
<th>T</th>
<th>U</th>
<th>U</th>
<th>U</th>
<th>F</th>
<th>F</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>T</td>
<td>U</td>
<td>F</td>
<td>T</td>
<td>U</td>
<td>F</td>
<td>T</td>
<td>U</td>
<td>F</td>
</tr>
<tr>
<td>A (\land) B</td>
<td>T</td>
<td>U</td>
<td>F</td>
<td>U</td>
<td>U</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>-322</td>
</tr>
<tr>
<td>A (\lor) B</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>U</td>
<td>U</td>
<td>T</td>
<td>U</td>
<td>F</td>
</tr>
<tr>
<td>A (\oplus) B</td>
<td>F</td>
<td>U</td>
<td>T</td>
<td>U</td>
<td>U</td>
<td>F</td>
<td>T</td>
<td>U</td>
<td>F</td>
</tr>
<tr>
<td>A (\text{BUT}) B</td>
<td>T</td>
<td>U</td>
<td>F</td>
<td>U</td>
<td>U</td>
<td>F</td>
<td>U</td>
<td>F</td>
<td>-241</td>
</tr>
<tr>
<td>A shift B</td>
<td>F</td>
<td>T</td>
<td>U</td>
<td>T</td>
<td>U</td>
<td>F</td>
<td>U</td>
<td>T</td>
<td>F</td>
</tr>
<tr>
<td>A shift w/o rollover B</td>
<td>T</td>
<td>T</td>
<td>U</td>
<td>T</td>
<td>U</td>
<td>F</td>
<td>U</td>
<td>F</td>
<td>-312</td>
</tr>
</tbody>
</table>
Appendix A

Tunguska specifications

Tunguska uses balanced ternary arithmetic, True-Unknown-False logic, tryte width 6. Address width and word size 12. Standard notation balanced base-9 (nonary). Accessible address range \( \text{DDD}:\text{DDD}_9 \) to \( 444:444_9 \). Total accessible memory \( 531_{10} \) ktrytes. Big endian address storage.

A.1 Registers

Tunguska has relatively few general purpose registers, but the speed of memory access is more or less identical to register access, so this is not that big of a deal. Directly user-accessible registers are indicated by bold.

<table>
<thead>
<tr>
<th>Name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Accumulator</td>
</tr>
<tr>
<td>X</td>
<td>Address register</td>
</tr>
<tr>
<td>Y</td>
<td>Address register</td>
</tr>
<tr>
<td>PC</td>
<td>Program counter</td>
</tr>
<tr>
<td>S</td>
<td>Stack index</td>
</tr>
<tr>
<td>CL</td>
<td>Clock register</td>
</tr>
<tr>
<td>P</td>
<td>Processor status</td>
</tr>
</tbody>
</table>

A.1.1 Processor status register specification

The processor status register (P) has the following tritfields, and it is set by most operations.

<table>
<thead>
<tr>
<th>MST</th>
<th>LST</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>V</td>
</tr>
</tbody>
</table>

More elaborately, the flags have the following names and functionality

<table>
<thead>
<tr>
<th>Flag</th>
<th>Full name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Carry</td>
<td>Carry of the last operation.</td>
</tr>
<tr>
<td>G</td>
<td>Comparison</td>
<td>The sign of the last operation.</td>
</tr>
<tr>
<td>I</td>
<td>No-Interrupt</td>
<td>Put interrupts on hold.</td>
</tr>
<tr>
<td>B</td>
<td>Break in progress</td>
<td>Set during interrupts.</td>
</tr>
<tr>
<td>V</td>
<td>Overflow</td>
<td>Set by CMP, much like G. Used in jumps.</td>
</tr>
<tr>
<td>PR</td>
<td>Parity</td>
<td>The sign of the trit sum of the last operation.</td>
</tr>
</tbody>
</table>

When the No-Interrupt flag is set, all interrupts will be put on hold until it is cleared. The only limiting factor in how many interrupts can be kept waiting is the host system memory. The break flag is set when an interrupt is in progress. It is cleared when the interrupt is over. It also acts like the I-flag, blocking interrupts. The I and B flags may merge in the future to make better use of ternary capabilities.
A.2 Op-code specifications

The tunguska operation codes are following as following, where A is addressing mode and C is operation. In general, there are no forbidden combinations of addressing modes and operations, specifying an unsupported mode may be unpredictable, but will not crash the system.

