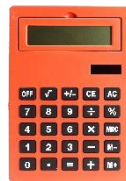


函数的渐进比较:  $O$  符号

- 在实际应用中，计算某个问题的精确解可能非常困难。此时，一个可行的方案是：不直接寻找精确解，转而寻找可接受的**估值(estimate)**。

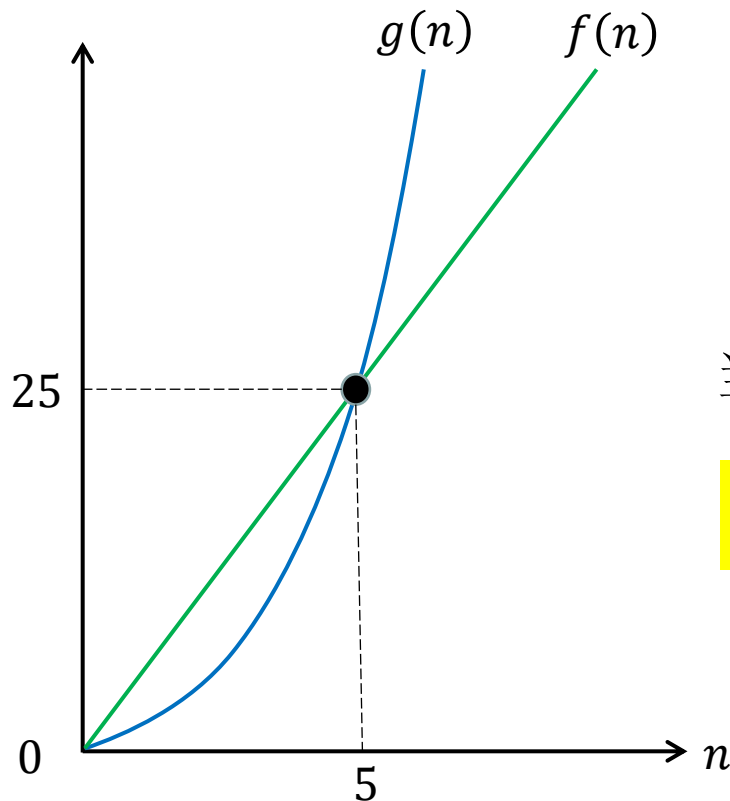
- 精确解困难的原因：
  - 物理设备的差异
  - 数据量激增
  - 精确计算公式复杂
  - 网络环境、自然环境
  - .....

- 1 Bit = Binary Digit
- 8 Bits = 1 Byte
- 1024 Bytes = 1 Kilobyte
- 1024 Kilobytes = 1 Megabyte
- 1024 Megabytes = 1 Gigabyte
- 1024 Gigabytes = 1 Terabyte
- 1024 Terabytes = 1 Petabyte
- 1024 Petabytes = 1 Exabyte
- 1024 Exabytes = 1 Zettabyte
- 1024 Zettabytes = 1 Yottabyte
- 1024 Yottabytes = 1 Brontobyte
- 1024 Brontobytes = 1 Geopbyte



