

Problems In Mathematics for Computer Science

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Preface

This is a research project in which I try to read the notes and solve all the problems from [1]

Contents

Preface	i
Contents	ii
I Notes	1
1 What is a Proof?	3
1.1 Propositions	3
1.2 Predicates	3
1.3 The Axiomatic Method	4
1.4 Our axioms	4
1.4.1 Logical deductions	4
1.4.2 Patterns of Proof	4
1.5 Proving an Implication	4
1.5.1 Method #1: $P \Rightarrow Q$	4
1.5.2 Method #2: Contrapositive: $\neg Q \Rightarrow \neg P$	4
1.6 Proving an “if and only if”	4
1.6.1 Method #1: Prove each statement implies the other	4
1.6.2 Method #2: Construct a chain of iffs	4
1.7 Proof by Cases	4
1.8 Proof by Contradiction	5
II Problems and Exercises	7
1 What is a Proof?	9
Bibliography	21

Part I

Notes

Chapter 1

What is a Proof?

1.1 Propositions

Definition 1.1. A *proposition* is a statement (communication) that is either true or false.

Claim 1.1.1. $\forall n \in \mathbb{N}, p ::= n^2 + n + 41$ is prime

Question: Is this claim true or false?

Claim 1.1.2. No polynomial with integer coefficients can map all nonnegative numbers into primes, unless it's a constant.

Question: Is this true or false?

Claim 1.1.3 (Euler's Conjecture). $\forall a, b, c, d \in \mathbb{Z}^+. a^4 + b^4 + c^4 \neq d^4$

Claim 1.1.4. $313(x^3 + y^3) = z^3$ has no solution when $x, y, z \in \mathbb{Z}^+$

Claim 1.1.5 (Four Color Theorem). Every map can be colored with 4 colors so that adjacent regions have different colors.

Claim 1.1.6 (Fermat's Last Theorem). $\forall a, b, c \in \mathbb{Z}^+ \forall n > 2, n \in \mathbb{Z}. a^n + b^n \neq c^n$

Claim 1.1.7 (Goldbach). Every even integer greater than 2 is the sum of two primes.

1.2 Predicates

Definition 1.2. A *predicate* is a proposition whose truth depends on the value of one or more variables.

If P is a predicate, then $P(n)$ is either *true* or *false*, depending on the value of n .

1.3 The Axiomatic Method

Definition 1.3. A *proof* is a sequence of logical deductions from a set of axioms and previous proved propositions that concludes with the proposition in question.

- *Theorems*
- *Lemma*
- *Corollary*

\Rightarrow Axiomatic Method

1.4 Our axioms

1.4.1 Logical deductions

Keywords: *Logical deductions*(inference rules), *antecedents*, *conclusion*, *modus ponens*

1.4.2 Patterns of Proof

Many proofs follow specific templates. . . Many special techniques later on.

1.5 Proving an Implication

Definition 1.4. *Implications* means $P \Rightarrow Q$

1.5.1 Method #1: $P \Rightarrow Q$

1.5.2 Method #2: Contrapositive: $\neg Q \Rightarrow \neg P$

1.6 Proving an “if and only if”

1.6.1 Method #1: Prove each statement implies the other

1.6.2 Method #2: Construct a chain of iffs

1.7 Proof by Cases

Amusing theorem

Theorem 1.7.1. *Every collection of 6 people includes a club of 3 people or a group of 3 strangers.*

Proof. The proof is by case analysis. Let x be one of those 6 people. Among 5 other people, there are two scenarios:

1. At least 3 people have met x
2. At least 3 people have not met x

We argue that these two cases are exhaustive since we are dividing the 5 people into two groups: those who have met x and those who have not.

Case 1: Suppose that at least 3 people have met x

This is divided further more into two subcases:

Case 1.1: No pairs among those people have met each other. In this case, they form a group of at least 3 strangers. Thus, the theorem holds in this subcase.

Case 1.2: At least one pair in those people have met. Adding x to such pair forms a club of at least 3 people. The theorem is proved in this subcase.

This implies that the theorem holds for Case 1.

Case 2: Suppose that at least 3 people have not met x

This again splits the case into two subcases:

Case 2.1: All pairs among those people have met each other. In this case, they form a club of at least 3 people. Thus the theorem holds in this subcase.