<table>
<thead>
<tr>
<th>MST</th>
<th></th>
<th></th>
<th></th>
<th>LST</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

A.2.1 Addressing modes

<table>
<thead>
<tr>
<th>DEC</th>
<th>B9</th>
<th>Symbol</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4</td>
<td>D</td>
<td>ABS</td>
<td>3</td>
<td>Value at memory position directly specified</td>
</tr>
<tr>
<td>-3</td>
<td>C</td>
<td>IMM</td>
<td>2</td>
<td>Value immediately following op-code</td>
</tr>
<tr>
<td>-2</td>
<td>B</td>
<td>AX</td>
<td>3</td>
<td>ABS with offset X</td>
</tr>
<tr>
<td>-1</td>
<td>A</td>
<td>YY</td>
<td>3</td>
<td>ABS with offset Y</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>ACC</td>
<td>1</td>
<td>Accumulator</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>IMP</td>
<td>1</td>
<td>Implicit – no argument</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>INDX</td>
<td>3</td>
<td>Value at (Memory position + X)</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>INDY</td>
<td>3</td>
<td>Value at (Memory position)+Y</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>INDIRECT</td>
<td>3</td>
<td>Value pointed to by the memory position directly specified</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>X:Y</td>
<td>1</td>
<td>Memory at page X, index Y</td>
</tr>
</tbody>
</table>

