

# Fast Inverse Square Root

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## Instructor's Handout

This handout contains solutions and notes.  
Recompile without solutions before distributing.

## Section 1: Introduction

In 2005, ID Software published the source code of *Quake III Arena*, a popular game released in 1999. This caused quite a stir: ID Software was responsible for many games popular among old-school engineers (most notably *Doom*, which has a place in programmer humor even today).

Naturally, this community immediately began dissecting *Quake's* source. One particularly interesting function is reproduced below, with original comments:

```
float Q_rsqrt( float number ) {
    long i;
    float x2, y;
    const float threehalfs = 1.5F;

    x2 = number * 0.5F;
    y = number;
    i = * ( long * ) &y;           // evil floating point bit level hacking
    i = 0x5f3759df - ( i >> 1 );  // [redacted]
    y = * ( float * ) &i;
    y = y * ( threehalfs - ( x2 * y * y ) ); // 1st iteration
    // y = y * ( threehalfs - ( x2 * y * y ) ); // 2nd iteration, this can be removed

    return y;
}
```

This code defines a function `Q_sqrt`, which was used as a fast approximation of the inverse square root in graphics routines. (in other words, `Q_sqrt` efficiently approximates  $1 \div \sqrt{x}$ )

The key word here is “fast”: *Quake* ran on very limited hardware, and traditional approximation techniques (like Taylor series)<sup>1</sup> were too computationally expensive to be viable.

Our goal today is to understand how `Q_sqrt` works. To do that, we'll first need to understand how computers represent numbers. We'll start with simple binary integers—turn the page.

<sup>1</sup>Taylor series aren't used today, and for the same reason. There are better ways.

## Section 2: Integers

### Definition 1:

A *bit string* is a string of binary digits.

In this handout, we'll denote bit strings with the prefix `0b`.

This prefix is only notation—it is *not* part of the string itself.

For example, `1001` is the number “one thousand and one,” while `0b1001` is the string of bits “1 0 0 1”.

We will separate long bit strings with underscores for readability.

Underscores have no meaning: `0b1111_0000` = `0b11110000`.

### Problem 2:

What is the value of the following bit strings, if we interpret them as integers in base 2?

- `0b0001_1010`
- `0b0110_0001`

### Solution:

- `0b0001_1010` =  $2 + 8 + 16 = 26$
- `0b0110_0001` =  $1 + 32 + 64 = 95$

### Definition 3:

We can interpret a bit string in any number of ways.

One such interpretation is the *unsigned integer*, or `uint` for short.

`uints` allow us to represent positive (hence “unsigned”) integers using 32-bit strings.

The value of a `uint` is simply its value as a binary number:

- `0b00000000_00000000_00000000_00000000` = 0
- `0b00000000_00000000_00000000_00000011` = 3
- `0b00000000_00000000_00000000_00100000` = 32
- `0b00000000_00000000_00000000_10000010` = 130

### Problem 4:

What is the largest number we can represent with a 32-bit `uint`?

### Solution:

$$\text{0b11111111\_11111111\_11111111\_11111111} = 2^{32} - 1$$

**Problem 5:**

Find the value of each of the following 32-bit unsigned integers:

- `0b00000000_00000000_00000101_00111001`
- `0b00000000_00000000_00000001_00101100`
- `0b00000000_00000000_00000100_10110000`

*Hint:* The third conversion is easy—look carefully at the second.

**Instructor note:**

Consider making a list of the powers of two  $\geq 1024$  on the board.

**Solution:**

- `0b00000000_00000000_00000101_00111001 = 1337`
- `0b00000000_00000000_00000001_00101100 = 300`
- `0b00000000_00000000_00000010_01011000 = 1200`

Notice that the third int is the second shifted left twice (i.e, multiplied by 4)

**Definition 6:**

In general, fast division of `uints` is difficult<sup>2</sup>.

Division by powers of two, however, is incredibly easy:

To divide by two, all we need to do is shift the bits of our integer right.

For example, consider `0b0000_0110 = 6`.

If we insert a zero at the left end of this string and delete the zero at the right (thus “shifting” each bit right), we get `0b0000_0011`, which is 3.

Of course, we lose the remainder when we right-shift an odd number:

9 shifted right is 4, since `0b0000_1001` shifted right is `0b0000_0100`.

