

Baby42

A simple RISC processor

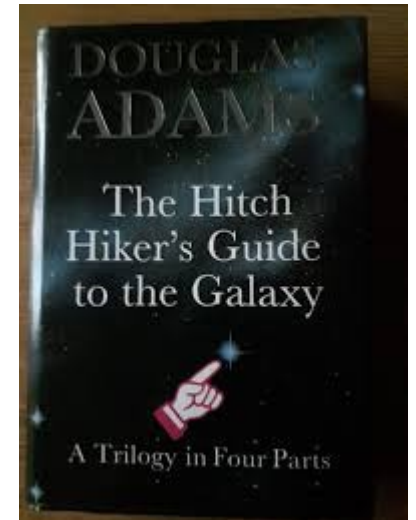
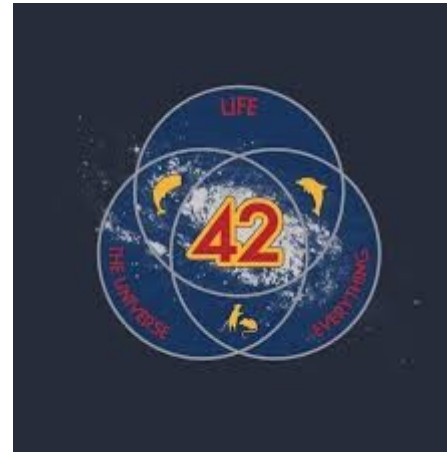
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name



- The Manchester Baby (Small-Scale Experimental Machine – SSEM) ran a stored memory program in June 1948

- 4 bytes (32 bits) of data with 2 bytes of instruction
- And:



state

General purpose
registers

Program Counter

	31	24	23	16	15	8	7	0
r15	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r14	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r13	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r12	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r11	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r10	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r9	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r8	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r7	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r6	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r5	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r4	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r3	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r2	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r1	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
r0	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

31	24	23	16	15	8	7	0
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

17 words = 68 bytes =
136 hexadecimal digits
+ external memory

Manchester Baby: 3 registers
+ 32 words of memory of 32
bits each

RISC style

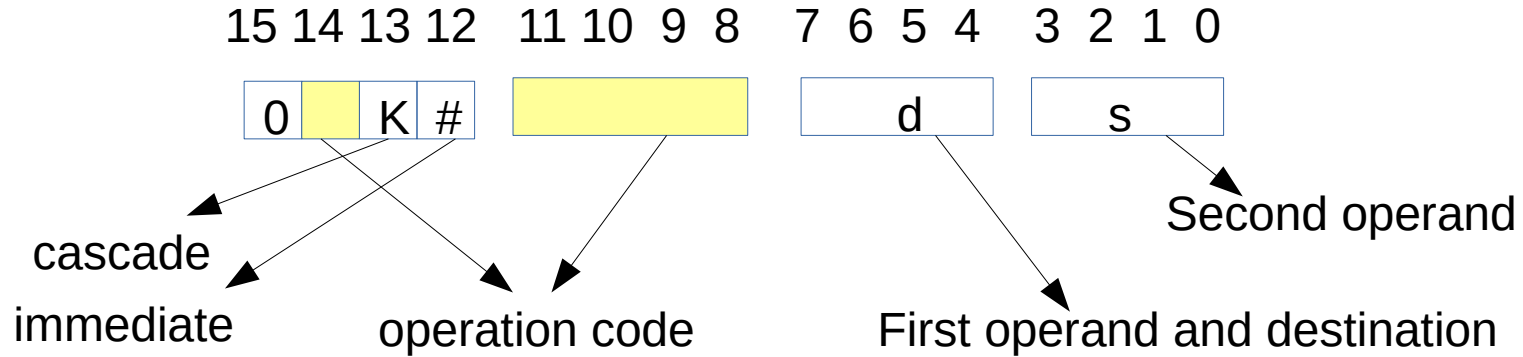
Two instruction formats:

- Data manipulation instructions only operate on registers, or a register and an immediate value present in the instruction itself
- Data storage transfer a register to/from memory (jump and link has the same format, though it should be considered a third kind of instruction)

RISC: how many instructions?

- Counting all variations in assembly syntax we have 106 standard instructions and 12 optional ones (multiplication)
- Not counting the variations we have 30 standard instructions and 3 optional ones
- The control unit deals with only five instruction types:
 - 1)ALU (Math, Logic and Multiply)
 - 2)Comparison
 - 3)Load
 - 4)Store
 - 5)Jump and Link

Data Manipulation Instructions



30 of the 32 possible op codes are used, but due to # and K nearly all instructions have 4 variations.