Case 2.2: At least one pair in those people have not met. Adding x to such pair forms a group of at least 3 strangers. The theorem holds in this subcase.

This implies that the theorem holds for Case 2.

We have proved the theorem. □

1.8 Proof by Contradiction

Theorem 1.8.1. $\sqrt{2}$ is irrational

Proof. We use proof by contradiction. Suppose $\sqrt{2}$ is rational, then $\sqrt{2} = \frac{p}{q}$,

where p and q are integers that have no common factors. Then $2 = \frac{p^2}{q^2}$, which means $p^2 = 2q^2$. Since p^2 is even, p must be even (easily proved by contradiction again). W.l.o.g, assume $p = 2k$ for some integer k . Then $4k^2 = 2q^2 \Rightarrow q^2 = 2k^2$, which implies that q is also even. However, this contradicts the fact that p and q have no common factors. Therefore $\sqrt{2}$ is irrational. □

Part II

Problems and Exercises

Chapter 1

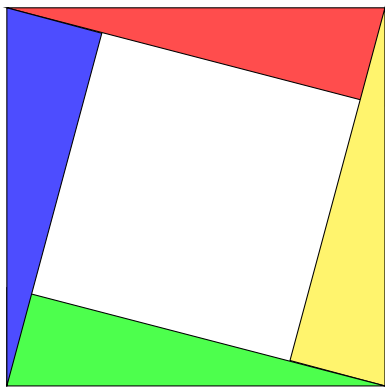
What is a Proof?

There are many problems in this chapter in which we will use this specific Lemma. So we state it here for convenience.

Lemma 1.1 (Unique prime factorization/Fundamental Theorem of Algebra).
Every natural number can be expressed as a unique product of primes.

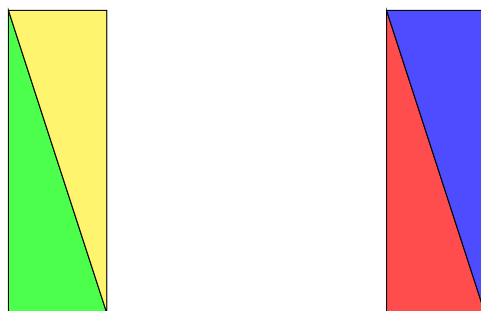
Problem 1.1.

- (a) Colors of the triangles are arbitrary since I do not remember the exact ones in the text.



The middle square is a square of $(b - a) \times (b - a)$

- (b) [*Possible Errata:* Arrange the same shapes so they form two rectangles, both $a \times b$.]



We prove by construct a chain of iffs.

$$\begin{aligned}
 & (b-a)^2 = c^2 - 2ab \\
 \Leftrightarrow & a^2 + b^2 - 2ab = c^2 - 2ab \\
 \Leftrightarrow & a^2 + b^2 = c^2
 \end{aligned}$$

- (c) The equation would still hold true since $a = b$ is not a requirement for the proof. In fact, note that if $a = b$, the area of the bigger square in (a) will now be exactly equal to the sum of area of all triangles inside it, which is equal to the sum of area of two smaller squares in (b). That is, $c^2 = a^2 + b^2$.
- (d) Some assumptions about right triangles, squares and lines are,
- 4 identical right triangles.
 - For every 2 points, there is a line.

Problem 1.2.

- (a) Mistake:

$$\sqrt{(-1)(-1)} = \sqrt{-1}\sqrt{-1}$$

The right-hand side of this equation is undefined while the left-hand side is defined.

- (b) Suppose $1 = -1$, then

$$\begin{aligned}
 & 0 = 0 \\
 \Rightarrow & 1^2 - 1^2 = 1 + 1 \\
 \Rightarrow & (1-1)(1+1) = 1+1
 \end{aligned}$$

At this stage, we cancel off $1+1$ on each side since they are non-zero, the equation then becomes,

$$\begin{aligned}
 \Rightarrow & 1-1 = 1 \\
 \Rightarrow & 1+1 = 1 \\
 \Rightarrow & 2 = 1
 \end{aligned}$$

where the second equation is by the antecedent $1 = -1$. Hence, we have proved $2 = 1$.

