

Field Theory

Book 2

Claim: $\sqrt{3} \notin \mathbb{Q}[\sqrt{2}]$ i.e. $\sqrt{3} = a + b\sqrt{2}$ has no solution with $a, b \in \mathbb{Q}$.

Suppose $\sqrt{3} = a + b\sqrt{2}$ where $a, b \in \mathbb{Q}$. Then $3 = a^2 + 2b^2 + 2ab\sqrt{2}$ so $2ab\sqrt{2} = 3 - a^2 - 2b^2$.

If $ab \neq 0$ then $\sqrt{2} = \frac{3 - a^2 - 2b^2}{2ab} \in \mathbb{Q}$, a contradiction.

If $b = 0$ then $0 = 3 - a^2$ so $a^2 = 3$, $a = \pm\sqrt{3} \notin \mathbb{Q}$, a contradiction.

If $a = 0$ then $0 = 3 - 2b^2$ so $2b^2 = 3$, $4b^2 = 6$, $2b = \pm\sqrt{6} \notin \mathbb{Q}$, a contradiction. \square

So $1, \sqrt{2}, \sqrt{3} \in \mathbb{R}$ are linearly independent over \mathbb{Q} .

- $1 \neq 0$
- $\sqrt{2} \neq$ scalar multiple of 1 . ($\sqrt{2} \notin \mathbb{Q}$ by Euclid)
- $\sqrt{3} \neq$ linear combination of $1, \sqrt{2}$. (proved above)

$$\sqrt{8} = 2\sqrt{2}$$

$1, \sqrt{2}, \sqrt{3}, \sqrt{5}, \sqrt{7}, \sqrt{11}, \sqrt{13}, \sqrt{17}, \sqrt{19}, \sqrt{23}, \dots$ are linearly independent.

$[\mathbb{R} : \mathbb{Q}] = \infty$ (in fact uncountable)

Also $1, \pi, \pi^2, \pi^3, \dots$ are linearly independent over \mathbb{Q} . (since π is transcendental).

An extension $E \supseteq F$ is finite if $[E : F] < \infty$, i.e. $[E : F] = n$ is a positive integer.

eg. $\mathbb{C} \supseteq \mathbb{R}$ is a quadratic extension, hence finite, $[\mathbb{C} : \mathbb{R}] = 2$.

A finite extension of \mathbb{Q} i.e. $E \supseteq \mathbb{Q}$ with $[E : \mathbb{Q}] = n$, a positive integer, is called a number field (or algebraic number field). Here every element $\alpha \in E$ is algebraic over \mathbb{Q} . Why?

$1, \alpha, \alpha^2, \dots, \alpha^n$ are $n+1$ vectors in an n -dimensional vector space $E \supseteq \mathbb{Q}$ so this list is linearly dependent i.e. $a_0 + a_1\alpha + a_2\alpha^2 + \dots + a_n\alpha^n = 0$ for some $a_0, a_1, \dots, a_n \in \mathbb{Q}$, not all zero, i.e. α is a root of some nonzero polynomial $f(x) = a_0 + a_1x + a_2x^2 + \dots + a_nx^n \in \mathbb{Q}[x]$.

If $f(x) = a_0 + a_1x + a_2x^2 + \dots + a_nx^n$ then the degree of $f(x)$, denoted $\deg f(x)$, is the largest d such that $a_d \neq 0$.

$$\deg(3x^2 + 5x + 7) = 2$$

$$\deg(0x^2 + 5x + 7) = \deg(5x + 7) = 1$$

$$\deg(7) = \deg(7x^0) = 0$$

$\deg 0$ is sometimes left undefined (not 0) or $\deg 0 = -\infty$.

$$\deg[(3x^2 + 5x + 7)(x^3 - 4x - 11)] = \deg(3x^5 + \dots - 77) = 5$$

$$\deg[f(x)g(x)] = \deg f(x) + \deg g(x)$$

If $g(x) = x^3 - 4x - 11$ then $\deg g(x) = 3$

$$\deg(0g(x)) = \deg 0$$

$$\deg 0 + \deg g(x) = \deg 0 + 3$$

$$\deg 0 = (\deg 0) + 3$$

There is no integer value for $\deg 0$ that satisfies this.
(We don't choose $+\infty$; we choose $-\infty$.)

Let $\alpha \in \mathbb{C}$. If α is the root of some nonzero poly. $f(x) \in \mathbb{Q}[x]$ (i.e. $f(\alpha) = 0$) then α is algebraic of degree n where n is the smallest degree of any such polynomial $f(x)$. In this case, the smallest degree monic polynomial having α as a root is the minimal polynomial of α (over \mathbb{Q}).

eg. $\sqrt{14}$ is algebraic of degree 2 with min. poly. $x^2 - 14 \in \mathbb{Q}[x]$.

Look at powers $1, \alpha, \alpha^2, \alpha^3, \dots$

$$\alpha = \sqrt{14} \Rightarrow 1, \alpha \text{ lin. indep.}$$

$$1, \alpha, \alpha^2 \text{ lin. dep.}$$

$$\alpha^2 = 0 \cdot \alpha + 14 \cdot 1$$

$\alpha = \sqrt{2} + \sqrt{5}$ is algebraic of degree 4 with min. poly. $x^4 - 10x^2 + 1$. Why is $\alpha = \sqrt{2} + \sqrt{5}$ not a root of any smaller degree poly. with rational coefficients?

If $x^4 - 10x^2 + 1 = f(x)g(x)$ where $f(x), g(x) \in \mathbb{Q}[x]$ then one of $f(x), g(x)$ is a constant polynomial. Assuming we start with a monic poly. with integer coefficients, it suffices to check that there is no nontrivial factorization over $\mathbb{Z}[x]$.