A.2.2 Operations

<table>
<thead>
<tr>
<th>DEC</th>
<th>B9</th>
<th>Symbol</th>
<th>Valid addressing mods</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>DD</td>
<td>CLV</td>
<td>IMP</td>
<td>Clear overflow</td>
</tr>
<tr>
<td>-39</td>
<td>DC</td>
<td>BRK</td>
<td>IMP</td>
<td>Trigger interrupt</td>
</tr>
<tr>
<td>-38</td>
<td>DB</td>
<td>RTI</td>
<td>IMP</td>
<td>Return from interrupt</td>
</tr>
<tr>
<td>-37</td>
<td>DA</td>
<td>LDA</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Set accumulator to memory value</td>
</tr>
<tr>
<td>-36</td>
<td>D0</td>
<td>LDX</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Set Y register to memory value</td>
</tr>
<tr>
<td>-35</td>
<td>D1</td>
<td>LDY</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Set X register to memory value</td>
</tr>
<tr>
<td>-34</td>
<td>D2</td>
<td>STA</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Store accumulator’s value in memory</td>
</tr>
<tr>
<td>-33</td>
<td>D3</td>
<td>STX</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDY, INDY, X,Y</td>
<td>Store X register’s value in memory</td>
</tr>
<tr>
<td>-32</td>
<td>D4</td>
<td>STY</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDY, INDY, X,Y</td>
<td>Store Y register’s value in memory</td>
</tr>
<tr>
<td>-31</td>
<td>CD</td>
<td>TAX</td>
<td>IMP</td>
<td>Transfer A to X</td>
</tr>
<tr>
<td>-30</td>
<td>CC</td>
<td>TAY</td>
<td>IMP</td>
<td>Transfer A to Y</td>
</tr>
<tr>
<td>-29</td>
<td>CB</td>
<td>TXA</td>
<td>IMP</td>
<td>Transfer X to A</td>
</tr>
<tr>
<td>-28</td>
<td>CA</td>
<td>TYA</td>
<td>IMP</td>
<td>Transfer Y to A</td>
</tr>
<tr>
<td>-27</td>
<td>C0</td>
<td>TSK</td>
<td>IMP</td>
<td>Transfer Stack index to X</td>
</tr>
<tr>
<td>-26</td>
<td>CI</td>
<td>TXS</td>
<td>IMP</td>
<td>Transfer X to Stack index</td>
</tr>
<tr>
<td>-25</td>
<td>C2</td>
<td>PHA</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Push to stack</td>
</tr>
<tr>
<td>-24</td>
<td>C3</td>
<td>PHP</td>
<td>IMP</td>
<td>Push processor status to stack</td>
</tr>
<tr>
<td>-23</td>
<td>C4</td>
<td>PLA</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Pull from stack</td>
</tr>
<tr>
<td>-22</td>
<td>BD</td>
<td>PLP</td>
<td>IMP</td>
<td>Pull processor status from stack</td>
</tr>
<tr>
<td>-21</td>
<td>BC</td>
<td>AND</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>A=A\memory</td>
</tr>
<tr>
<td>-20</td>
<td>BB</td>
<td>EOR</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>A=\A\memory</td>
</tr>
<tr>
<td>-19</td>
<td>BA</td>
<td>ORA</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>A=A\memory</td>
</tr>
<tr>
<td>-18</td>
<td>B0</td>
<td>BIT</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Set status flag as though AND</td>
</tr>
<tr>
<td>-17</td>
<td>B1</td>
<td>ADD</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>A=A+memory</td>
</tr>
<tr>
<td>-16</td>
<td>B2</td>
<td>CMP</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Set status flag as though A-memory</td>
</tr>
<tr>
<td>-15</td>
<td>B3</td>
<td>INC</td>
<td>ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X,Y</td>
<td>Increase value by 1</td>
</tr>
<tr>
<td>-14</td>
<td>B4</td>
<td>INX</td>
<td>IMP</td>
<td>Increase X register by 1</td>
</tr>
<tr>
<td>-13</td>
<td>AD</td>
<td>INY</td>
<td>IMP</td>
<td>Increase Y register by 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEC</th>
<th>B9</th>
<th>Symbol</th>
<th>Valid addressing mods</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEC</td>
<td>B9</td>
<td>Symbol</td>
<td>Valid addressing mods</td>
<td>Comment</td>
</tr>
<tr>
<td>-----</td>
<td>----</td>
<td>--------</td>
<td>-----------------------</td>
<td>---------</td>
</tr>
<tr>
<td>-12</td>
<td>AC</td>
<td>DEC</td>
<td>ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Decrease value by 1</td>
</tr>
<tr>
<td>-11</td>
<td>AB</td>
<td>DEX</td>
<td>IMP</td>
<td>Decrease X register by 1</td>
</tr>
<tr>
<td>-10</td>
<td>AA</td>
<td>DEY</td>
<td>IMP</td>
<td>Decrease Y register by 1</td>
</tr>
<tr>
<td>-9</td>
<td>A0</td>
<td>ASL</td>
<td>ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Shift value left, spillover in carry</td>
</tr>
<tr>
<td>-8</td>
<td>A1</td>
<td>LSR</td>
<td>ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Shift value right, spillover in carry</td>
</tr>
<tr>
<td>-7</td>
<td>A2</td>
<td>ROL</td>
<td>ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Rotate left</td>
</tr>
<tr>
<td>-6</td>
<td>A3</td>
<td>ROR</td>
<td>ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Rotate right</td>
</tr>
<tr>
<td>-5</td>
<td>A4</td>
<td>JMP</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump</td>
</tr>
<tr>
<td>-4</td>
<td>0D</td>
<td>JSR</td>
<td>IMP</td>
<td>Jump to subroutine</td>
</tr>
<tr>
<td>-3</td>
<td>0C</td>
<td>RST</td>
<td>IMP</td>
<td>Return from subroutine</td>
</tr>
<tr>
<td>-2</td>
<td>0B</td>
<td>CLC</td>
<td>IMP</td>
<td>Clear carry</td>