(c) We shall prove the following lemma,

Lemma 1.2.1. *If $r, s > 0$, then $\sqrt{rs} = \sqrt{r}\sqrt{s}$*

Proof. Assume $r, s > 0$. For every positive integer x , there is one $\sqrt{x} > 0$ such that $x = (\sqrt{x})^2$; therefore,

$$(\sqrt{r})^2(\sqrt{s})^2 = rs \quad (1.1)$$

By commutative and associative property of multiplication,

$$(\sqrt{r})^2(\sqrt{s})^2 = (\sqrt{r}\sqrt{s})^2 \quad (1.2)$$

which leads to

$$(\sqrt{r}\sqrt{s})^2 = rs \quad (1.3)$$

Since $rs > 0$, there is also one $\sqrt{rs} > 0$ such that $(\sqrt{rs})^2 = rs$. Therefore,

$$(\sqrt{r}\sqrt{s})^2 = (\sqrt{rs})^2 \quad (1.4)$$

Since $\sqrt{r}\sqrt{s} > 0$ and $\sqrt{rs} > 0$, we conclude

$$\sqrt{r}\sqrt{s} = \sqrt{rs} \quad (1.5)$$

□

Problem 1.3.

(a) Mistake,

$$\begin{aligned} 3 &> 2 \\ 3 \log_{10}(1/2) &> 2 \log_{10}(1/2) \end{aligned}$$

since $\log_{10} n \forall 0 < n < 1$ is always negative.

(b) Wrong because all arithmetic operations must be done on numbers with the same currency, so that they will be in the same field.

(c) Since $a = b$, $a - b = 0$, and therefore we cannot cancel $a - b$ on both sides since we cannot divide each side by 0.

Problem 1.4. The questionable step is from step 2 to step 3, namely,

$$\begin{aligned} a + b &\stackrel{?}{\geq} 2\sqrt{ab} \\ a^2 + 2ab + b^2 &\stackrel{?}{\geq} 4ab \end{aligned}$$

Assume that $a, b < 0$. Then even though the first inequality is false, the second inequality is true, which will lead to all subsequent inequalities to be true. Therefore, we have just “proved” that arithmetic mean is at least as large as geometric mean for all negative numbers a, b !

To fix this,

$$\begin{aligned} \frac{a+b}{2} &\geq \sqrt{ab} \\ a+b-2\sqrt{ab} &\geq 0 \\ (\sqrt{a}-\sqrt{b})^2 &\geq 0 \end{aligned}$$

This ensures that $a, b \geq 0$ so that the last inequality can be defined.

Problem 1.5.

The reasoning is wrong because of the implicit assumption on Monday.

Assumption 1.5.1. *If Albert didn't give the quiz **before** Monday, by Midnight Sunday, we know the quiz has to be on Monday.*

The contrapositive of this statement is,

Assumption 1.5.2 (equivalent to 1.5.1). *If the quiz is not on Monday, then Albert gave the quiz **before** Monday.*

This is a false assumption since we know Albert gives out his quiz on next week. This collapses the chain of arguments and therefore the reasoning is false.

Problem 1.6.

We prove by case analysis. Let $x = \log_7 n \forall n \in \mathbb{Z}^+$ so that $7^x = n$. We argue that there are two scenarios,

1. x is an integer
2. x is a non-integer

These cases are clearly exhaustive.

Case 1: x is an integer

We use a certain fact called the fundamental theorem of algebra,

Fact 1.6.1. *All positive integers are products of unique primes.*

Therefore, for all n that are a product of $7s$ (e.g, $7, 7^2, 7^3, \dots$), x is an integer.

Case 2: x is a non-integer

We prove by contradiction. Assume x is rational, then $x = \frac{p}{q}$ for all integers $p, q \in \mathbb{Z}^+$ that do not share common factor such that $7^{\frac{p}{q}} = n$. Then $n^q = 7^p$. By fact 1.6.1, $n = 7^k$ for some positive integer k , which means $7^{qk} = 7^p$. Then $\frac{p}{q} = k$, which contradicts the fact p and q do not share a common factor. We conclude that x is irrational.

Problem 1.7.

Case 1: $r \geq s$

$$\max(r, s) + \min(r, s) = r + s$$

Case 2: $r < s$

$$\max(r, s) + \min(r, s) = s + r = r + s$$

Problem 1.8.