If $x^4 - 10x^2 + 1 = f(x)g(x)$, $f(x), g(x) \in \mathbb{Z}[x]$, neither $f(x)$ nor $g(x)$ is constant then either

(i) $\deg f(x) = 1$, $\deg g(x) = 3$; or

(ii) $\deg f(x) = \deg g(x) = 2$.

(The case $\deg f(x) = 3, \deg g(x) = 1$ is essentially case (i)).

In both cases we obtain a contradiction.

In case (i), $x^4 - 10x^2 + 1 = (x+a)(x^3+bx^2+cx+d)$, $ad=1$, $a=d=\pm 1$.

In this case $m(x)$ has ± 1 as a root but $m(1) = -8 = m(-1)$, a contradiction.

In case (ii), $m(x) = x^4 - 10x^2 + 1 = (x^2+ax+b)(x^2-ax+c)$, $a, b, c \in \mathbb{Z}$ (since there is no x^3 term on the left).

Once again, $bc=1$ so $b=c=\pm 1$. Now

$m(x) = x^4 - 10x^2 + 1 = (x^2+ax\pm 1)(x^2-ax\pm 1)$. Comparing x^2 terms on both sides,

$$-10 = \pm 2 - a^2 \quad \text{i.e. } a^2 = 10 \pm 2 = 8 \text{ or } 12.$$

This is a final contradiction so $m(x) = x^4 - 10x^2 + 1$ is irreducible in $\mathbb{Z}[x]$ and in $\mathbb{Q}[x]$.

Note: $x^4 + x^2 + 1$ is reducible in $\mathbb{Z}[x]$ as well as in $\mathbb{Q}[x]$: it factors nontrivially as

$$x^4 + x^2 + 1 = (x^2 + x + 1)(x^2 - x + 1).$$

This polynomial has no roots in \mathbb{Z} or in \mathbb{Q} or in \mathbb{R} .

$x^4 - 10x^2 + 1$ is irreducible in $\mathbb{Z}[x]$ and in $\mathbb{Q}[x]$ but reducible in $\mathbb{R}[x]$. Every polynomial of degree ≥ 3 in $\mathbb{R}[x]$ is reducible.

$$x^4 - 10x^2 + 1 = x^4 + 2x^2 + 1 - 8x^2 = (x^2 + 1)^2 - (2\sqrt{2}x)^2 = (x^2 + 1 + 2\sqrt{2}x)(x^2 + 1 - 2\sqrt{2}x)$$

The polynomial $x - \sqrt{2}$ is irreducible in $\mathbb{Z}[x]$ and in $\mathbb{Q}[x]$ and in $\mathbb{R}[x]$. It has a root $\sqrt{2} \in \mathbb{Z}$.

Theorem: If $f(x) \in \mathbb{Z}[x]$ is monic, then $f(x)$ is reducible in $\mathbb{Q}[x]$ iff $f(x)$ is reducible in $\mathbb{Z}[x]$. Assume this, and use it!

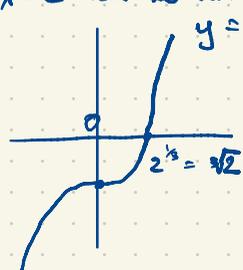
For $f(x) \in \mathbb{Q}[x]$ of degree ≥ 3 , $f(x)$ is reducible in $\mathbb{Q}[x]$ iff it has a root in \mathbb{Q} .

This is not true for $\deg f(x) \geq 4$.

Eg. $f(x) = x^4 + x^2 + 1$ has no roots in \mathbb{Q} but it is reducible in $\mathbb{Q}[x]$

eg. $x^3 - 2$ is irreducible in $\mathbb{Q}[x]$ since it has no roots in \mathbb{Q} . You need to master this point!

$x^3 - 2$ has no rational roots: it has one real root $2^{1/3} \notin \mathbb{Q}$ essentially by Euclid's argument.



$y = x^3 - 2$ If $x = 2^{1/3} \in \mathbb{Q}$, $x^3 = 2$, write $x = \frac{a}{b}$ with a, b positive integers in lowest terms ($\gcd(a, b) = 1$) then $\frac{a^3}{b^3} = 2$ so $a^3 = 2b^3$ is even so a is even.

ie. $a = 2r$ for some positive integer r , so $8r^3 = 2b^3$ and $b^3 = 4r^3$ is even so b is even ie. $b = 2s$ for some $s \in \mathbb{Z}$. This contradicts $\gcd(a, b) = 1$.

Now if $x^3 - 2$ is reducible in $\mathbb{Q}[x]$ then $x^3 - 2 = (x+a)(x^2+bx+c)$, $a, b, c \in \mathbb{Q}$ but then $-a \in \mathbb{Q}$ is a root, contradiction.

For $f(x) \in F[x]$ where F is a field ($f(x)$ is a polynomial in x with coefficients in the field F) and $r \in F$, we have:

r is a root of $f(x)$
ie. $f(r) = 0$
ie. r is a "zero" of $f(x)$

iff

$x-r$ is a ^{linear factor ie. factor of degree 1.} factor of $f(x)$

ie. $f(x) = (x-r)q(x)$, $q(x) \in F[x]$

In one direction this "iff" statement is obvious: if $f(x) = (x-r)q(x)$ then $f(r) = (r-r)q(r) = 0$.

What about the converse? By the Division Algorithm, $f(x) = q(x)(x-r) + a(x)$, $\deg a(x) < \deg(x-r)$

If r is a root of $f(x)$ then $f(r) = 0 = \frac{q(r)(r-r)}{0} + a \Rightarrow a = 0$
 $\Rightarrow f(x) = q(x)(x-r)$

$\deg a(x) < \deg(x-r)$
 $0 \text{ or } -\infty$
 $a(x) = a = \text{constant}$

We require the Division Algorithm for this.

Review the Division Algorithm for integers \mathbb{Z} :

Let $n, d \in \mathbb{Z}$ with $d \geq 1$. (OK for d negative but we cannot use $d=0$.) In general d won't divide n evenly; there is a remainder.