# 函数的比较

- 比较：  $f(n) = 5n$  以及  $g(n) = n^2$  ， 其中  $n \in N$  为自然数。



当  $n \rightarrow \infty$  时，  $f(n)$  的增长不快于  $g(n)$

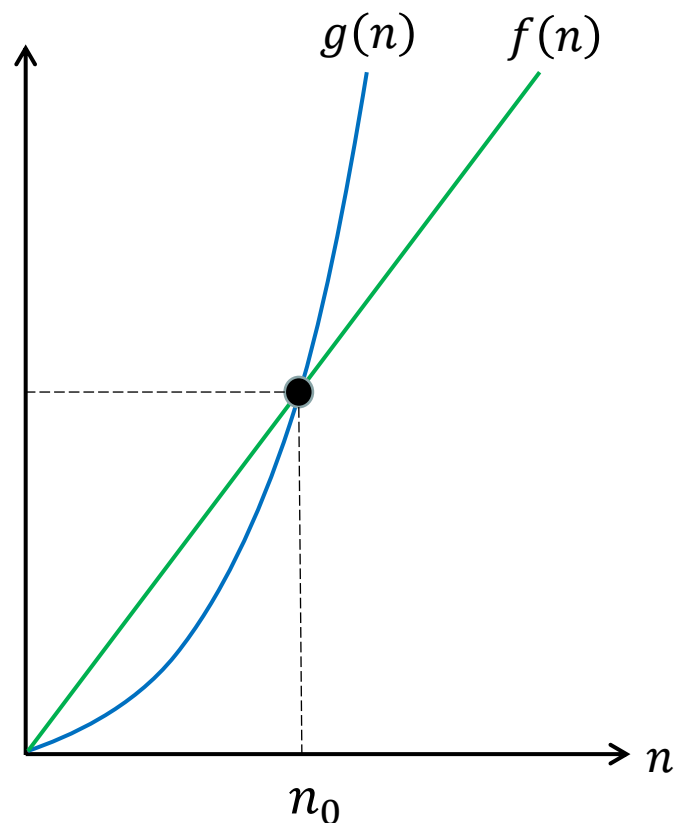
$$f(n) = O(g(n))$$

# 函数的渐进比较(Asymptotic comparison)

**定义：**  $f, g: N \rightarrow R$  是两个从自然数到实数的单变量方程

$$f(n) = O(g(n))$$

表示存在常数  $n_0$  和  $C$ ，使得对所有  $n \geq n_0$ ，不等式  $|f(n)| \leq C \cdot g(n)$  成立。



直观：  $f$  的增长不比  $g$  快很多。即：  $\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} \nrightarrow \infty$

# 一些例子

- $1000000 = O(1)$
- $(7n^2 + 6n + 1)(n^3 + 4) = O(n^5)$
- $\binom{n}{2} = n(n-1)/2 = \frac{1}{2}n^2 + O(n) = O(n^2)$
- $0 < \alpha \leq \beta \Rightarrow n^\alpha = O(n^\beta)$
- $\forall C > 0, a > 1 \quad n^C = O(a^n)$
- $\forall C > 0, \alpha > 0 \quad (\ln n)^C = O(n^\alpha)$
- 在函数的渐进比较中，部分常用的其他符号如下：

# 函数的渐进比较

符号	定义	含义
$f(n) = O(g(n))$	$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} \nrightarrow \infty$	$f$ 的增长不比 $g$ 快很多
$f(n) = o(g(n))$	$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 0$	$f$ 的增长远远慢于 $g$
$f(n) = \Omega(g(n))$	$g(n) = O(f(n))$	$f$ 的增长至少和 $g$ 一样快
$f(n) = \Theta(g(n))$	$f(n) = O(g(n))$ 且 $f(n) = \Omega(g(n))$	$f$ 和 $g$ 几乎是同一数量级
$f(n) \sim g(n)$	$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 1$	$f(n)$ 和 $g(n)$ 几乎是一样的

# 调和级数

- 调和级数(Harmonic number):

$$H_n = 1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n} = \sum_{i=1}^n \frac{1}{i}$$

# 调和级数估值

- 估计调和级数的值：用数列对调和级数的加项做分类。

$$\begin{array}{ccccccccc}
 \bullet & 1, & \frac{1}{2}, \frac{1}{3}, & \frac{1}{4}, \frac{1}{5}, \frac{1}{6}, \frac{1}{7}, & \frac{1}{8}, \frac{1}{9}, \dots, \frac{1}{15}, & \frac{1}{16}, \frac{1}{17}, \dots & & \\
 & \underbrace{\hspace{1.5cm}} & \underbrace{\hspace{1.5cm}} & \underbrace{\hspace{2.5cm}} & \underbrace{\hspace{2.5cm}} & \underbrace{\hspace{2.5cm}} & & \\
 & \left( \frac{1}{2^1}, \frac{1}{2^0} \right] & \left( \frac{1}{2^2}, \frac{1}{2^1} \right] & \left( \frac{1}{2^3}, \frac{1}{2^2} \right] & \left( \frac{1}{2^4}, \frac{1}{2^3} \right] & \left( \frac{1}{2^5}, \frac{1}{2^4} \right] & & \\
 & G_1 & G_2 & G_3 & G_4 & G_5 & & 
 \end{array}$$

$$\begin{aligned}
 G_k &= \left\{ \frac{1}{i} \mid \frac{1}{2^k} < \frac{1}{i} \leq \frac{1}{2^{k-1}} \right\} \\
 &= \left\{ \frac{1}{2^{k-1}}, \frac{1}{2^{k-2}}, \frac{1}{2^{k-3}}, \dots, \frac{1}{2^{k-1}} \right\}
 \end{aligned}$$



$$\underbrace{1}_{G_1}, \quad \underbrace{\frac{1}{2}, \frac{1}{3}}_{G_2}, \quad \underbrace{\frac{1}{4}, \frac{1}{5}, \frac{1}{6}, \frac{1}{7}}_{G_3}, \quad \underbrace{\frac{1}{8}, \frac{1}{9}, \dots, \frac{1}{15}}_{G_4}, \dots$$