The assembly language syntax is C-like, with an addition being indicated by

`rD += rS`

- Immediate values

"immediate" changes the second operand to be a number from -6 to 7 instead of a register. The value -7 (9 in hex) indicates that the actual operand is the next 32 bits and -8 (8 in hex) indicates 16 bits

In assembly, a # character is placed before the second operand to indicate that it is an immediate. Otherwise the numbers 0 to 15 indicate a register.

K - Cascade

"cascade" changes the destination to be the first operand of the following instruction. A sequence like

```
r3 <<= #2 ; multiply by four  
r3 += r1
```

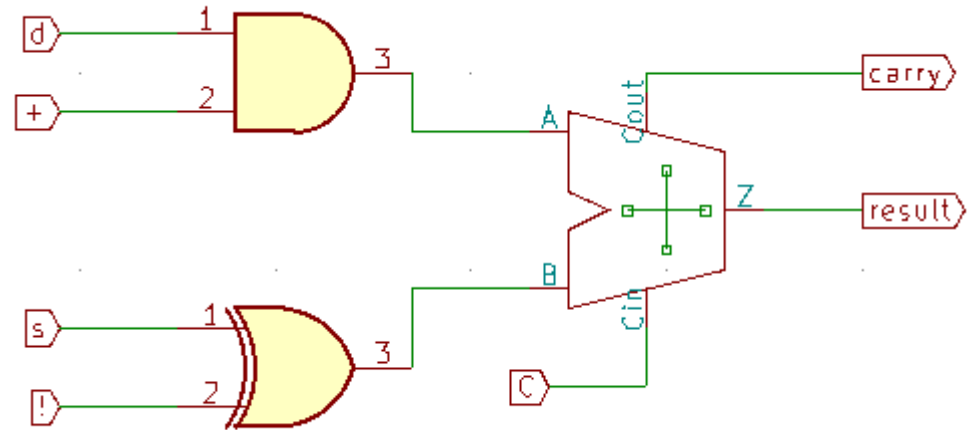
can be implemented with cascade as

```
r5 = {r3 << #2} + r1
```

Unlike the original code fragment, these two instructions don't destroy the value in r3. So though the architecture is a two address in general, it can have the functionality of three addresses (actually four) when needed. The second instruction's syntax is changed from "d op= s" to "d = {..} op s" and the cascaded instruction is placed in the curly brackets also in infix form. It is possible to have more than one level of cascade, but then the d field of intermediate instructions is wasted.

Math: op code is 0 0+!C

- + means that the destination is added to the source
- ! means that the source is bitwise inverted (one's complement)
- C means that the carry in is set