Theorem There exist unique $q, r \in \mathbb{Z}$ such that $n = qd + r$, $0 \leq r < d$.

Eg. $n=65$, $d=7$, $65 = \underline{9} \cdot 7 + \underline{2}$ $7 \nmid 65 \neq$

$$65 = \underline{8} \cdot 7 + \underline{9}$$

$$91 = \underline{13} \cdot 7 + \underline{0}$$

quotient remainder $7 \mid 91$

d divides n ($d \mid n$) $\iff n$ is a multiple of d , $n = qd$ (i.e. $r=0$).

Similarly in $F[x]$, F any field. eg. $\mathbb{Q}[x]$, $\mathbb{R}[x]$, ... not $\mathbb{Z}[x]$.

Theorem (Division Algorithm for polynomials) Let F be any field and let $f(x), d(x) \in F[x]$ where $\deg d(x) \geq 1$. Then there exist unique $q(x), r(x) \in F[x]$ such that

$$f(x) = q(x)d(x) + r(x), \quad \deg r(x) < \deg d(x).$$

Eg. $F = \mathbb{Q}$, $f(x) = x^3 - 2x - 3$, $d(x) = x^2 + x + 1$.

$$f(x) = x^3 - 2x - 3 = (x-1)(x^2 + x + 1) + (-2x - 2)$$

$d =$ "divisor"
 $q =$ "quotient"
 $r =$ "remainder"

$$\begin{array}{r} 9 \\ 7 \overline{) 65} \\ \underline{63} \\ 2 \end{array}$$

$$\begin{array}{r} x-1 \\ x^2+x+1 \overline{) x^3-2x-3} \\ \underline{x^3+x^2+x} \\ -x^2-3x-3 \\ \underline{-x^2-x-1} \\ -2x-2 \end{array}$$

$$x^2 + x + 1 = \left(-\frac{1}{2}x\right)(-2x-2) + (1)$$

$$-2x-2 \overline{) \begin{array}{l} x^2 + x + 1 \\ x^2 + x \\ \hline 1 \end{array}}$$

The Division Algorithm leads to Euclid's Algorithm (for \mathbb{Z} , $F[x]$, ...)
not $\mathbb{Z}[x]$

$$\gcd(100, 27) = 1 = a \cdot 100 + b \cdot 27 \quad \text{for some } a, b \in \mathbb{Z}$$

$$100 = 3 \times 27 + 19$$

$$27 = 1 \times 19 + 8$$

$$19 = 2 \times 8 + 3$$

$$8 = 2 \times 3 + 2$$

$$3 = 1 \times 2 + 1$$

$$2 = 2 \times 1 + 0$$

Last nonzero remainder

$$\gcd(100, 27) = 1 = 3 - 2$$

$$= 3 - (8 - 2 \times 3)$$

$$= 3 \times 3 - 8$$

$$= 3 \times (19 - 2 \times 8) - 8$$

$$= 3 \times 19 - 7 \times 8$$

$$= 3 \times 19 - 7 \times (27 - 19)$$

$$= 10 \times 19 - 7 \times 27$$

$$= 10 \times (100 - 3 \times 27) - 37 \times 27$$

$$= 10 \times 100 - 37 \times 27$$

$$= 1$$

Continue
Monday

Shorthand

100	27	
1	0	100
0	1	27
1	-3	19
-1	4	8
3	-11	3
-7	26	2
10	-37	1
*	*	0

$$\gcd(100, 27) = 1 = 10 \times 100 - 37 \times 27$$

Euclid's Algorithm uses repeated application of the Division Algorithm.
The last nonzero remainder is the gcd.

The gcd of two polynomials is the largest monic polynomial dividing both of them.
 Given $f(x), g(x) \in F[x]$ (F any field), $f(x), g(x)$ not both zero.

$d(x) = \gcd(f(x), g(x))$ is the largest monic polynomial such that $d(x) \mid f(x)$, $d(x) \mid g(x)$.
 We compute $d(x)$ using Euclid's Algorithm and it finds $a(x), b(x) \in F[x]$ such that
 $d(x) = a(x)f(x) + b(x)g(x)$.

Eg. $f(x) = x^3 - 2x - 3$
 $g(x) = x^2 + x + 1$

$f(x) = (x-1)g(x) + (-2x-2)$
 $\gcd(f(x), g(x)) = 1 = \left(\frac{1}{2}x\right)f(x) + \left(-\frac{1}{2}x^2 + \frac{1}{2}x + 1\right)g(x) \quad (*)$

$g(x) = \left(-\frac{1}{2}x\right)(-2x-2) + 1$
 $-2x-2 = (-2x-2)(1) + 0$
 $1 = g(x) + \left(\frac{1}{2}x\right)(-2x-2)$
 $= g(x) + \left(\frac{1}{2}x\right)(f(x) - (x-1)g(x))$
 $= \left(\frac{1}{2}x\right)f(x) + \left(1 - \frac{1}{2}x^2 + \frac{1}{2}x\right)g(x)$

Check: $\left(\frac{1}{2}x\right)(x^3 - 2x - 3) + \left(-\frac{1}{2}x^2 + \frac{1}{2}x + 1\right)(x^2 + x + 1) = 1$

x^2 terms: $-1 + 1 + \frac{1}{2} - \frac{1}{2} = 0$

x terms: $-\frac{3}{2} + \frac{1}{2} + 1 = 0$

constant: 1

Alternatively

	$f(x) = x^3 - 2x - 3$	$g(x) = x^2 + x + 1$	
①	1	0	$x^3 - 2x - 3$
②	0	1	$x^2 + x + 1$
③ = ① - (x)②	1	-x+1	-2x-2
④ = ② + ③	$\frac{1}{2}x$	$-\frac{1}{2}x^2 + \frac{1}{2}x + 1$	1
	*	*	0