</tr>
<tr>
<td>-1</td>
<td>0A</td>
<td>CLI</td>
<td>IMP</td>
<td>Clear interrupt flag</td>
</tr>
<tr>
<td>0</td>
<td>00</td>
<td>NOP</td>
<td>IMP</td>
<td>No operation</td>
</tr>
<tr>
<td>1</td>
<td>01</td>
<td>SEC</td>
<td>IMP</td>
<td>Set carry</td>
</tr>
<tr>
<td>2</td>
<td>02</td>
<td>SEI</td>
<td>IMP</td>
<td>Set interrupt flag</td>
</tr>
<tr>
<td>3</td>
<td>03</td>
<td>MLH</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>$A = \text{high tryte}(A \times \text{memory})$</td>
</tr>
<tr>
<td>4</td>
<td>04</td>
<td>MLL</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>$A = \text{low tryte}(A \times \text{memory})$</td>
</tr>
<tr>
<td>5</td>
<td>1D</td>
<td>DIV</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>$A = \text{integer}(\frac{A}{\text{memory}})$</td>
</tr>
<tr>
<td>6</td>
<td>1C</td>
<td>MOD</td>
<td>ACC, IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>$A = \text{remainder}(\frac{A}{\text{memory}})$</td>
</tr>
<tr>
<td>7</td>
<td>1B</td>
<td>PLX</td>
<td>IMP</td>
<td>Pull X from stack</td>
</tr>
<tr>
<td>8</td>
<td>1A</td>
<td>PLY</td>
<td>IMP</td>
<td>Pull Y from stack</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>PHX</td>
<td>IMP</td>
<td>Push X to stack</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>PHY</td>
<td>IMP</td>
<td>Push Y to stack</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>JCC</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if carry is clear</td>
</tr>
<tr>
<td>12</td>
<td>13</td>
<td>JCT</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if carry is positive</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>JCF</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if carry is negative</td>
</tr>
<tr>
<td>14</td>
<td>2D</td>
<td>JEQ</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if comparison flag is clear</td>
</tr>
<tr>
<td>15</td>
<td>2C</td>
<td>JNE</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if comparison flag isn’t clear</td>
</tr>
<tr>
<td>16</td>
<td>2B</td>
<td>JLT</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if comparison flag is negative</td>
</tr>
<tr>
<td>17</td>
<td>2A</td>
<td>JGT</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if comparison flag is positive</td>
</tr>
<tr>
<td>18</td>
<td>20</td>
<td>JVC</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if overflow is clear</td>
</tr>
<tr>
<td>19</td>
<td>21</td>
<td>JVS</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Jump if overflow is set</td>
</tr>
<tr>
<td>20</td>
<td>22</td>
<td>IVC</td>
<td>IMP</td>
<td>Invert carry flag</td>
</tr>
<tr>
<td>21</td>
<td>23</td>
<td>PRM</td>
<td>IMM, ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Permute value (tritwise add 1)</td>
</tr>
<tr>
<td>22</td>
<td>24</td>
<td>TSH</td>
<td>IMM, ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>PRM without roll over</td>
</tr>
<tr>
<td>23</td>
<td>3D</td>
<td>BUT</td>
<td>IMM, ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>A BUT Value</td>
</tr>
<tr>
<td>24</td>
<td>3C</td>
<td>LAD</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Load Address into X:Y</td>
</tr>
<tr>
<td>25</td>
<td>3B</td>
<td>PGT</td>
<td>IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Copy contents of page A to page mem</td>
</tr>
<tr>
<td>26</td>
<td>3A</td>
<td>PGS</td>
<td>IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Set contents of page A to mem</td>
</tr>
<tr>
<td>27</td>
<td>30</td>
<td>CAD</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY</td>
<td>Compare X:Y with argument address</td>
</tr>
<tr>
<td>28</td>
<td>31</td>
<td>XAM</td>
<td>IMM, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>Exchange A with memory value</td>
</tr>
<tr>
<td>29</td>
<td>32</td>
<td>XAX</td>
<td>IMP</td>
<td>Exchange A with X</td>
</tr>
<tr>
<td>30</td>
<td>33</td>
<td>XAY</td>
<td>IMP</td>
<td>Exchange A with Y</td>
</tr>
<tr>
<td>31</td>
<td>34</td>
<td>XYX</td>
<td>IMP</td>
<td>Exchange X with Y</td>
</tr>
<tr>
<td>32</td>
<td>4D</td>
<td>PLC</td>
<td>IMM, ACC, ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>A/M Commutative operation from stack</td>
</tr>
<tr>
<td>33</td>
<td>4C</td>
<td>ADW</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>12 trit addition</td>
</tr>
<tr>
<td>34</td>
<td>4B</td>
<td>MLW</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>12 trit multiplication</td>
</tr>
<tr>
<td>35</td>
<td>4A</td>
<td>DVW</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>12 trit division</td>
</tr>
<tr>
<td>36</td>
<td>40</td>
<td>MDW</td>
<td>ABS, ABSX, ABSY, IND, INDX, INDY, X, Y</td>
<td>12 trit modulo</td>
</tr>
<tr>
<td>37</td>
<td>41</td>
<td>RESV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>42</td>
<td>RESV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>43</td>
<td>PAUSE</td>
<td></td>
<td>PAUSE</td>
</tr>
<tr>
<td>40</td>
<td>44</td>
<td>DEBUG</td>
<td></td>
<td>DEBUG</td>
</tr>
</tbody>
</table>