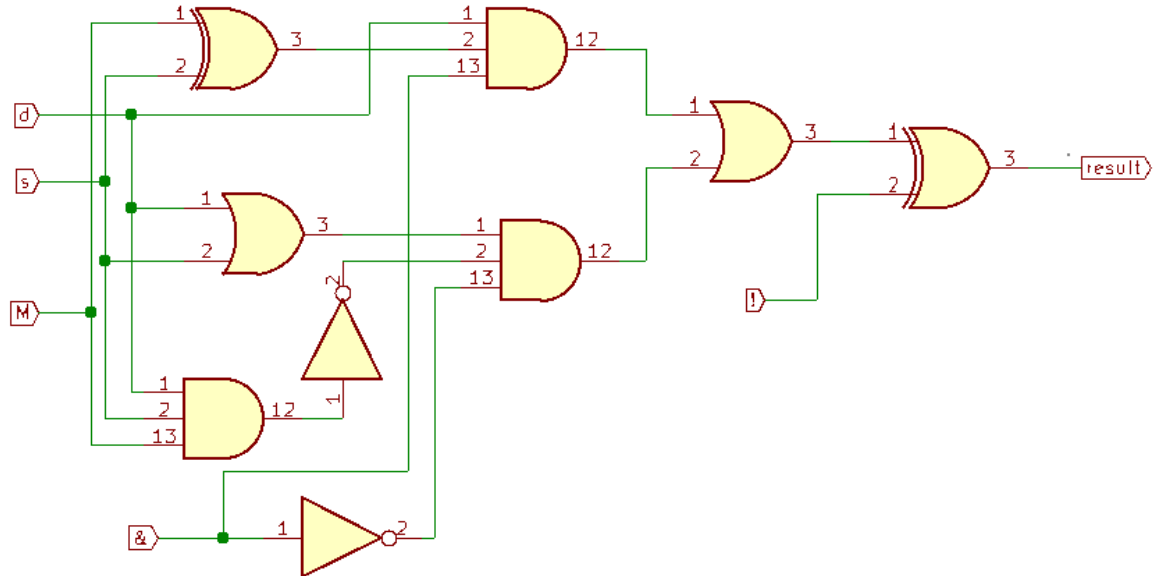


Math

		0?ds	1?ds	2?ds	3?ds
?0ds	move	$d = s$	$d = \#s$		
?1ds	increment	$d = s+1$	$d = \#s+1$		
?2ds	invert	$d = !s$	$d = !\#s$		
?3ds	negate	$d = \sim s$	$d = \sim \#s$		
?4ds	add	$d += s$	$d += \#s$	$\{d + s\}$	$\{d + \#s\}$
?5ds	add forcing carry	$d += s+1$	$d += \#s+1$	$\{d + s+1\}$	$\{d + \#s+1\}$
?6ds	subtract forcing borrow	$d -= s-1$	$d -= \#s-1$	$\{d - s-1\}$	$\{d - \#s-1\}$
?7ds	subtract	$d -= s$	$d -= \#s$	$\{d - s\}$	$\{d - \#s\}$

Logic: op code is 0 1&!M

- & means an AND operation, otherwise it is an OR
- ! means that output is bitwise inverted (one's complement)
- M means a modified version of the instruction



Logic (the 4 bits are !s!d s!d !sd sd)

		0?ds	1?ds	2?ds	3?ds
?8ds	0111 or	$d \mid= s$	$d \mid= \#s$	$\{d \mid s\}$	$\{d \mid \#s\}$
?9ds	0110 exclusive or	$d \wedge= s$	$d \wedge= \#s$	$\{d \wedge s\}$	$\{d \wedge \#s\}$
?Ads	1000 nor	$d \nmid= s$	$d \nmid= \#s$	$\{d \nmid s\}$	$\{d \nmid \#s\}$
?Bds	1001 equivalence	$d \nmid \wedge= s$	$d \nmid \wedge= \#s$	$\{d \nmid \wedge s\}$	$\{d \nmid \wedge \#s\}$
?Cds	0001 and	$d \&= s$	$d \&= \#s$	$\{d \& s\}$	$\{d \& \#s\}$
?Dds	0010 and invert	$d \& \nmid= s$	$d \& \nmid= \#s$	$\{d \& \nmid s\}$	$\{d \& \nmid \#s\}$
?Eds	1110 nand	$d \nmid \&= s$	$d \nmid \&= \#s$	$\{d \nmid \& s\}$	$\{d \nmid \& \#s\}$
?Fds	1101 nand invert	$d \nmid \& \nmid= s$	$d \nmid \& \nmid= \#s$	$\{d \nmid \& \nmid s\}$	$\{d \nmid \& \nmid \#s\}$

Logic: remaining rules

0000 clear	10d0	$d = \#0$
0011 destination	00dd	$d = d$
0100 other and invert	2Edd 0Cds	$d = \{d \text{ !\& } d\} \text{ \& } s$
0101 source	00ds	$d = s$
1010 not source	02ds	$d = !s$
1011 other nand invert	2Edd 0Eds	$d = \{d \text{ !\& } d\} \text{ !\& } s$
1100 not destination	02dd	$d = !d$
1111 set	10dF	$d = \#-1$

Shift: op code is 1 00\$<

		4?ds	5?ds	6?ds	7?ds
?0ds	shift right	d >>= s	d >>= #s	{d >> s}	{d >> #s}
?1ds	shift left	d <<= s	d <<= #s	{d << s}	{d << #s}
?2ds	signed shift right	d \$>>= s	d \$>>= #s	{d \$>> s}	{d \$>> #s}
?3ds	rotate left	d <>= s	d <>= #s	{d <> s}	{d <> #s}

$a = "<" ? s : 32 - s$
 $x = ("\$" \& !"<") \& 32\{d[31]\}$
 $z[63:0] = \{x, d\} << a$
 $result = (z[31:0] \& "<") \mid (z[63:32] \& !(!"\$" \& "<"))$