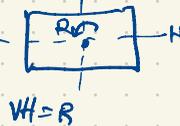
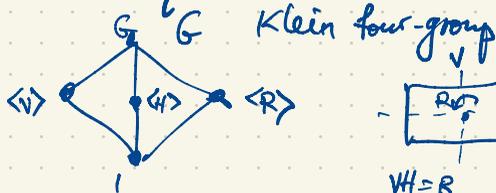
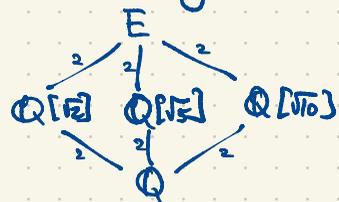
Recall: we considered the field $\mathbb{Q}[\theta] = \{a + b\theta + c\theta^2 : a, b, c \in \mathbb{Q}\}$, θ root of $f(x)$
 We computed $\alpha + \beta$, $\alpha - \beta$, $\alpha\beta$, $\frac{\alpha}{\beta}$ where $\alpha = \theta - 3$, $\beta = \theta^2 + \theta + 1 = g(\theta)$
 To find $\frac{1}{\beta}$, use $(*)$
 $\frac{1}{\beta} = -\frac{1}{2}\theta^2 + \frac{1}{2}\theta + 1$
 $1 = \left(\frac{1}{2}x\right)f(x) + \left(-\frac{1}{2}x^2 + \frac{1}{2}x + 1\right)g(x)$
 $1 = \left(\frac{1}{2}\theta\right)f(\theta) + \left(-\frac{1}{2}\theta^2 + \frac{1}{2}\theta + 1\right)g(\theta)$

$$E = \mathbb{Q}[\sqrt{2}, \sqrt{5}] = \{a + b\sqrt{2} + c\sqrt{5} + d\sqrt{10} : a, b, c, d \in \mathbb{Q}\}$$

$$[E : \mathbb{Q}] = 4 \text{ with basis } \{1, \sqrt{2}, \sqrt{5}, \sqrt{10}\}$$

E has subfields \mathbb{Q} , E , $\mathbb{Q}[\sqrt{2}]$, $\mathbb{Q}[\sqrt{5}]$, $\mathbb{Q}[\sqrt{10}]$

These are the only subfields (which is not quite obvious)



$$\mathbb{Q}[x], \mathbb{Q}[x, y]$$

$$\mathbb{Q}[x] \rightarrow \mathbb{Q}[\sqrt{2}] \subset \mathbb{R}$$

$$\begin{matrix} \cup \\ f(x) \mapsto f(\sqrt{2}) \end{matrix}$$

Evaluation maps are homomorphisms

$$f(x) + g(x) \mapsto f(\sqrt{2}) + g(\sqrt{2})$$

$$f(x)g(x) \mapsto f(\sqrt{2})g(\sqrt{2})$$

$$\mathbb{Q}[x, y] \rightarrow \mathbb{Q}[\sqrt{2}, \sqrt{5}] \subset \mathbb{R}$$

$$f(x, y) \mapsto f(\sqrt{2}, \sqrt{5})$$

homomorphism

$$[E : \mathbb{Q}[\sqrt{2}]] = 2 \text{ with basis } \{1, \sqrt{5}\}$$

Every $\alpha \in E$ i.e. $\alpha = a + b\sqrt{2} + c\sqrt{5} + d\sqrt{10}$ can be uniquely written as

$$\alpha = \underbrace{(a + b\sqrt{2})}_\uparrow \underbrace{1 + \sqrt{5}}_\uparrow$$

$\mathbb{Q}[\sqrt{2}] \quad \mathbb{Q}[\sqrt{2}]$

$$[E : E] = 1 \text{ with basis } \{1\}$$

Every $\alpha \in E$ can be uniquely expressed as

$$\alpha = (\alpha) \cdot 1$$

$$\text{Note: } [E : \mathbb{Q}] = [E : \mathbb{Q}[\sqrt{2}]] [\mathbb{Q}[\sqrt{2}] : \mathbb{Q}]$$

4 2 * 2

Given a "tower" of fields $E \supseteq K \supseteq F$ we have

$$[E : F] = [E : K][K : F]$$

$$\text{eg. } \underbrace{[\mathbb{C} : \mathbb{Q}]}_\infty = \underbrace{[\mathbb{C} : \mathbb{R}]}_2 \underbrace{[\mathbb{R} : \mathbb{Q}]}_\infty$$

Given a "tower" of fields $E \supseteq K \supseteq F$ we have
 $[E:F] = [E:K][K:F]$.

eg. $\underbrace{[C:\mathbb{Q}] = [C:\mathbb{R}][\mathbb{R}:\mathbb{Q}]}_{\infty = 2 \cdot \infty}$

If $[K:F] = m$ and $[E:K] = n$ then we have
 a basis $\{\alpha_1, \dots, \alpha_m\}$ we can choose a basis for K over F
 so every $\alpha \in K$ can be uniquely written as
 $\alpha = c_1\alpha_1 + c_2\alpha_2 + \dots + c_m\alpha_m$, $c_1, \dots, c_m \in F$.

Every $\beta \in E$ can be written uniquely as
 $\beta = b_1\beta_1 + b_2\beta_2 + \dots + b_n\beta_n$, $b_j \in K$
 $\{\beta_1, \dots, \beta_n\}$ basis for E over K .

$$b_j = a_{1j}\alpha_1 + a_{2j}\alpha_2 + \dots + a_{mj}\alpha_m, \quad a_{ij} \in F$$

$$= \sum_{i=1}^m a_{ij}\alpha_i$$

$$\beta = \sum_{j=1}^n b_j\beta_j = \sum_{j=1}^n \left(\sum_{i=1}^m a_{ij}\alpha_i \right) \beta_j = \sum_{i=1}^m \underbrace{\sum_{j=1}^n a_{ij}\alpha_i}_{\in F} \underbrace{\beta_j}_{\in E}$$

Note: $\sqrt[3]{2} \notin \mathbb{Q}[\sqrt{2}, \sqrt{5}]$.