APPENDIX A. TUNGUSKA SPECIFICATIONS
APPENDIX A. TUNGUSKA SPECIFICATIONS

A.3 Reserved addresses

The following memory addresses have special functionality, and should not be used for general purpose code or data storage.

<table>
<thead>
<tr>
<th>Address range</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDD:DDD/D/C</td>
<td>IRQ, IRQ data</td>
</tr>
<tr>
<td>DDD:DDB</td>
<td>Screen mode</td>
</tr>
<tr>
<td>DDD/DDA</td>
<td>Disk I/O</td>
</tr>
<tr>
<td>DDD:DDD0</td>
<td>AGDP Operation</td>
</tr>
<tr>
<td>DDD:DDD1/2</td>
<td>AGDP Register 1</td>
</tr>
<tr>
<td>DDD:DDD3/4</td>
<td>AGDP Register 2</td>
</tr>
<tr>
<td>DDD:DCD/C</td>
<td>AGDP Register 3</td>
</tr>
<tr>
<td>DDC:DDD-DDC:444</td>
<td>Stack</td>
</tr>
<tr>
<td>DDB:DDD-DDA444</td>
<td>Screen buffer, text mode</td>
</tr>
<tr>
<td>DDB:DDD-DDB:444</td>
<td>Screen buffer, vector mode</td>
</tr>
<tr>
<td>DDB:DDD-CAB:444</td>
<td>Screen buffer, raster mode</td>
</tr>
<tr>
<td>444:441</td>
<td>Clock interrupt interval (^1)</td>
</tr>
<tr>
<td>444:442/3</td>
<td>Interrupt handler vector</td>
</tr>
</tbody>
</table>

A.3.1 Screen

The Screen Mode tryte (DDD:DDB) has the following function

<table>
<thead>
<tr>
<th>MST</th>
<th>RES</th>
<th>RES</th>
<th>Aux graphics mode</th>
<th>Graphics mode</th>
<th>Redraw</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST</td>
<td>RES</td>
<td>RES</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Screen redraws when Redraw is set to 1, and allowed graphics mode are raster(-1), text (0) and vector (1).