Barrel shifter: $x[63:0] << a[4:0]$
 $z0[63:0] = a[0] ? \{x[62:0], 0\} : x$
 $z1[63:0] = a[1] ? \{z0[61:0], 2\{0\}\} : z0$
 $z2[63:0] = a[2] ? \{z1[59:0], 4\{0\}\} : z1$
 $z3[63:0] = a[3] ? \{z2[55:0], 8\{0\}\} : z2$
 $z[63:0] = a[4] ? \{z3[47:0], 16\{0\}\} : z3$

Multiply (optional)

		4?ds	5?ds	6?ds	7?ds
?4ds	multiply high	d *= s	d *= #s	{d * s}	{d * #s}
?5ds	multiply low	d *>= s	d *>= #s	{d *> s}	{d *> #s}
?6ds	multiply signed high	d \$*= s	d \$*= #s	{d \$* s}	{d \$* #s}
?7ds					

unsigned

signed

4 bit examples
with 8 bit
result:

hex (decimal)

4 (4)
x F (15)

3C (60)

C (12)
x F (15)

B4 (180)

4 (4)
x F (-1)

FC (-4)

C (-4)
x F (-1)

04 (4)

Comparison (calculation)

Greater than
d-s ==> !z&c

Equal
d-s ==> z

Greater than or equal
d-s ==> c

Not equal
d-s ==> !z

Signed greater than
d-s ==> !z&(n!^v)

Carry on add
d+s ==> c

Signed greater than or equal
d-s ==> n!^v

c = result[32]
z = !(\\result)
n = result[31]
v = (n&!d[31]&!s[31]) | (!n&d[31]&s[31])

Comparison

		4?ds	5?ds	6?ds	7?ds
?8ds	Greater than	$d > s ? \dots$	$d > \#s ? \dots$	$\{d > s\}$	$\{d > \#s\}$
?9ds	Greater or equal	$d \geq s ? \dots$	$d \geq \#s ? \dots$	$\{d \geq s\}$	$\{d \geq \#s\}$
?Ads	Signed greater than	$d \$> s ? \dots$	$d \$> \#s ? \dots$	$\{d \$> s\}$	$\{d \$> \#s\}$
?Bds	Signed greater or equal	$d \$\geq s ? \dots$	$d \$\geq \#s ? \dots$	$\{d \$\geq s\}$	$\{d \$\geq \#s\}$
?Cds	Equal	$d == s ? \dots$	$d == \#s ? \dots$	$\{d == s\}$	$\{d == \#s\}$
?Dds	Not equal	$d != s ? \dots$	$d != \#s ? \dots$	$\{d != s\}$	$\{d != \#s\}$
?Eds	Carry on add	$d ++ s ? \dots$	$d ++ \#s ? \dots$	$\{d ++ s\}$	$\{d ++ \#s\}$
?Fds					

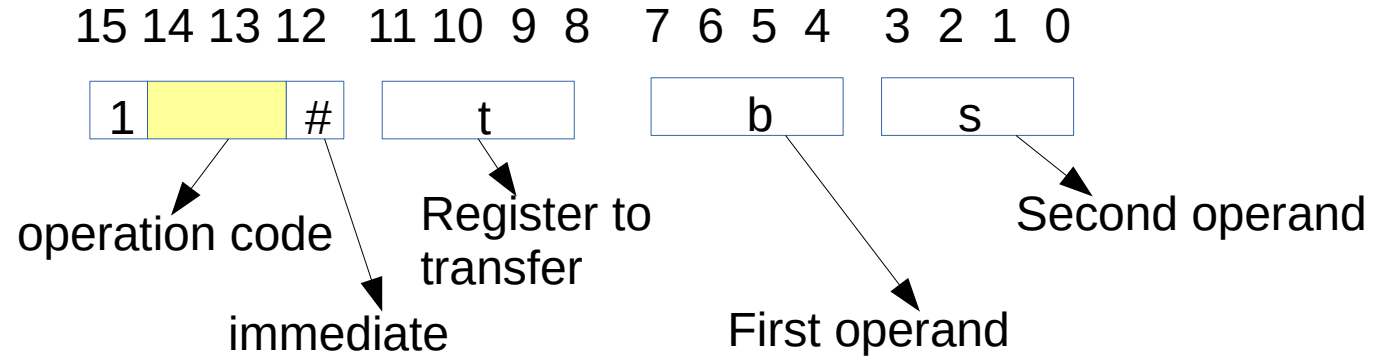
Comparison (trivia)

The comparison instructions will produce a 0 or a 1 result for the next instruction when cascade is used or will skip the next instruction in the normal case when the comparison fails (note that d is not modified)

Note that a comparison that wants less than results can use greater than and swap the operands. This doesn't work if the second operand is an immediate value, but since "if (r3<200) x1 else x2" does the same thing as "if (r3>=200) x2 else x1" it is normally not a problem.