$\mathbb{Q}[\sqrt[3]{2}] \supset \mathbb{Q}$ is an extension of degree 3.

Denoting $\alpha = \sqrt[3]{2} = 2^{1/3}$ we have $\mathbb{Q}[\alpha] = \{a + b\alpha + c\alpha^2 : a, b, c \in \mathbb{Q}\}$.

$\{1, \alpha, \alpha^2\}$ is a basis for $\mathbb{Q}[\alpha]$ over \mathbb{Q} . α has min. poly. $x^3 - 2$.

$E = \mathbb{Q}[\sqrt{2}, \sqrt{5}]$ cannot contain $\alpha = 2^{1/3}$.

If it did, we would have

$$E \supseteq \mathbb{Q}[\alpha] \supseteq \mathbb{Q}$$

$$[E:\mathbb{Q}] = [E:\mathbb{Q}[\alpha]][\mathbb{Q}[\alpha]:\mathbb{Q}]$$

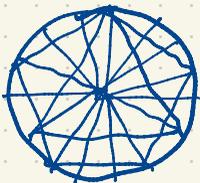
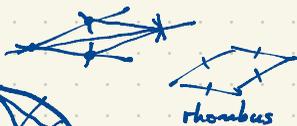
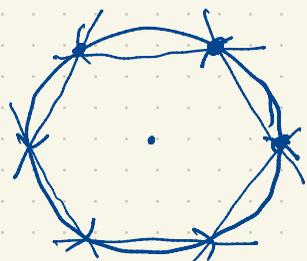
$$4 \qquad \qquad ? \qquad \qquad 3$$

contradiction.

Straightedge and Compass Constructions

Which regular n -gons are constructible using straightedge and compass?

$$n = 3, 8, 10, 4, 17, 5, \dots$$



A regular n -gon is constructible using straightedge and compass iff n is a power of 2 times a product of distinct Fermat primes.

A Fermat prime is a prime number that is one bigger than a power of 2 i.e.

$$2^m + 1$$

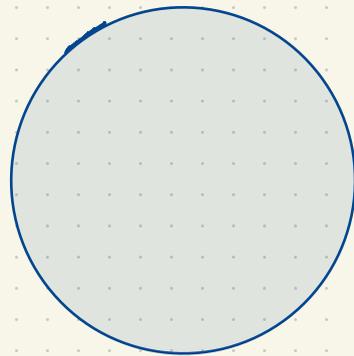
$$m = 2^k$$

We will prove that a regular 9-gon is not constructible using straightedge and compass.

k	$F_k = 2^{2^k} + 1$
0	3
1	5
2	17
3	257
4	65537
5	not prime

$$(2^2)^k = 2^{2k}$$

$$F_5 = 2^{32} + 1 = 4294967297$$



Are there any other Fermat primes? Unknown.

We suspect not.

This number theory!

Compare: for which n can we construct the roots of a poly. $f(x)$ of degree n using field operations $+, -, \times, \div$ and n^{th} roots

Answer: $n \leq 4$ only. Galois theory shows this, relying on facts about the group S_n which is not solvable for $n \geq 5$.

Compare: $\int x e^{x^2} dx = \frac{1}{2} e^{x^2} + C$.

$\int x^n e^{x^2} dx$ can be written in elementary form iff n is odd.

$\int e^{x^2} dx$ cannot be found in "elementary form"

Field theory

Has been used to prove impossibility of certain tasks eg.

- constructing a regular nonagon (9-gon), trisecting angle, etc. using straightedge and compass;
- "finding" roots of a typical poly. $f(x)$ of degree ≥ 5 using only $+, -, \times, \div, n^{\text{th}}$ roots
- finding $\int e^{x^2} dx$ in "elementary form"

Field theory also provides the tools/techniques/algorithms needed to constructively solve certain problems of these types eg.

- construct regular 17-gon
- finding roots of poly's when expressible using $+, -, \times, \div, n^{\text{th}}$ roots
- expressing antiderivatives in elementary form when possible

$$\int e^{x^2} dx = \int_0^x e^{t^2} dt + C$$

a^b^c means $a^{(b^c)}$ or $(a^b)^c$

$$(a^b)^c = a^{bc} = (a^c)^b$$

$\sqrt{2}^{\sqrt{2}^{\sqrt{2}^{\sqrt{2}}}}$ is the limit of a sequence $\sqrt{2}, \sqrt{2}^{\sqrt{2}}, \sqrt{2}^{\sqrt{2}^{\sqrt{2}}}, \sqrt{2}^{\sqrt{2}^{\sqrt{2}^{\sqrt{2}}}}, \dots$

i.e. the sequence $a_1, a_2, a_3, a_4, \dots$ where $a_1 = \sqrt{2}; a_{n+1} = \sqrt{2}^{a_n}$

Compare: $x = 1 + \frac{1}{1 + \frac{1}{1 + \frac{1}{1 + \frac{1}{1 + \frac{1}{\ddots}}}}}$ is the limit of the sequence $1, 1 + \frac{1}{1}, 1 + \frac{1}{1 + \frac{1}{1}}, 1 + \frac{1}{1 + \frac{1}{1 + \frac{1}{1}}}, \dots$

i.e. $b_0, b_1, b_2, b_3, \dots$ where $b_0 = 1;$

$$b_{n+1} = 1 + \frac{1}{b_n}$$

i.e. $1, 2, \frac{3}{2}, \frac{5}{3}, \frac{8}{5}, \frac{13}{8}, \frac{21}{13}, \frac{34}{21}, \frac{55}{34}, \frac{89}{55}, \frac{144}{89}, \dots$

$$x = 1 + \frac{1}{x}$$

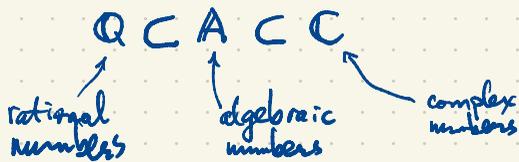
$$x^2 = x + 1$$

$$x^2 - x - 1 = 0$$

x is a root of $x^2 - x - 1$ so $x = \frac{1 \pm \sqrt{1+4}}{2} = \frac{1 \pm \sqrt{5}}{2}$

Since $x > 0$, $x = \frac{1 + \sqrt{5}}{2} \approx 1.618$ (Golden Ratio)

Use similar reasoning in #3, 4.