**Problem 7:**

Right shifts are denoted by the `>>` symbol:

`00110 >> n` means “shift `0b0110` right  $n$  times.”

Find the value of the following:

- `12 >> 1`
- `27 >> 3`
- `16 >> 8`

Naturally, you’ll have to convert these integers to binary first.

**Solution:**

- `12 >> 1 = 6`
- `27 >> 3 = 3`
- `16 >> 8 = 0`

<sup>2</sup>One may use repeated subtraction, but this isn’t efficient.

## Section 3: Floats

### Definition 8:

*Binary decimals*<sup>3</sup> are very similar to base-10 decimals.

In base 10, we interpret place value as follows:

- $0.1 = 10^{-1}$
- $0.03 = 3 \times 10^{-2}$
- $0.0208 = 2 \times 10^{-2} + 8 \times 10^{-4}$

We can do the same in base 2:

- $0.1 = 2^{-1} = 0.5$
- $0.011 = 2^{-2} + 2^{-3} = 0.375$
- $101.01 = 5.125$

### Problem 9:

Rewrite the following binary decimals in base 10:

You may leave your answer as a fraction.

- $1011.101$
- $110.1101$

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<sup>3</sup>Note that “binary decimal” is a misnomer—“deci” means “ten”!

**Definition 10:**

Another way we can interpret a bit string is as a *signed floating-point decimal*, or a **float** for short. Floats represent a subset of the real numbers, and are interpreted as follows: The following only applies to floats that consist of 32 bits. We won't encounter any others today.

$$\begin{array}{c} 0\ b\ 0\_00000000\_00000000\_00000000\_00000000 \\ \hline s \quad \text{exponent} \quad \text{fraction} \end{array}$$

- The first bit denotes the sign of the float's value We'll label it  $s$ .  
If  $s = 1$ , this float is negative; if  $s = 0$ , it is positive.
- The next eight bits represent the *exponent* of this float. (we'll see what that means soon)  
We'll call the value of this eight-bit binary integer  $E$ .  
Naturally,  $0 \leq E \leq 255$  (since  $E$  consist of eight bits)
- The remaining 23 bits represent the *fraction* of this float.  
They are interpreted as the fractional part of a binary decimal.  
For example, the bits `0b10100000_00000000_00000000` represent  $0.5 + 0.125 = 0.625$ .  
We'll call the value of these bits as a binary integer  $F$ .  
Their value as a binary decimal is then  $F \div 2^{23}$ . (convince yourself of this)

**Problem 11:**

Consider `0b01000001_10101000_00000000_00000000`.

*Hint:* The underscores here do *not* match those in Definition 10

Find the  $s$ ,  $E$ , and  $F$  we get if we interpret this bit string as a float.

Leave  $F$  as a sum of powers of two.

**Solution:**

$$\begin{aligned} s &= 0 \\ E &= 131 \\ F &= 2^{21} + 2^{19} \end{aligned}$$

**Definition 12:**

The final value of a float with sign  $s$ , exponent  $E$ , and fraction  $F$  is

$$(-1)^s \times 2^{E-127} \times \left(1 + \frac{F}{2^{23}}\right)$$

Notice that this is very similar to base-10 scientific notation, which is written as

$$(-1)^s \times 10^e \times (f)$$

We subtract 127 from  $E$  so we can represent positive and negative numbers.

$E$  is an eight bit binary integer, so  $0 \leq E \leq 255$  and thus  $-127 \leq (E - 127) \leq 127$ .

**Problem 13:**

Consider `0b01000001_10101000_00000000_00000000`.

This is the same bit string we used in Problem 11.

What value do we get if we interpret this bit string as a float?

*Hint:*  $21 \div 16 = 1.3125$

**Solution:**

This is 21:

$$2^4 \times \left(1 + \frac{2^{21} + 2^{19}}{2^{23}}\right) = 2^4 \times (1 + 2^{-2} + 2^{-4}) = 16 + 4 + 1 = 21$$

**Problem 14:**

Encode 12.5 as a float.

*Hint:*  $12.5 \div 8 = 1.5625$

**Solution:**

$$12.5 = 8 \times 1.5625 = 2^3 \times (1 + (0.5 + 0.0625)) = 2^{130} \times \left(1 + \frac{2^{22} + 2^{19}}{2^{23}}\right)$$

which is `0b01000001_01001000_00000000_00000000`.

**Definition 15:**

Say we have a bit string  $x$ .