A.3.1.1 Vector mode

Vector mode only uses the first page of the screen buffer (that is, DDB:DDB/444), and stores vector information in sets of three trytes (allowing for a total of 121 interconnected lines in 729 colors). They are drawn in succession, and black lines are not painted (there won’t be black spots where black lines intersect visible ones.)

\[
\begin{array}{cccc}
\text{MST} & \text{LST} \\
\text{First tryte} & \text{MRed} & \text{LRed} & \text{MGreen} & \text{LGreen} & \text{MBlue} & \text{LBlue} \\
\text{Second tryte} & \text{UNUSED} & \text{X} & \text{Coo} & \text{-rdi} & \text{-na} & \text{-te} \\
\text{Third tryte} & \text{UNUSED} & \text{Y} & \text{Coo} & \text{-rdi} & \text{-na} & \text{-te} \\
\end{array}
\]

A.3.1.2 Raster mode

Raster mode resolution is 324x243\(^2\) and uses a total of 108 memory pages, with two color depths:

- One pixel per tryte, allowing for a total of 729 colors. They are encoded like in the first tryte in vector mode above, addressed according to (1).

\[
T(x, y) = DDBDDD_9b + 324y + x \quad (A.1)
\]

- One trit per pixel, allowing for a total of three gray light intensities, memory addressed according to (2), color intensity specified by (3):

\[
T(x, y) = DDBDDD_9b + 54y + \left\lfloor \frac{x}{6} \right\rfloor \quad (A.2)
\]

\(^1\)Don’t set it to zero or less, unpredictable behavior will ensue

\(^2\)Observant people will notice that this is 400b\(_{10}\)x300b\(_{10}\)
APPENDIX A. TUNGUSKA SPECIFICATIONS

\[ R(x) = x \mod 6 \] 

(A.3)

A.3.1.3 Text mode

Text mode resolution is 27 rows by 54 columns (2 memory pages). Visible and control characters are in the range 0..99, and arranged in the following fashion:

<table>
<thead>
<tr>
<th>x0</th>
<th>x1</th>
<th>x2</th>
<th>x3</th>
<th>x4</th>
<th>x5</th>
<th>x6</th>
<th>x7</th>
<th>x8</th>
<th>x9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x</td>
<td>NUL</td>
<td>BS</td>
<td>NL</td>
<td>RES</td>
<td>RES</td>
<td>RES</td>
<td>RES</td>
<td>RES</td>
<td>RES</td>
</tr>
<tr>
<td>1x</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
<td>H</td>
<td>I</td>
</tr>
<tr>
<td>2x</td>
<td>K</td>
<td>L</td>
<td>M</td>
<td>N</td>
<td>O</td>
<td>P</td>
<td>Q</td>
<td>R</td>
<td>S</td>
</tr>
<tr>
<td>3x</td>
<td>U</td>
<td>V</td>
<td>W</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4x</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>.</td>
<td>,</td>
<td>!</td>
</tr>
<tr>
<td>5x</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
<td>f</td>
<td>g</td>
<td>h</td>
<td>i</td>
</tr>
<tr>
<td>6x</td>
<td>k</td>
<td>l</td>
<td>m</td>
<td>n</td>
<td>o</td>
<td>p</td>
<td>q</td>
<td>r</td>
<td>s</td>
</tr>
<tr>
<td>7x</td>
<td>u</td>
<td>v</td>
<td>w</td>
<td>x</td>
<td>y</td>
<td>z</td>
<td>BB</td>
<td>BB</td>
<td>BB</td>
</tr>
<tr>
<td>8x</td>
<td>BB</td>
<td>BB</td>
<td>BB</td>
<td>BB</td>
<td>BB</td>
<td>BB</td>
<td>=</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>9x</td>
<td>%</td>
<td>&lt;</td>
<td>&gt;</td>
<td>( \leq )</td>
<td>( \geq )</td>
<td>(</td>
<td>)</td>
<td>$</td>
<td>+</td>
</tr>
</tbody>
</table>

Symbol | Description
---|---
NUL | Null
BS | Back space
NL | New line
RES | Reserved
BB | Graphical block