Can you find irrational numbers a, b such that a^b is rational?

Do these exist irrational $a, b > 0$ (positive real) such that a^b is rational?

..... $a, b > 0$ such that $a+b$ is rational? $\sqrt{2} + (7-\sqrt{2}) = 7$

..... ab is rational? eg $\sqrt{2} \cdot \sqrt{2} = 2$
 or $\sqrt{2} \cdot \frac{1}{\sqrt{2}} = 1$

Is $\sqrt{2}^{\sqrt{2}}$ rational or irrational?

If $\sqrt{2}^{\sqrt{2}} \in \mathbb{Q}$ then take $a = \sqrt{2}$ and $b = \sqrt{2}$.

If $\sqrt{2}^{\sqrt{2}} \notin \mathbb{Q}$ then take $a = \sqrt{2}^{\sqrt{2}}$ and $b = \sqrt{2}$, giving $a^b = (\sqrt{2}^{\sqrt{2}})^{\sqrt{2}} = \sqrt{2}^2 = 2 \in \mathbb{Q}$.

Theorem There do exist a, b positive real irrational numbers such that a^b is rational.

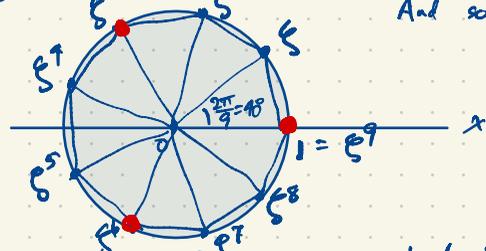
This is a nonconstructive proof.

Compare: the existence of transcendental numbers has an easy nonconstructive proof.

Liouville's constant $\sum_{n=1}^{\infty} \frac{1}{10^{n!}} = 0.11000100000000000000000001000\dots$

this was the first known explicit transcendental number.

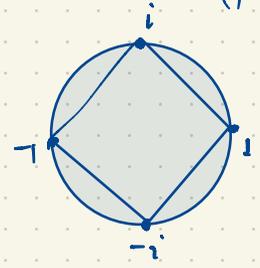
Regular 9-gon in the unit circle.



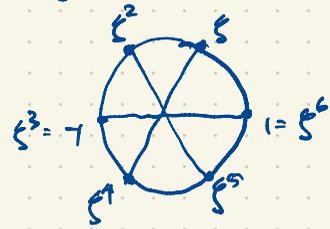
We will show that this figure is not constructible using straightedge and compass. And so it follows that a 120° angle cannot be trisected using " " " " You cannot trisect 60° angle.

Our argument will show that most angles cannot be trisected using straightedge and compass. But some can, e.g. 90° angles.

The vertices of the regular n -gon inscribed in a unit circle starting at $(1,0)$ are the n^{th} roots of unity in \mathbb{C} .



$n=4$

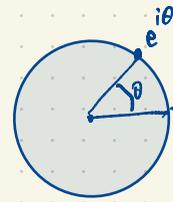


$n=6$

De Moivre's formula (see 'review' on complex numbers linked on the course website)

$$e^{i\theta} = \cos\theta + i \sin\theta \quad \text{for all } \theta \in \mathbb{C}$$

When $\theta \in \mathbb{R}$, $e^{i\theta} = (\cos\theta, \sin\theta)$ parameterizes the unit circle for $\theta \in [0, 2\pi]$.



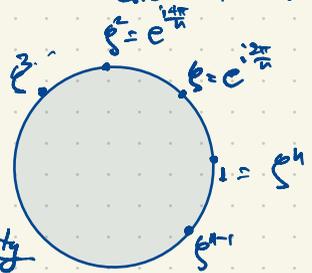
$\zeta = e^{2\pi i/n}$ is an algebraic number: it is a root of $x^n - 1 = (x-1)(x-\zeta)(x-\zeta^2)\dots(x-\zeta^{n-1})$

$$(\zeta^k)^n = (\zeta^n)^k = 1^k = 1$$

The n vertices of the regular n -gon are the n^{th} roots of unity in \mathbb{C} .

$\{1, \zeta, \zeta^2, \dots, \zeta^{n-1}\}$ is a multiplicative cyclic group. $\zeta^j \zeta^k = \zeta^{j+k}$ (exponents mod n).

Any element in this group generates a subgroup. If ζ^j generates the whole group, it's called a primitive n^{th} root of unity.



$$\zeta^n = (e^{i2\pi/n})^n = e^{i2\pi} = 1$$

Ex. for $n=9$, the 9th roots of unity form a cyclic group $\langle \zeta \rangle = \{1, \zeta, \zeta^2, \dots, \zeta^8\}$, $\zeta^9 = 1$

where $\zeta = e^{2\pi i/9}$ $\langle \zeta^3 \rangle = \{1, \zeta^3, \zeta^6\}$

There are six primitive 9th roots of unity: $\zeta, \zeta^2, \zeta^4, \zeta^5, \zeta^7, \zeta^8$. (every 9th root which is not a cube root of 1)