We'll let  $x_f$  denote the value we get if we interpret  $x$  as a float, and we'll let  $x_i$  denote the value we get if we interpret  $x$  as an integer.

**Problem 16:**

Let  $x = 0b01000001_01001000_00000000_00000000$ .

What are  $x_f$  and  $x_i$ ? As always, you may leave big numbers as powers of two.

**Solution:**

$$x_f = 12.5$$

$$x_i = 2^{30} + 2^{24} + 2^{22} + 2^{19} = 11,095,237,632$$

## Section 4: Integers and Floats

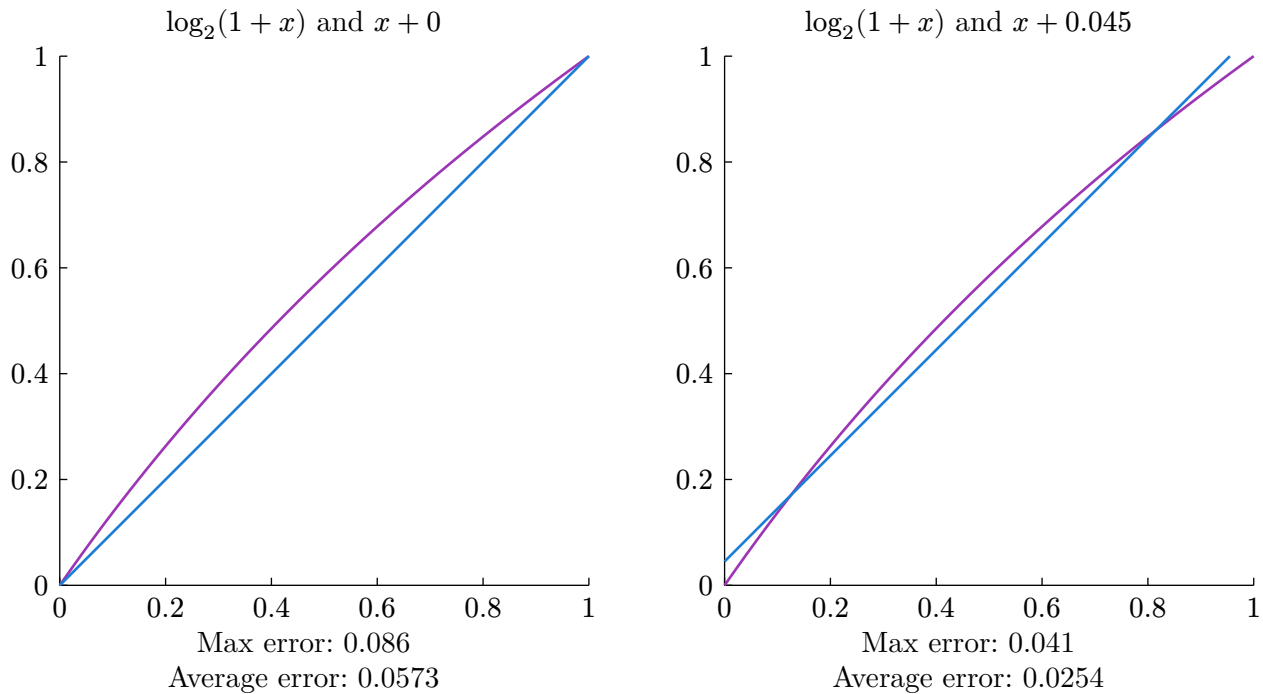
### Observation:

If  $x$  is smaller than 1,  $\log_2(1+x)$  is approximately equal to  $x$ .

Note that this equality is exact for  $x = 0$  and  $x = 1$ , since  $\log_2(1) = 0$  and  $\log_2(2) = 1$ .

We'll add the *correction term*  $\varepsilon$  to our approximation:  $\log_2(1+a) \approx a + \varepsilon$ .

This allows us to improve the average error of our linear approximation:



A suitable value of  $\varepsilon$  can be found using calculus or with computational trial-and-error.

We won't bother with this—we'll simply leave the correction term as an opaque constant  $\varepsilon$ .

*Note:* "Average error" above is simply the area of the region between the two graphs:

$$\int_0^1 | \log(1+x)_2 - (x + \varepsilon) |$$

Feel free to ignore this note, it isn't a critical part of this handout.