We claim that,

Predicate 1.8.1. *An irrational number powered to an irrational number can be rational.*

We prove by case analysis. Let's consider $\sqrt{2}^{\sqrt{2}}$ to be one of the two cases,

1. $\sqrt{2}^{\sqrt{2}}$ is rational
2. $\sqrt{2}^{\sqrt{2}}$ is irrational

In case 1, we have the conclusion. In case 2, suppose $x = \sqrt{2}^{\sqrt{2}}$ and $y = \sqrt{2}$, then

$$x^y = \sqrt{2}^{(\sqrt{2})^2} = (\sqrt{2})^2 = 2$$

Therefore, we conclude that an irrational number powered to an irrational number can be rational.

Problem 1.9.

We prove $|r + s| \leq |r| + |s| \forall r, s \in \mathbb{R}$ by case analysis.

Case 1: $r > 0, s > 0$

$$(r + s) = r + s$$

Case 2: $r > 0, s < 0$

$$|r + s| \leq r - s$$

There are two subcases in this one,

Case 2.1: $r + s \geq 0$

$$r + s < r - s$$

Case 2.2: $r + s < 0$

$$-r - s < r - s$$

Case 3: $r < 0, s > 0$

Very similar to the case above, interchange the role of r, s .

Case 4: $r < 0, s < 0$

Then $-(r + s) = -r - s = (-r) + (-s)$.

Problem 1.10.

- (a) We prove by case analysis. Without loss of generality, assume $z = a + b$ and $d = z + c$ where $a, b, c, d \in \mathbb{Z}^+$, then one of the following four cases happens,

Case 1: z is odd and c is odd

z is odd IFF one and only one of the summands is even and the other is odd. In this case, d is even if one of a, b, c is even.

Case 2: z is even and c is even

For z to be even, there are two sub-cases,

Case 2.1: Both a and b are evens

d is even if all of a, b, c are even.

Case 2.2: Both a and b are odds

d is even if one and only one of a, b, c is even.

Case 3: z is even and c is odd

d is odd in this case.

Case 4: z is odd and c is even

d is also odd in this case.

We conclude that d is even IFF either one and only one of a, b, c is even or all a, b, c are evens.

- (b) We shall first prove a lemma,

Lemma 1.10.1. *If x is even, x^2 is a multiple of 4. If x is odd, x^2 is one more than a multiple of 4.*

Proof. If x is even, $x = 2k$ for some integer k , then $x^2 = 4k^2$. If x is odd, $x = 2m + 1$ for some integer m , then $x^2 = 4(m^2 + m) + 1$. \square

Suppose,

$$w^2 + x^2 + y^2 = z^2$$

for all $w, x, y, z \in \mathbb{Z}^+$. We shall prove the statement,

Theorem 1.10.1. *z is even IFF all w, x, y are even.*

Proof. We shall prove by case analysis. Assume if w, x, y are even, then $w = 2i, x = 2j, y = 2k$ for some integer i, j, k ; if w, x, y are odd, then $w = 2m + 1, x = 2n + 1, y = 2l + 1$ for some integer m, n, l . Then one of the following four cases happen,

Case 1: All w, x, y are odd

$$\begin{aligned} z^2 &= (2m + 1)^2 + (2n + 1)^2 + (2l + 1)^2 \\ &= 4(m^2 + n^2 + l^2 + m + n + l) + 3 \end{aligned}$$

Case 2: One of w, x, y is even

$$\begin{aligned} z^2 &= (2i)^2 + (2n + 1)^2 + (2l + 1)^2 \\ &= 4(i^2 + n^2 + l^2 + n + l) + 2 \end{aligned}$$

Case 3: Two of w, x, y are even

$$\begin{aligned} z^2 &= (2i)^2 + (2j)^2 + (2l + 1)^2 \\ &= 4(i^2 + j^2 + l^2 + l) + 1 \end{aligned}$$

Case 4: All of w, x, y are even

$$\begin{aligned} z^2 &= (2i)^2 + (2j)^2 + (2k)^2 \\ &= 4(i^2 + j^2 + k^2) \end{aligned}$$

Therefore, if either one and only one of w, x, y is even or all of w, x, y are even, then z^2 is even, which implies z is even. Conversely, if z is even, by the above lemma, z^2 does not exist in Case 2. We conclude that z is even IFF all of w, x, y are even. \square

Problem 1.11.

We want to prove the theorem,

Theorem 1.11.1. *There exists an irrational number a such that $a^{\sqrt{3}}$ is rational.*

Proof. We prove by case analysis. The number $x = \sqrt[3]{2}^{\sqrt{3}}$ must be one of the two cases,

Case 1: x is rational.