The 9 ninth roots of unity are the roots of

$$x^9 - 1 = (x-1)(x^8 + x^7 + x^6 + \dots + x + 1)$$

$$= (x^3 - 1)(x^6 + x^3 + 1) = (x-1)(x^2 + x + 1)(x^6 + x^3 + 1) \quad (\text{irreducible factors in } \mathbb{Q}[x])$$

root: 1
(the 1st root of unity)

roots: ζ^3, ζ^6
(the primitive cube roots of unity)

roots: $\zeta, \zeta^2, \zeta^4, \zeta^5, \zeta^7, \zeta^8$
(the primitive 9th roots of unity)

$$\phi(9) = 6$$

The 9th roots of unity add up to 0:

$$1 + \zeta + \zeta^2 + \dots + \zeta^8 = 0$$

The minimal poly. of ζ (over \mathbb{Q}) is $x^6 + x^3 + 1$.

$$\zeta = e^{2\pi i/9} = \cos \frac{2\pi}{9} + i \sin \frac{2\pi}{9} \quad \text{algebraic of degree 6}$$

$$\alpha = 2 \cos \frac{2\pi}{9} = \zeta + \zeta^{-1} = \zeta + \zeta^8 = \zeta + \bar{\zeta}$$

is algebraic of degree 3

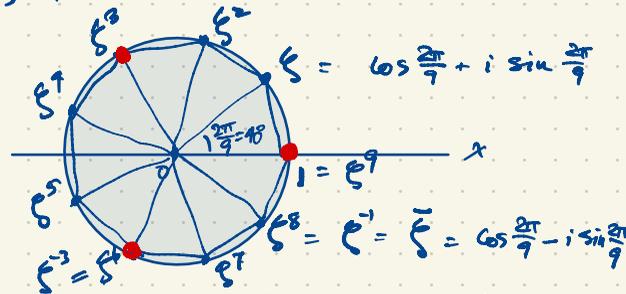
$$\alpha = \zeta + \zeta^{-1}$$

$$\alpha^2 = (\zeta + \zeta^{-1})(\zeta + \zeta^{-1}) = \zeta^2 + 2 + \zeta^{-2}$$

$$\alpha^3 = (\zeta + \zeta^{-1})^3 = \zeta^3 + 3\zeta + 3\zeta^{-1} + \zeta^{-3}$$

$$\alpha^3 - 3\alpha + 1 = 0 \quad = -1 + 3\alpha$$

the min. poly. of α is $x^3 - 3x + 1$



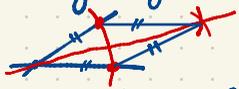
$$1 + \zeta^3 + \zeta^6 = 0 \Rightarrow \zeta^3 + \zeta^6 = -1$$

$$\zeta^3 + \zeta^{-3} = -1$$

$$(a+b)^3 = a^3 + 3a^2b + 3ab^2 + b^3$$

Now you can do hw2 #5.

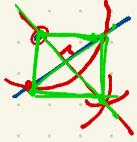
Straitedge & Compass Constructions



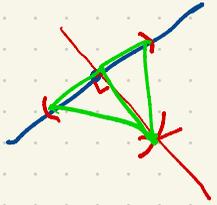
Rhombus

(parallelogram with sides of equal length)

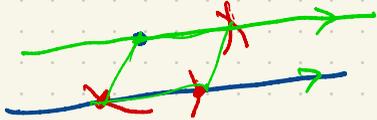
Bisecting an angle



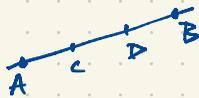
Dropping a perpendicular



Raising a perpendicular



Constructing a parallel line

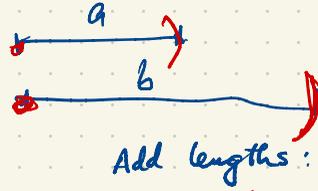


Trisecting a line segment

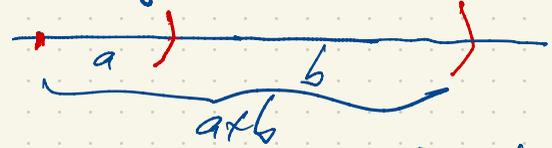
(or divide a line segment into n equal segments for any n)

Given points $A \neq B$, find (construct) points C, D on line AB such that AC, CD, DB all have the same length.

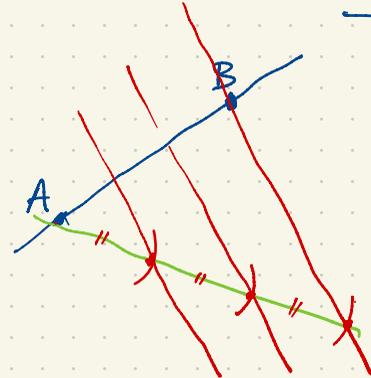
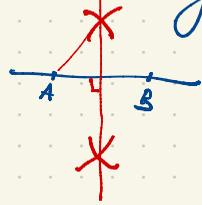
Given a line segment, multiply its length by any rational number.



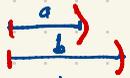
Add lengths:



Bisect line segment



Can we multiply the lengths of two line segments?



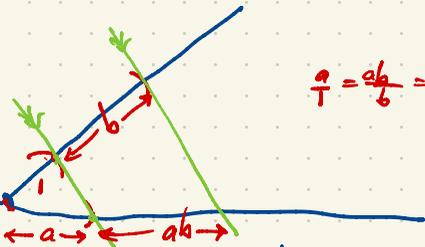
Given line segments of length a, b , can we construct a line segment of length ab ?