$$\begin{aligned} G_k &= \left\{ \frac{1}{i} \mid \frac{1}{2^k} < \frac{1}{i} \leq \frac{1}{2^{k-1}} \right\} \\ &= \left\{ \frac{1}{2^{k-1}}, \frac{1}{2^{k-2}}, \frac{1}{2^{k-3}}, \dots, \frac{1}{2^{k-1}} \right\} \\ &= \left\{ \frac{1}{2^{k-1}}, \frac{1}{2^{k-1}+1}, \frac{1}{2^{k-1}+2}, \dots, \frac{1}{2^{k-1}} \right\} \end{aligned}$$

$$|G_k| = 2^{k-1}$$

每一个  $G_k$  中的调和级数加项和：

$$\begin{aligned} \sum_{x \in G_k} x &\leq |G_k| \max G_k \\ &= 2^{k-1} \cdot \frac{1}{2^{k-1}} \\ &= 1 \\ \sum_{x \in G_k} x &\geq |G_k| \min G_k \\ &> 2^{k-1} \cdot \frac{1}{2^k} \\ &= \frac{1}{2} \end{aligned}$$

$$\underbrace{1}_{G_1}, \quad \underbrace{\frac{1}{2}, \frac{1}{3}}_{G_2}, \quad \underbrace{\frac{1}{4}, \frac{1}{5}, \frac{1}{6}, \frac{1}{7}}_{G_3}, \quad \underbrace{\frac{1}{8}, \frac{1}{9}, \dots, \frac{1}{15}}_{G_4}, \dots$$

$$\begin{aligned} G_k &= \left\{ \frac{1}{i} \mid \frac{1}{2^k} < \frac{1}{i} \leq \frac{1}{2^{k-1}} \right\} \\ &= \left\{ \frac{1}{2^{k-1}}, \frac{1}{2^{k-2}}, \frac{1}{2^{k-3}}, \dots, \frac{1}{2^{k-1}} \right\} \\ &= \left\{ \frac{1}{2^{k-1}}, \frac{1}{2^{k-1}+1}, \frac{1}{2^{k-1}+2}, \dots, \frac{1}{2^{k-1}} \right\} \end{aligned}$$

$$|G_k| = 2^{k-1}$$

每一个  $G_k$  中的调和级数加项和：

$$\begin{aligned} \sum_{x \in G_k} x &\leq |G_k| \max G_k \\ &= 2^{k-1} \cdot \frac{1}{2^{k-1}} \\ &= 1 \end{aligned}$$

$$\frac{1}{2} < \sum_{x \in G_k} x \leq 1$$

$$= \frac{1}{2}$$

$$H_n = \underbrace{1}_{G_1} + \underbrace{\frac{1}{2} + \frac{1}{3}}_{G_2} + \frac{1}{4} + \cdots + \underbrace{\frac{1}{n-2} + \frac{1}{n-1} + \frac{1}{n}}_{G_t}$$

$$G_k = \left\{ \frac{1}{i} \mid \frac{1}{2^k} < \frac{1}{i} \leq \frac{1}{2^{k-1}} \right\}$$

$$\frac{1}{2} < \sum_{x \in G_k} x \leq 1$$

$$2^{k-1} \leq i < 2^k$$

$$k = \lfloor \log_2 i \rfloor + 1 \quad \text{故 } t = \lfloor \log_2 n \rfloor + 1$$

$$H_n \leq t \cdot 1 \leq \log_2 n + 1$$

$$H_n > (t - 1) \cdot \frac{1}{2} \geq \frac{1}{2} \lfloor \log_2 n \rfloor$$

$$H_n = \underbrace{1}_{G_0} + \underbrace{\frac{1}{2} + \frac{1}{3}}_{G_1} + \frac{1}{4} + \cdots + \underbrace{\frac{1}{n-2} + \frac{1}{n-1} + \frac{1}{n}}_{G_t}$$

$$G_k = \left\{ \frac{1}{i} \mid \frac{1}{2^k} < \frac{1}{i} \leq \frac{1}{2^{k-1}} \right\}$$

$$\frac{1}{2} < \sum_{x \in G_k} x \leq 1$$

$$2^{k-1} \leq i < 2^k$$

$$k = \lfloor \log_2 i \rfloor + 1 \quad \text{故} \quad t = \lfloor \log_2 n \rfloor + 1$$

$$\left. \begin{aligned} H_n &\leq t \cdot 1 \leq \log_2 n + 1 \\ H_n &> (t-1) \cdot \frac{1}{2} \geq \frac{1}{2} \lfloor \log_2 n \rfloor \end{aligned} \right\} \quad \begin{aligned} H_n &= \Theta(\log_2 n) \\ &= \Theta(\ln n) \end{aligned}$$