

Catalan Numbers

c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}
1	1	2	5	14	42	132	429	1430	4862	16796

On-Line Encyclopedia of Integer Sequences, <http://oeis.org/>

$$c_n = \frac{1}{n+1} \binom{2n}{n}.$$

Catalan Numbers

c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}
1	1	2	5	14	42	132	429	1430	4862	16796

On-Line Encyclopedia of Integer Sequences, <http://oeis.org/>

$$c_n = \frac{1}{n+1} \binom{2n}{n}.$$

Richard Stanley has compiled a list of combinatorial interpretations of Catalan numbers. As of 5/13, numbered (a) to (z), ... (a⁸) to (y⁸).²⁰⁷

Catalan Numbers

c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}
1	1	2	5	14	42	132	429	1430	4862	16796

On-Line Encyclopedia of Integer Sequences, <http://oeis.org/>

$$c_n = \frac{1}{n+1} \binom{2n}{n}.$$

Richard Stanley has compiled a list of combinatorial interpretations of Catalan numbers. As of 5/13, numbered (a) to (z), ... (a⁸) to (y⁸).207

triangulations
of an $(n+2)$ -gon

lattice paths from $(0, 0)$
to (n, n) above $y = x$

sequences with n +1's, n -1's
with positive partial sums

multiplication schemes
to multiply $n + 1$ numbers

Catalan Number Interpretations

When $n = 3$, there are $c_3 = 5$ members of these families of objects:

1. Triangulations of an $(n + 2)$ -gon

Catalan Number Interpretations

When $n = 3$, there are $c_3 = 5$ members of these families of objects:

1. Triangulations of an $(n + 2)$ -gon
2. Lattice paths from $(0, 0)$ to (n, n) staying above $y = x$

Catalan Number Interpretations

When $n = 3$, there are $c_3 = 5$ members of these families of objects:

1. Triangulations of an $(n + 2)$ -gon
2. Lattice paths from $(0, 0)$ to (n, n) staying above $y = x$
3. Sequences of length $2n$ with $n + 1$'s and $n - 1$'s such that every partial sum is ≥ 0

Catalan Number Interpretations

When $n = 3$, there are $c_3 = 5$ members of these families of objects:

1. Triangulations of an $(n + 2)$ -gon
2. Lattice paths from $(0, 0)$ to (n, n) staying above $y = x$
3. Sequences of length $2n$ with $n + 1$'s and $n - 1$'s such that every partial sum is ≥ 0
4. Ways to multiply $n + 1$ numbers together two at a time.

Catalan Bijections

We claim that these objects are all counted by the Catalan numbers.
So there should be **bijections** between the sets!

Catalan Bijections

We claim that these objects are all counted by the Catalan numbers. So there should be **bijections** between the sets!

Bijection 1:

triangulations of an $(n+2)$ -gon

 \longleftrightarrow

multiplication schemes to multiply $n+1$ numbers

Rule: Label all but one side of the $(n+2)$ -gon in order. Work your way in from the outside to label the interior edges of the triangulation: When you know two sides of a triangle, the third edge is the product of the two others. Determine the mult. scheme on the last edge.

Catalan Bijections

Bijection 2:

multiplication schemes to multiply $n + 1$ #'s

 \longleftrightarrow

seqs with $n + 1$'s, $n - 1$'s with positive partial sums

Rule: Place dots to represent multiplications. Ignore everything except the dots and right parentheses. Replace the dots by $+1$'s and the parentheses by -1 's.

Catalan Bijections

Bijection 3: seqs with n $+1$'s, n -1 's
with positive partial sums \longleftrightarrow lattice paths $(0, 0)$ to
 (n, n) above $y = x$

A sequence of $+$'s and $-$'s converts to a sequence of N 's and E 's, which is a path in the lattice.

Catalan Numbers

The underlying reason why so many combinatorial families are counted by the Catalan numbers comes back to the **generating function equation** that $C(x)$ satisfies:

$$C(x) = 1 + xC(x)^2.$$

Catalan Numbers

The underlying reason why so many combinatorial families are counted by the Catalan numbers comes back to the **generating function equation** that $C(x)$ satisfies:

$$C(x) = 1 + xC(x)^2.$$

Example.

triangulations
of an $(n+2)$ -gon

Here, x represents
one side of the polygon

Either the triangulation has a side or not.

1. No side: Empty triangulation (of *digon*): x^0 .
2. Every other triangulation has one side (x contribution) and is a **sequence of** two other triangulations $C(x)^2$.

Catalan Numbers

Example.

lattice paths $(0, 0)$ to
 (n, n) above $y = x$

Here, x represents an
up-step down-step pair.