**Problem 17:**

Use the fact that  $\log_2(1 + a) \approx a + \varepsilon$  to approximate  $\log_2(x_f)$  in terms of  $x_i$ .  
Namely, show that

$$\log_2(x_f) = \frac{x_i}{2^{23}} - 127 + \varepsilon$$

In other words, we're finding an expression for  $x$  as a float in terms of  $x$  as an int.

**Solution:**

Let  $E$  and  $F$  be the exponent and float bits of  $x_f$ .

We then have:

$$\begin{aligned}\log_2(x_f) &= \log_2\left(2^{E-127} \times \left(1 + \frac{F}{2^{23}}\right)\right) \\ &= E - 127 + \log_2\left(1 + \frac{F}{2^{23}}\right) \\ &\approx E - 127 + \frac{F}{2^{23}} + \varepsilon \\ &= \frac{1}{2^{23}}(2^{23}E + F) - 127 + \varepsilon \\ &= \frac{1}{2^{23}}(x_i) - 127 + \varepsilon\end{aligned}$$

**Problem 18:**

Using basic log rules, rewrite  $\log_2\left(\frac{1}{\sqrt{x}}\right)$  in terms of  $\log_2(x)$ .

**Solution:**

$$\log_2\left(\frac{1}{\sqrt{x}}\right) = \frac{-1}{2} \log_2(x)$$

## Section 5: The Fast Inverse Square Root

A simplified version of the *Quake* routine we are studying is reproduced below.

```
float Q_rsqrt( float number ) {  
    long i = * ( long * ) &number;  
    i = 0x5f3759df - ( i >> 1 );  
    return * ( float * ) &i;  
}
```

This code defines a function `Q_rsqrt` that consumes a `float number` and approximates its inverse square root. If we rewrite this using notation we're familiar with, we get the following:

$$Q\_sqrt(n_f) = 6240089 - (n_i \div 2) \approx \frac{1}{\sqrt{n_f}}$$

`0x5f3759df` is 6240089 in hexadecimal.

Ask an instructor to explain if you don't know what this means.

It is a magic number hard-coded into `Q_sqrt`.

Our goal in this section is to understand why this works:

- How does *Quake* approximate  $\frac{1}{\sqrt{x}}$  by simply subtracting and dividing by two?
- What's special about 6240089?

### Remark 19:

For those that are interested, here are the details of the “code-to-math” translation:

- “`long i = * ( long * ) &number`” is C magic that tells the compiler to set `i` to the `uint` value of the bits of `number`.  
“`long`” refers to a “long integer”, which has 32 bits.  
Normal ints have 16 bits, short ints have 8.  
In other words, `number` is  $n_f$  and `i` is  $n_i$ .
- Notice the right-shift in the second line of the function.  
We translated `( i >> 1 )` into  $(n_i \div 2)$ .
- “`return * ( float * ) &i`” is again C magic.  
Much like before, it tells us to return the value of the bits of `i` as a float.

**Setup:**

We are now ready to show that `Q_sqrt` ( $x$ ) effectively approximates  $\frac{1}{\sqrt{x}}$ .

For convenience, let's call the bit string of the inverse square root  $r$ .

In other words,

$$r_f := \frac{1}{\sqrt{n_f}}$$

This is the value we want to approximate.

**Problem 20:**

Find an approximation for  $\log_2(r_f)$  in terms of  $n_i$  and  $\varepsilon$

Remember,  $\varepsilon$  is the correction constant in our approximation of  $\log_2(1+x)$ .

**Solution:**

$$\log_2(r_f) = \log_2\left(\frac{1}{\sqrt{n_f}}\right) = \frac{-1}{2} \log_2(n_f) \approx \frac{-1}{2} \left(\frac{n_i}{2^{23}} + \varepsilon - 127\right)$$

**Problem 21:**

Let's call the "magic number" in the code above  $\kappa$ , so that

$$\text{Q\_sqrt}(n_f) = \kappa - (n_i \div 2)$$

Use Problem 17 and Problem 20 to show that  $\text{Q\_sqrt}(n_f) \approx r_i$

*Note:* If we know  $r_i$ , we know  $r_f$ .

We don't even need to convert between the two—the underlying bits are the same!