A.4 Interrupts

<table>
<thead>
<tr>
<th>IRQ</th>
<th>Function</th>
<th>IRQ data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Keypress interrupt</td>
<td>Key</td>
</tr>
<tr>
<td>1</td>
<td>Clock interrupt</td>
<td>Random value</td>
</tr>
<tr>
<td>2</td>
<td>Keyboard break sent</td>
<td>undef.</td>
</tr>
<tr>
<td>3</td>
<td>Arithmetic error</td>
<td>undef.</td>
</tr>
<tr>
<td>4</td>
<td>Soft interrupt</td>
<td>undef.</td>
</tr>
<tr>
<td>5</td>
<td>Mouse motion</td>
<td>relative X : relative Y</td>
</tr>
<tr>
<td>6</td>
<td>Mouse event</td>
<td>click = 1, release = -1</td>
</tr>
</tbody>
</table>

Interrupts cause the system to push all registers onto stack, and jump to the Interrupt Service Routine (ISR), whose location is stored in 444:442/3. Arguments to the ISR are stored in two memory locations, IRQ and IRQDATA, DDD:DDD and DDD:DDC respectively. Interrupts are queued if the I-flag is set, or there already is an interrupt being processed.

An important interrupt is the clock interrupt, it is raised whenever the CL register (which increments with every cycle), exceeds the value stored at 444:441. The RTI instruction is used to properly return from an ISR.
A.5 Disk I/O

Tunguska features a floppydisk-like virtual disk drive. It is controlled through the Disk I/O tryte (DDD:DDA). It is the same size as the main memory \( (729^2 \text{ trytes}) \). All data transfer is on the block level, and block size is 729 trytes. The following operations are allowed:

<table>
<thead>
<tr>
<th>Name</th>
<th>Number</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOOP</td>
<td>0</td>
<td>Idle</td>
</tr>
<tr>
<td>READ</td>
<td>1</td>
<td>Read from disk to memory</td>
</tr>
<tr>
<td>WRITE</td>
<td>2</td>
<td>Write from memory to disk</td>
</tr>
<tr>
<td>SYNC</td>
<td>3</td>
<td>Write from virtual disk to physical file</td>
</tr>
<tr>
<td>SEEK</td>
<td>4</td>
<td>Set disk position to page</td>
</tr>
<tr>
<td>GETPOS</td>
<td>5</td>
<td>Get disk position</td>
</tr>
</tbody>
</table>

SEEK and GETPOS use the accumulator as input. Data is read to and from memory page specified by the Y register.

The disk image format is \( 729^2 \) consecutive 16 bit short integers, each storing a single memory cell. To save space, the images are compressed with zlib.

A.6 Auxiliary General Data Processor (AGDP)

