The Complexity of Mathematical Problems

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Do the following statements

- the four colour theorem,
- Fermat's great theorem,
- the Riemann hypothesis,
- the Collatz's conjecture?

share a common mathematical property?

And, if there is such a property, how can we use it for a better understanding of these statements?

Universality theorem. There exists (and can be constructed) a (Turing) machine U—called *universal*—such that for every machine V there exists a constant $c = c_{U,V}$ such that for every program σ there exists a σ' for which the following two conditions hold:

- $U(\sigma') = V(\sigma)$,
- $|\sigma'| \leq |\sigma| + c$.

The **halting problem** for a machine V is the function Λ_V defined by

$$\Lambda_V(\sigma) = \begin{cases} 1, & \text{if } V(\sigma) = \infty, \\ 0, & \text{otherwise}. \end{cases}$$

Undecidability theorem. If U is universal, then Λ_U is incomputable, i.e. the halting problem for a universal machine is undecidable.

Π_1–problems

A problem π of the form

$$\forall \sigma P(\sigma),$$

where P is a computable predicate is called a Π_1–*problem*.

- Any Π_1–problem is finitely refutable.
- For every Π_1–problem $\pi = \forall \sigma P(\sigma)$ we associate the program

$$\sigma_\pi = \inf\{n : P(n) = \text{ false}\}$$

  which satisfies:

$$\pi \text{ is true iff } U(\sigma_\pi) = \infty.$$

- Solving the halting problem for U solves all Π_1–problems.

Examples

The problems

- the four colour theorem,
- Fermat's great theorem,
- the Riemann hypothesis,
- the Collatz's conjecture

are all Π_1–problems.

Of course, not all problems are Π_1–problems. For example, the twin prime conjecture.

Complexity

$$C_U(\pi) = \min\{|\Pi_P| : \pi = \forall n P(n)\}.$$

Invariance theorem. If U, U' are universal, then there exists a constant $c = c_{U,U'}$ such that for all $\pi = \forall n P(n)$, P computable:

$$|C_U(\pi) - C_{U'}(\pi)| \leq c.$$

Incomputability theorem. If U is universal, then C_U is incomputable.

Because of the incomputability theorem, we work with upper bounds for C_U. As the exact value of C_U is not important, we classify Π_1–problems into the following classes:

$$\mathfrak{C}_{U,n} = \{\pi : \pi \text{ is a } \Pi_1\text{–problem}, C_U(\pi) \leq n \text{ kbit}\}.$$

Some Results

- $\mathfrak{C}_{U,1}$: *Legendre's conjecture* (there is a prime number between n^2 and $(n+1)^2$, for every positive integer n), *Fermat's last theorem* (there are no positive integers x, y, z satisfying the equation $x^n + y^n = z^n$, for any integer value $n > 2$) and *Goldbach's conjecture* (every even integer greater than 2 can be expressed as the sum of two primes)
- $\mathfrak{C}_{U,2}$: *Dyson's conjecture* (the reverse of a power of two is never a power of five)
- $\mathfrak{C}_{U,3}$: *the Riemann hypothesis* (all non-trivial zeros of the Riemann zeta function have real part 1/2)
- $\mathfrak{C}_{U,4}$ *the four colour theorem* (the vertices of every planar graph can be coloured with at most four colours so that no two adjacent vertices receive the same colour)

More Results and Open Questions

- $\mathfrak{C}_{U,5}$: ?
- $\mathfrak{C}_{U,6}$: ?
- $\mathfrak{C}_{U,7}$: *Euler's integer partition theorem* (the number of partitions of an integer into odd integers is equal to the number of partitions into distinct integers).
- In which class is *the Collatz conjecture*? (given any positive integer a_1 there exists a natural N such that $a_N = 1$, where

$$a_{n+1} = \begin{cases} a_n/2, & \text{if } a_n \text{ is even,} \\ 3a_n + 1, & \text{otherwise}. \end{cases} \Bigg)$$

Inductive Complexity and Complexity Classes of First Order

By transforming each program Π_P for U into a program $\Pi_P^{ind,1}$ for U^{ind} (U working in "inductive mode") we can define the inductive complexity of first order by

$$C_U^{ind,1}(\pi) = \min\{|\Pi_P^{ind,1}| : \pi = \forall n P(n)\},$$

the inductive complexity classes of order one by

$$\mathfrak{C}_{U,n}^{ind,1} = \{\pi : \pi \text{ is a } \Pi_1\text{–statement}, C_U^{ind,1}(\pi) \leq n \text{ kbit}\},$$

and prove that

$$\mathfrak{C}_{U,n} = \mathfrak{C}_{U,n}^{ind,1}.$$

By allowing inductive programs of order 1 as routines we get inductive programs of order 2, so we can define the inductive complexity of second order (for more complex problems)

$$C_U^{ind,2}(\rho) = \min\{|M_R^{ind,2}| : \rho = \forall n \exists i R(n,i)\},$$

and the inductive complexity class of second order:

$$\mathfrak{C}_{U,n}^{ind,2} = \{\rho : \rho = \forall n \exists i R(n,i), C_U^{ind,2}(\rho) \leq n \text{ kbit}\}.$$

The Collatz conjecture is in the class $\mathfrak{C}_{U,3}^{ind,2}$.

Two open problems

What is the complexity of

- P vs NP problem?
- Poincaré's conjecture?

Thank you

VIVE ERIC!