In this case, $a = \sqrt[3]{2}$ and a is irrational.

Case 2: x is irrational.

Let $a = \sqrt[3]{2}^{\sqrt{3}}$. Then a is irrational such that,

$$\begin{aligned} a^{\sqrt{3}} &= (\sqrt[3]{2})^{(\sqrt{3})^2} \\ &= (\sqrt[3]{2})^3 \\ &= 2 \end{aligned}$$

We conclude that there exists an irrational a such that $a^{\sqrt{3}}$ is rational. \square

Problem 1.12. The proof is by contradiction. Suppose a is odd, then $a = 2k + 1$ for some integer k , then for all $n > 0$,

$$a^n = (2k + 1)^n = \sum_{i=1}^n C_i^n (2k)^i + 1 = 2 \left(\sum_{i=1}^n C_i^n 2^{i-1} k^i \right) + 1$$

Therefore, a^n is odd, a contradiction. We conclude that if a^n is even, a is even.

Problem 1.13. Assume by contradiction that both a and $b > \sqrt{n}$. Then, since $a, b \geq 0$,

$$a \cdot b > \sqrt{n} \cdot \sqrt{n} = n$$

which contradicts the antecedent $a \cdot b = n$.

Problem 1.14.

- (a) Suppose by contradiction $n = 2k + 1$ for some integer k , then $n^2 = 4(k^2 + k) + 1$ is odd. Therefore, n must be even.
- (b) Suppose by contradiction either $n = 3l + 1$ or $n = 3l + 2$ for some integer l , then either $n^2 = 3(3l^2 + 2l) + 1$ or $n^2 = 3(3l^2 + 2l + 1) + 1$, contradicting the antecedent n^2 is a multiple of 3. Therefore, n must be a multiple of 3.

Problem 1.15. Let $n = 4$ and $m = 8$. Then $16 = 4^2$ is a multiple of 8, but 4 is not a multiple of 8. If $m < n$, $n = mk + l$ for some integer k and $l < m$, and we will prove that if n^2 is a multiple of m , then n is a multiple of m .

Proof. We will prove by contradiction. Suppose $n = mk + l$ for some positive integer k and $m < n$ and $l < m$, then $n^2 = m(mk^2 + 2kl) + l^2 < 2m(mk^2 + 2kl)$. Therefore, n^2 is not a multiple of m , a contradiction. \square

Problem 1.16.

We can generalize the proof to only for some nonnegative integer n . For example, $\sqrt{4} = 2$ is rational. $\sqrt{3}$, however, is irrational. Using Problem 1.14 (b), we can easily prove such statement.

Problem 1.17.

We shall prove by contradiction. Let $\log_4 6 = \frac{m}{n}$ for some integer m, n in its simplest form such that $4^{\frac{m}{n}} = 6$. Then

$$2^{2\frac{m}{n}} = (2 \cdot 3)$$

Powering to n on both sides, we have,

$$2^{2m} = (2 \cdot 3)^n$$

Dividing both sides by 2^n , we have,

$$2^{2m-n} = 3^n$$

By unique factorization of primes, this cannot happen unless both $2m - n = 0$ and $n = 0$, but this implies that $m = n = 0$. Hence, this is a contradiction.

We conclude that $\log_4 6$ is irrational.

Problem 1.18.

We shall prove by contradiction. Note that,

$$(\sqrt{3} + \sqrt{2})(\sqrt{3} - \sqrt{2}) = 3 - 2 = 1$$

Therefore, $\sqrt{3} + \sqrt{2}$ is rational/irrational IFF $\sqrt{3} - \sqrt{2}$ is rational/irrational since $\sqrt{3} + \sqrt{2} = \frac{1}{\sqrt{3} - \sqrt{2}}$. Suppose $\sqrt{3} + \sqrt{2}$ is rational, then $\sqrt{3} - \sqrt{2}$ is also rational, but then,

$$(\sqrt{3} + \sqrt{2}) + (\sqrt{3} - \sqrt{2}) = 2\sqrt{3}$$

Since we know that $2\sqrt{3}$ is irrational, this is a contradiction. Therefore, $\sqrt{3} + \sqrt{2}$ is irrational.

Problem 1.19.