First specify a unit length: $\rightarrow 1$

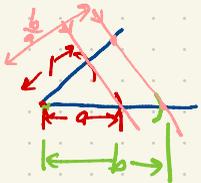
Now:

Draw any angle (not 0° or 180°)

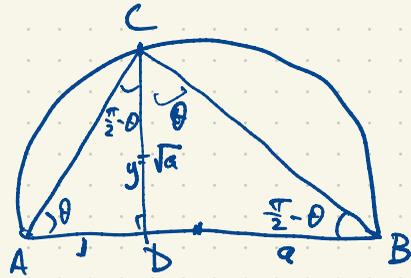


$$\frac{a}{1} = \frac{ab}{b} = \frac{a+ab}{1+b}$$

We can also divide $\frac{b}{a}$



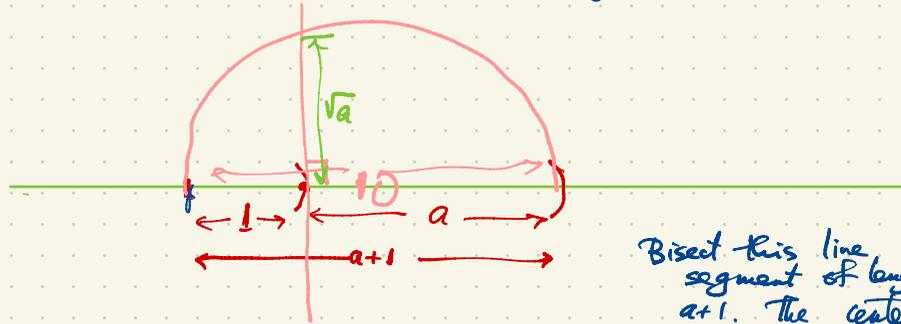
Can we find a line segment of length \sqrt{a} , given line segments of length 1 and a ?



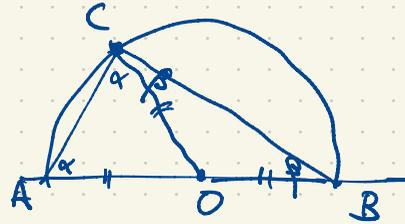
The three triangles in this picture are similar:

$\triangle ADC$, $\triangle CDB$, $\triangle ACB$

$$\frac{y}{1} = \frac{y}{a} \Rightarrow y^2 = a \Rightarrow y = \sqrt{a}$$



Bisect this line segment of length $a+1$. The center is at a point we'll call O . Construct the semicircle centered at O of radius equal to the distance shown.



$$\alpha + (\alpha + \beta) + \beta = \pi$$

$$\alpha + \beta = \frac{\pi}{2}$$

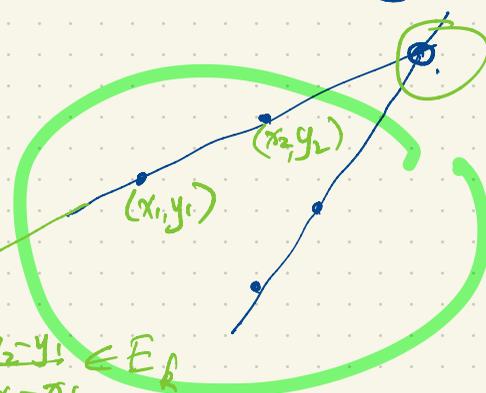
At the start, all points in our construction are in \mathbb{Q}^2 .
 Let E_k be the field generated by all coordinates of points up to step k .

$$E_0 = \mathbb{Q}$$

By induction we have $[E_{k+1} : E_k] = 1 \text{ or } 2 \Rightarrow [E_n : \mathbb{Q}] \in \{1, 2, 4, 8, \dots, 2^n\}$.

We only need to consider a step which produces new points.

If in step k we are intersecting two lines through previously constructed points



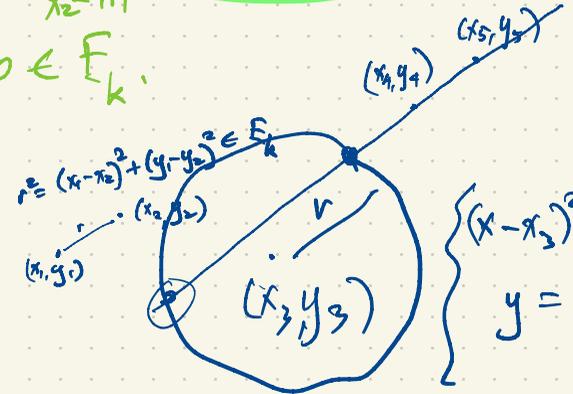
new point will have coordinates also in E_k
 $\Rightarrow E_{k+1} = E_k$.

$$y = mx + b$$

$$m = \frac{y_2 - y_1}{x_2 - x_1} \in E_k$$

$$b \in E_k$$

Coordinates in E_k .



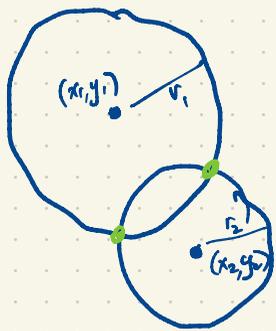
If in step k we are intersecting a previous line with a previous circle, the new points (x, y) will have coordinates in E_{k+1} , where $[E_{k+1} : E_k] = 1 \text{ or } 2$.

$$\begin{cases} (x-x_3)^2 + (y-y_3)^2 = r^2 \\ y = mx + b \end{cases}$$

$$\begin{aligned} x_3, y_3, r^2 &\in E_k \\ m = \frac{y_5 - y_4}{x_5 - x_4} &\in E_k \\ b &\in E_k \end{aligned}$$

If in step k we are intersecting two previous circles

$$x_1, x_2, y_1, y_2, r_1, r_2 \in E_k$$



$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 = r_1^2 \\ (x-x_2)^2 + (y-y_2)^2 = r_2^2 \end{cases}$$

$$\Leftrightarrow \begin{cases} x^2 - 2x_1x + x_1^2 + y^2 - 2y_1y + y_1^2 = r_1^2 \\ x^2 - 2x_2x + x_2^2 + y^2 - 2y_2y + y_2^2 = r_2^2 \end{cases}$$

$$\Leftrightarrow \begin{cases} x^2 - 2x_1x + x_1^2 + y^2 - 2y_1y + y_1^2 = r_1^2 \\ 2(x_1-x_2)x + x_2^2 - x_1^2 + 2(y_1-y_2)y + y_2^2 - y_1^2 = r_2^2 - r_1^2 \end{cases}$$