The "d >= s" instruction can be used as a "borrow on subtract" to complement the "d ++ s" (carry on add) instruction.

Data Storage Instructions



Store	8tbs	$b[s] = t$	9tbs	$b[\#s] = t$
Load	Atbs	$t = b[s]$	Btbs	$t = b[\#s]$
Jump and Link	Ctbs	$====> b[s]/t$	Dtbs	$====> b[\#s]/t$
	E???		F???	

Jump and Link

In the case of JL the t register will hold the previous value of the PC (unless t is 15, in which case the old value of the PC is discarded. "/t" can be omitted).

CFbs ====> b[s]
DFbs ====> b[#s]

The new value of the PC will be the sum of b and s (unless b is 15, in this case it will be the sum of s and the previous value of the PC. The "b" can be omitted).

CtFs ====> [s]/t
DtFs ====> [#s]/t
CFFs ====> [s]
DFFs ====> [#s]

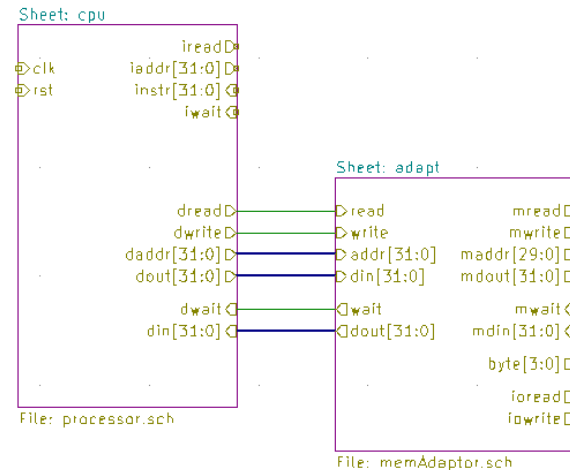
Syntactic sugar for the assembler allows "====> label" and "====> label/t" to be written in place of "====> [#label-.]" and "====> [#label-.]/t" respectively.

Bytes 1: Load/Store Adapter

Baby42 natively only transfers 32 bit words to and from memory. It is possible to have an adapter circuit between the processor and memory/cache to make 16 and 8 bit transfers possible, as well as allowing non aligned 32 bit transfers (addresses that are not a multiple of 4).

Bits 31 and 30 of an address indicate the size of the data to be fetched or stored while the rest of the address points to one of 1G bytes:

- 00 = 8 bit value
- 01 = 16 bit value
- 10 = 32 bit value
- 11 = I/O (32 bit value)



Bytes 2: Store byte instruction

```
        ; code to load a byte from memory
Loadb:
        ; r1 is the address
        ; r2 is the destination
        ; r3 is scratch
r2 = r1[#0]
r3 = {r1 & #3} << #3
r2 = {r2 >> r3} & #255
```

This isn't too bad. If we redefine load to rotate the word it read on a non aligned address then just two instructions would be needed:

```
        ; code to load a byte from memory
Loadb:
r2 = r1[#0] ; might be rotated
r2 &= #255
```

```
        ; code to store a byte to memory
Storeb:
        ; r1 is the address
        ; r2 is the byte to be stored
        ; r3 and r4 are scratch
r4 = r1[#0] ; previous word
r3 = {r1 & #3} << #3
r2 &= #255 ; make sure it is a byte
r5 = #255
r5 <<= r3
r4 &~= r5 ; clear destination byte
r4 = {r2 << r3} | r4
r1[#0] = r4
```

We could define the remaining data storage instruction to be a store byte:

```
        ; code to store a byte to memory
Storeb:
r1[#0] B= r2
```

Assembly language directives: define

Symbols can be defined by

name: expression

A period character in an expression indicates the value of the PC for that instruction. An empty expression is equivalent to just a period, so is equivalent of defining a label in other assemblers. This means that labels must be on a line of their own instead of coming before an instruction.

Assembly language directives: origin

The value of the PC can be changed with

`% expression`

This is equivalent of "org" in other assemblers. If 120 bytes need to be allocated, then "`% .+120`" will do the job.