The AGDP offers block operations and floating point arithmetics. It has three 12 trit registers, AGDP R1-R3; and one memory position that determines it’s operation.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Number</th>
<th>Function</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOOP</td>
<td>0</td>
<td>Nothing</td>
<td>-</td>
</tr>
<tr>
<td>ITOF</td>
<td>1</td>
<td>Convert Integer to Float</td>
<td>R1 -&gt; R1</td>
</tr>
<tr>
<td>FTOI</td>
<td>2</td>
<td>Convert Float to Integer</td>
<td>R1 -&gt; R1</td>
</tr>
<tr>
<td>FADD</td>
<td>3</td>
<td>Add two float numbers</td>
<td>R1, R2 -&gt; R1</td>
</tr>
<tr>
<td>FMUL</td>
<td>4</td>
<td>Multiply two float numbers</td>
<td>R1, R2 -&gt; R1</td>
</tr>
<tr>
<td>FDIV</td>
<td>5</td>
<td>Divide two float numbers</td>
<td>R1, R2 -&gt; R1</td>
</tr>
<tr>
<td>FEXP</td>
<td>6</td>
<td>Exponent of R1</td>
<td>R1 -&gt; R1</td>
</tr>
<tr>
<td>FLOG</td>
<td>7</td>
<td>Natural logarithm of R1</td>
<td>R1 -&gt; R1</td>
</tr>
<tr>
<td>FCOS</td>
<td>8</td>
<td>Cosine of R1</td>
<td>R1 -&gt; R1</td>
</tr>
<tr>
<td>FSIN</td>
<td>9</td>
<td>Sine of R1</td>
<td>R1 -&gt; R1</td>
</tr>
<tr>
<td>BLT</td>
<td>10</td>
<td>Block transfer R1 to R2</td>
<td>Length R3</td>
</tr>
<tr>
<td>BLS</td>
<td>11</td>
<td>Block set R1 to val R2+1</td>
<td>R2+1-&gt;R1:(R1+R3)</td>
</tr>
<tr>
<td>BLA*</td>
<td>12</td>
<td>Blockwise AND R1 vs. R2</td>
<td>Length R3</td>
</tr>
<tr>
<td>BLX*</td>
<td>13</td>
<td>Blockwise XOR R1 vs. R2</td>
<td>Length R3</td>
</tr>
<tr>
<td>BLO*</td>
<td>14</td>
<td>Blockwise OR R1 vs. R2</td>
<td>Length R3</td>
</tr>
<tr>
<td>BSH*</td>
<td>15</td>
<td>Blockwise “TSH” R1 vs. R2</td>
<td>Length R3</td>
</tr>
<tr>
<td>BLP**</td>
<td>16</td>
<td>Blockwise “PRM” R1 vs. R2</td>
<td>Length R3</td>
</tr>
<tr>
<td>WHEN</td>
<td>17</td>
<td>First six fields of struct tm is inserted in R1:R3</td>
<td>-</td>
</tr>
</tbody>
</table>

* Overlap undefined.

A.7 Floating point

Tunguska has support for the equivalent of half-precision floating point numbers, with base 3, a \([-40,40]\) range exponent, and \([-3280, 3280]\) range significand. Where the numbers are packed in two trits in the following fashion.

\[
\begin{array}{cccccc}
\text{MST} & \text{LST} & \text{MST} & \text{LST} \\
E & E & E & E & S & S & S & S & S & S & S & S
\end{array}
\]

The mathematics are more or less identical to binary floating point, the only significant difference is
that there is no need for bias or a sign bit (sign is determined by the significand \( S \)). The mathematics
behind it is as follows.

\[
F = S \cdot 3^E \tag{A.4}
\]

\[
S = F \cdot 3^{-E} \tag{A.5}
\]

\[
E = \left\lfloor \frac{\ln |F|}{\ln 3} \right\rfloor \tag{A.6}
\]

A.8  Notes for 6502 programmers

There are some major differences between the 6502 and this machine. Beyond the obvious differences in
endianess, and processor status flag, some instructions have changed. PHA is replaced by a general
purpose PSH (“PHA A” will replicate the behavior of PHA), that will push any memory value onto
the stack. PLL is it’s respective pull operation. ADC has changed name to ADD with no change in
functionality. RTS has changed name to RST with no change in functionality.

X:Y addressing is a new mode that uses both the X and Y register to address a memory location.
The LAD operator is a quick way to transfer a complex memory location onto X:Y (compare with
the x86 “LEA” operation). Tunguska has an address comparison operation CAD that compares the
argument with X:Y, and sets flags accordingly.

Branching has been abandoned, use jumps instead. The same behavior can be acheived with the
$\$\$-token.

There is also a series of convenience operations XAM, XAX, XAY, XYX that serve to swap the
contents of registers or memory in one atomic instruction.

A.9  Debugging

Tunguska operates some built-in debugging facilities, mainly the DEBUG instruction which prints the
contents of all registers to stdout, and the PAUSE instruction which acts like a breakpoint and halts
execution at a specific point in the code, to allow for instruction stepping with the F11 key (execution
is resumed by pressing the Pause key.)
Appendix B

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