**Solution:**

From Problem 17, we know that

$$\log_2(r_f) \approx \frac{r_i}{2^{23}} + \varepsilon - 127$$

Combining this with the result from Problem 20, we get:

$$\frac{r_i}{2^{23}} + \varepsilon - 127 \approx \frac{-1}{2} \left(\frac{n_i}{2^{23}} + \varepsilon - 127\right)$$

$$\frac{r_i}{2^{23}} \approx \frac{-1}{2} \left(\frac{n_i}{2^{23}}\right) + \frac{3}{2}(127 - \varepsilon)$$

$$r_i \approx \frac{-1}{2}(n_i) + 2^{23} \frac{3}{2}(127 - \varepsilon) = 2^{23} \frac{3}{2}(127 - \varepsilon) - \frac{n_i}{2}$$

This is exactly what we need! If we set  $\kappa$  to  $(3 \times 2^{22})(127 - \varepsilon)$ , then

$$r_i \approx \kappa - (n_i \div 2) = \text{Q\_sqrt}(n_f)$$

**Problem 22:**

What is the exact value of  $\kappa$  in terms of  $\varepsilon$ ?

*Hint:* Look at Problem 21. We already found it!

**Solution:**

This problem makes sure our students see that  $\kappa = (3 \times 2^{22})(127 - \varepsilon)$ .

See the solution to Problem 21.

**Remark 23:**

In Problem 22 we saw that  $\kappa = (3 \times 2^{22})(127 - \varepsilon)$ .

Looking at the code again, we see that  $\kappa = 0x5f3759df$  in *Quake*:

```
float Q_rsqrt( float number ) {
    long i = * ( long * ) &number;
    i = 0x5f3759df - ( i >> 1 );
    return * ( float * ) &i;
}
```

Using a calculator and some basic algebra, we can find the  $\varepsilon$  this code uses:

Remember,  $0x5f3759df$  is 6240089 in hexadecimal.

$$\begin{aligned}(3 \times 2^{22})(127 - \varepsilon) &= 6240089 \\ (127 - \varepsilon) &= 126.955 \\ \varepsilon &= 0.0450466\end{aligned}$$

So, 0.045 is the  $\varepsilon$  used by *Quake*.

Online sources state that this constant was generated by trial-and-error, though it is fairly close to the ideal  $\varepsilon$ .

**Remark 24:**

And now, we're done!

We've shown that  $Q\_sqrt(x)$  approximates  $\frac{1}{\sqrt{x}}$  fairly well.

Notably,  $Q\_sqrt$  uses *zero* divisions or multiplications ( $\gg$  doesn't count).

This makes it *very* fast when compared to more traditional approximation techniques (i.e, Taylor series).

In the case of *Quake*, this is very important. 3D graphics require thousands of inverse-square-root calculations to render a single frame<sup>4</sup>, which is not an easy task for a Playstation running at 300MHz.

**Instructor note:**

Let  $x$  be a bit string. If we assume  $x_f$  is positive and  $E$  is even, then

$$(x \gg 1)_f = 2^{(E \div 2) - 127} \times \left( 1 + \frac{F \div 2}{2^{23}} \right)$$

Notably: a right-shift divides the exponent of  $x_f$  by two, which is, of course, a square root!

This intuition is hand-wavy, though:

If  $E$  is odd, its lowest-order bit becomes the highest-order bit of  $F$  when we shift  $x$  right.

Also, a right shift doesn't divide the *entire* exponent, skipping the  $-127$  offset.

Remarkably, this intuition is still somewhat correct.

The bits align *just so*, and our approximation still works.

One can think of the fast inverse root as a "digital slide rule":

The integer representation of  $x_f$  already contains  $\log_2(x_f)$ , offset and scaled.

By subtracting and dividing in "log space", we effectively invert and root  $x_f$ !

After all,

$$-\frac{1}{2} \log_2(n_f) = \frac{1}{\sqrt{n_f}}$$

<sup>4</sup>e.g, to generate normal vectors

## Section 6: Bonus – More about Floats

**Problem 25:**

Convince yourself that all numbers that can be represented as a float are rational.

**Problem 26:**

Find a rational number that cannot be represented as a float.

**Problem 27:**

What is the smallest positive 32-bit float?

**Problem 28:**

What is the largest positive 32-bit float?

**Problem 29:**

How many floats are between  $-1$  and  $1$ ?

**Problem 30:**

How many floats are between  $1$  and  $2$ ?

**Problem 31:**

How many floats are between  $1$  and  $128$ ?