Instructions should always be aligned on an even byte. This expression can force that to be the case:

`% ((.+1)/2)*2`

Assembly language directives: constants

Constants can be inserted into the instruction stream with

`# expr1, expr2, expr3, B# expr4, expr5, H# expr6, # expr7, expr8`

The `#` interprets the following expressions as 32 bit values, while `B#` inserts 8 bit values and `H#` 16 bit values.

Placing ASCII characters between two `"` has the same effect as `B#` followed by the list of the characters' numeric value.

Example 1

Jan Gray used this simple C program to illustrate the assembly language of his XR16 processor (<http://www.fpgacpu.org/papers/xsoc-series-drafts.pdf>)

```
typedef struct TN {
    int k;
    struct TN *left, *right;
} *T;

T search(int key, T p) {
    while (p && p->k != key)
        if (p->k < key)
            p = p->right;
        else
            p = p->left;
    return p;
}
```

; Example 1 Baby42 machine language and assembly with LCC style

k: 0

left: 4

right: 8

search: ; r3=key r4=p r9=scratch r2=return

DFF8 000E ====> L3

L2:

B940 r9 = r4[#k]

4893 DFF6 r9 > r3 ? ====> L5

B448 0008 r4 = r4[#right]

DFF2 ====> L6

L5:

B444 r4 = r4[#left]

L6:

L3:

0094 r9 = r4

5C90 DFF8 0008 r9 == #0 ? ====> L7

B940 r9 = r4[#k]

4D93 DFF8 FFE2 r9 != r3 ? ====> L2

L7:

0024 r2 = r4

L1:

DFD0 ====> r13[#0] ; return address was in r13

```

; Example 1 Baby42 machine language and assembly with better compiler
;      that optimizes jumps to jumps and jumps to returns
k:      0
left:   4
right:  8

```

```

search: ; r3=key r4=p r9=scratch r4=return value
5C90 DFD0      r4 == #0 ? ====> r13[#0] ; return
B940          r9 = r4[#k]
5C93 DFD0      r9 == r3 ? ====> r13[#0]
4893 DFF8 0008  r3 > r9 ? ====> L5
B448 0008      r4 = r4[#right]
DFF8 FFE8      ====> search

L5:
B444          r4 = r4[#left]
DFF8 FFE2      ====> search

```

Example 2

Here is the famous Sieve of Eratosthenes benchmark published in Byte magazine:

```
1 SIZE = 8190
2 DIM FLAGS(8191)
3 PRINT "Only 1 iteration"
5 COUNT = 0
6 FOR I = 0 TO SIZE
7   FLAGS (I) = 1
8 NEXT I
9 FOR I = 0 TO SIZE
10  IF FLAGS (I) = 0 THEN 18
11  PRIME = I+I + 3
12  K = I + PRIME
13  IF K > SIZE THEN 17
14  FLAGS (K) = 0
15  K = K + PRIME
16 GOTO 13
17 COUNT = COUNT + 1
18 NEXT I
19 PRINT COUNT," PRIMES"
```

	size: 8190		
	true: r10		
	false: r11		
	flags: r12		
	flg:		
???? .. ??	% .+8191	DDF8 ????	====> PrintText/r13
	count: r1		; library subroutine expects
	i: r2		; return address in r13
	prime: r3	1010	count = #0
	k: r4	1020	i = #0
	text1:		for1:
4F 6E6C	"Only 1 iteration", B# 0	5828 1FFE	i > #size ? ====> endfor1
7920 3120		DFF8 0008	
6974 6572		8AC2	flags[i] = true
6174 696F		1421	i += #1
6E00		DFF8 FFF0	====> for1
	text2:		endfor1:
2050 5249	" PRIMES", B# 0	1020	i = #0
4D45 5300			for2:
	sieve:		i > #size ? ====> endfor2
10C0	flags = #flg	5828 1FFE	
10A1	true = #1	DFF8 0028	
10B0	false = #0	A5A2	r5 = flags[i]
1008 1FFF	r0 = #text1	5C50 DFF8	r5 == #0 ? ====> L18
		001A	
		2422 1433	prime = {i+i} + #3
		2423 1440	k = {i + prime} + #0

```

L13:
5848 1FFE      k > #size ? ====> L17
DFF8 0008
8BA4          flags[k] = false
0443          k += prime
DFF8 FFF0      ====> L13

L17:
1411          count += #1

L18:
1421          i += #1
DFF8 FFD0      ====> for2
endfor2
0001          r0 = count
DDF8 ????      ====> PrintInt/r13
1008 2010      r0 = #text2
DDF8 ????      ====> PrintText/r13
DFF8 ????      ====> Stop

```

There is also a C version of the benchmark in the Wikipedia article (https://en.wikipedia.org/wiki/Byte_Sieve). But Basic, specially a version as primitive as this, corresponds a lot more directly to the assembly language implementation.