Let us first re-state the lemma,

Lemma 1.19.1. *Let the coefficients of the polynomial*

$$a_0 + a_1x + a_2x^2 + \dots + a_{m-1}x^{m-1} + x^m$$

be integers. Then any real root of the polynomial is either integer or irrational.

(a) Let $\sqrt[m]{k} = x_0$, where x_0 is a real root of the polynomial. Suppose $\sqrt[m]{k}$ is rational, then by the lemma, x_0 must be an integer, which implies that $k = x_0^m$. Therefore, $\sqrt[m]{k}$ is irrational whenever $k \neq x_0^m$ for some integer x_0 .

(b) We shall first prove a lemma,

Lemma 1.19.2. *If a prime p is a factor of some power of an integer, then it is also a factor of that integer.*

Proof. We prove by contradiction. Suppose p is not a factor of some integer, by unique prime factorization, it cannot be a factor of some power of that integer as well. We conclude that the lemma must hold. \square

We shall prove the first lemma in this problem by direct proof. Suppose the real root of the polynomial is x_0 . Then x_0 is either rational or irrational. Let $x_0 = \frac{r}{s}$ for some integer r, s in the lowest term possible. Hence,

$$\begin{aligned} a_0 + a_1 \left(\frac{r}{s}\right) + a_2 \left(\frac{r}{s}\right)^2 + \dots + a_{m-1} \left(\frac{r}{s}\right)^{m-1} + \left(\frac{r}{s}\right)^m &= 0 \\ a_0 s^m + a_1 r s^{m-1} + a_2 r^2 s^{m-2} + \dots + a_{m-1} r^{m-1} s &= -r^m \\ s(a_0 s^{m-1} + a_1 r s^{m-2} + a_2 r^2 s^{m-3} + \dots + a_{m-1} r^{m-1}) &= -r^m \end{aligned}$$

By unique prime factorization, $s = pk$ where p is a prime and k is some integer. This implies r^m is divisible by p . By the lemma proved above, this means r is also divisible by p . But this contradicts that r and s are in its simplest form. Therefore, it must be the case that $s = \pm 1$ or x_0 is irrational. We conclude that any real root of the polynomial is either integer or irrational.

Problem 1.20.

Let $x = \log_9 12$. We shall prove that x is irrational by contradiction. Assume that $x = \frac{p}{q}$ in the lowest term possible for some integer p, q . Then,

$$3^{\left(\frac{2p}{q}\right)} = (2^2 \cdot 3)$$

Powering both sides to q , we have,

$$3^{2p} = (2^{2q} \cdot 3^q)$$

Dividing both sides by 3^q , yielding,

$$3^{2p-q} = 2^q$$

By unique prime factorization lemma, the last equation is impossible unless both powers on both sides equal to 0, but this implies that $p = q = 0$. Therefore, x must be irrational.

Problem 1.21.

Let $x = \log_{12} 18$. We shall prove that x is irrational by contradiction. Assume that $x = \frac{p}{q}$ in the lowest term possible for some integer p, q . Then,

$$(2^2 \cdot 3)^{\frac{p}{q}} = (3^2 \cdot 2)$$

Powering both sides to q ,

$$(2^2 \cdot 3)^p = (2 \cdot 3^2)^q$$

Equivalently,

$$2^{2p} \cdot 3^p = 2^q \cdot 3^{2q}$$

Finally, dividing both sides by $2^q 3^p$ yields,

$$2^{2p-q} = 3^{2q-p}$$

By unique prime factorization lemma, this is impossible unless $p = q = 0$, but this contradicts x is rational. We conclude that x is irrational.

Problem 1.22.

The unsatisfiable equation is $a^3 = 7^2 b^3$. Assume $\sqrt[3]{7^2} = \frac{a}{b}$ for some integer a, b in the lowest term possible. By lemma 1.19.2, since 7 is a factor of a^3 , 7 is also a factor of a , but this means that 7 is also a factor b^3 and, by implication, b . This contradicts that a and b are in the lowest term possible. Hence, the equation is not satisfied.

Problem 1.23.

From the problems above, it is easy to show that $2 \log_2 3$ is irrational.

Problem 1.24.

MIT sucks

Bibliography

- [1] Eric Lehman, Tom Leighton, and Albert Meyer. *Mathematics for Computer Science*. MIT OCW, 2018.