Normally code that calls other subroutines should save the return address on the stack, but in this case we end with a jump instead of a return.

Since the address of flags happens to be 0 (it is a byte pointer), it would be possible to use "i[#FLG]" in the load and store instructions instead of "flag[i]", which would save one register. But that is not something that would normally happen, so it wasn't used in this example either.

Example 3: ARM and Baby42

```
AREA LOG, CODE, READONLY
EXPORT log
; r0 = input variable n
; r0 = output variable m (0 by default)
; r1 = output variable k ( $n \leq 2^k$ )
```

Log

```
MOV r2, #0 ; set m = 0
```

```
MOV r1, #-1 ; set k = -1
```

log_loop

```
TST r0, #1 ; test LSB(n) == 1
```

```
ADDNE r2, r2, #1 ; set m = m+1 if true
```

```
ADD r1, r1, #1 ; set k = k+1
```

```
MOVS r0, r0, LSR #1 ; set n =  $n \gg 1$ 
```

```
BNE log_loop ; continue if  $n \neq 0$ 
```

```
CMP r2, #1 ; test m == 1
```

```
MOVEQ r0, #1 ; set m = 1 if true
```

log_rtn

```
MOV pc, lr
```

END

40 bytes, hence Thumb

```
; AREA LOG, CODE, READONLY
```

```
; EXPORT log
```

```
; r0 = input variable n
```

```
; r0 = output variable m (0 by default)
```

```
; r1 = output variable k ( $n \leq 2^k$ )
```

Log:

```
r2 = #0 ; set m = 0
```

```
r1 = #-1 ; set k = -1
```

log_loop:

```
{r0 & #1} == #1 ? r2 += #1 ; test LSB(n) == 1
```

```
; set m = m+1 if true
```

```
r1 += #1 ; set k = k+1
```

```
r0 >>= #1 ; set n =  $n \gg 1$ 
```

```
r0 != #0 ? =====>log_loop ; continue if  $n \neq 0$ 
```

```
r2 == #1 ? r0 = #1 ; test m == 1
```

```
; set m = 1 if true
```

log_rtn:

```
=====>[lr]
```

26 bytes

What is missing?

- No floating point math
- No interrupts
- No exceptions (if the missing op codes are defined as either NOPs or redundant)
- No MMU (memory management unit) or supervisor mode
- No debug interface (JTAG or control panel)

Variation 1: baby22

- It is possible to have a 16 bit datapath so the processor would have both 2 byte instructions and 2 byte data. This is limited to 64KB of memory, but that is enough for many applications
- The only change from baby42 is that immediate value -7 does not indicate a 32 bit immediate

Variation 2: baby042

- Operating on groups of 6 bits instead of 8 bit bytes we could have 24 bit data and 12 bit instructions. It is more natural to use octal instead of hexadecimal numbers
- With 4 fewer bits in each instruction it would be better to have 8 registers instead of 16. Instead of a dedicated immediate bit, when the second operand is register 6 or 7 the actual value is a 24 or 12 bit immediate after the instruction.
- 0XDS: $d=s, ,$
- 1XDS: $d+=s, \{d+s\}, d+=s+1, \{d+s+s\}, d-=s-1, \{d-s-1\}, d-=s, \{d-s\}$
- 2XDS: $d|=s, \{d|s\}, d^+=s, \{d^+s\}, d\&s, \{d\&s\}, d!\&s, \{d!\&s\}$
- 3XDS: $d>>=s, \{d>>s\}, d<<=s, \{d<<s\}, d\$>>=s, \{d\$>>s\}, d<>=s, \{d<>=s\}$
- 4XDS: $d>s?, \{d>s\}, d>=s?, \{d>=s\}, d==s?, \{d==s\}, d!=s?, \{d!=s\}$
- 5TBS: $===> b[s]/t$
- 6TBS: $b[s] = t$
- 7TBS: $t = b[s]$