Either the lattice path starts with a vertical step or not.

1. No step: Empty lattice path: x^0 .
2. Every other lattice path has one vertical step up from diag. and a first horizontal step returning to diag. (x contribution).
“Between the V & H steps” and “after the H step”
is a sequence of two lattice paths $C(x)^2$.

Therefore, $C(x) = 1 + xC(x)^2$.

A formula for the Catalan Numbers

Solve the generating function equation to find $C(x) = \frac{1 \pm \sqrt{1 - 4x}}{2x}$.

A formula for the Catalan Numbers

Solve the generating function equation to find $C(x) = \frac{1 \pm \sqrt{1 - 4x}}{2x}$.
Do we take the positive or negative root? Check $x = 0$.

A formula for the Catalan Numbers

Solve the generating function equation to find $C(x) = \frac{1 \pm \sqrt{1 - 4x}}{2x}$.
Do we take the positive or negative root? Check $x = 0$.

Now extract coefficients to prove the formula for c_n .

Claim: $\sqrt{1 - 4x} = 1 + \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$. (Next slide.)

A formula for the Catalan Numbers

Solve the generating function equation to find $C(x) = \frac{1 \pm \sqrt{1 - 4x}}{2x}$.
Do we take the positive or negative root? Check $x = 0$.

Now extract coefficients to prove the formula for c_n .

Claim: $\sqrt{1 - 4x} = 1 + \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$. (Next slide.)

Conclusion. $\frac{1}{2x}(1 - \sqrt{1 - 4x}) = -\frac{1}{2x} \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$

A formula for the Catalan Numbers

Solve the generating function equation to find $C(x) = \frac{1 \pm \sqrt{1 - 4x}}{2x}$.
Do we take the positive or negative root? Check $x = 0$.

Now extract coefficients to prove the formula for c_n .

Claim: $\sqrt{1 - 4x} = 1 + \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$. (Next slide.)

Conclusion. $\frac{1}{2x}(1 - \sqrt{1 - 4x}) = -\frac{1}{2x} \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$
 $= \sum_{k \geq 1} \frac{1}{k} \binom{2(k-1)}{k-1} x^{k-1}$

A formula for the Catalan Numbers

Solve the generating function equation to find $C(x) = \frac{1 \pm \sqrt{1 - 4x}}{2x}$.
Do we take the positive or negative root? Check $x = 0$.

Now extract coefficients to prove the formula for c_n .

Claim: $\sqrt{1 - 4x} = 1 + \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$. (Next slide.)

Conclusion. $\frac{1}{2x}(1 - \sqrt{1 - 4x}) = -\frac{1}{2x} \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$
 $= \sum_{k \geq 1} \frac{1}{k} \binom{2(k-1)}{k-1} x^{k-1}$
 $= \sum_{n \geq 0} \frac{1}{n+1} \binom{2n}{n} x^n$

A formula for the Catalan Numbers

Solve the generating function equation to find $C(x) = \frac{1 \pm \sqrt{1 - 4x}}{2x}$.
Do we take the positive or negative root? Check $x = 0$.

Now extract coefficients to prove the formula for c_n .

Claim: $\sqrt{1 - 4x} = 1 + \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$. (Next slide.)

Conclusion. $\frac{1}{2x}(1 - \sqrt{1 - 4x}) = -\frac{1}{2x} \sum_{k \geq 1} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k$
 $= \sum_{k \geq 1} \frac{1}{k} \binom{2(k-1)}{k-1} x^{k-1}$
 $= \sum_{n \geq 0} \frac{1}{n+1} \binom{2n}{n} x^n$

Therefore, $c_n = \frac{1}{n+1} \binom{2n}{n}$.

Expansion of $\sqrt{1 - 4x}$

What is the power series expansion of $\sqrt{1 - 4x}$?

$$\sqrt{1 - 4x} = ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k \quad \text{Expand } \binom{1/2}{k}$$

Expansion of $\sqrt{1-4x}$

What is the power series expansion of $\sqrt{1-4x}$?

$$\begin{aligned}\sqrt{1-4x} &= ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k && \text{Expand } \binom{1/2}{k} \\ &= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(\frac{1}{2}-1)\cdots(\frac{1}{2}-k+1)}{k!} (-4x)^k && \text{Denom. of } \frac{1}{2}\end{aligned}$$

Expansion of $\sqrt{1-4x}$

What is the power series expansion of $\sqrt{1-4x}$?

$$\begin{aligned} \sqrt{1-4x} &= ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k && \text{Expand } \binom{1/2}{k} \\ &= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(\frac{1}{2}-1)\cdots(\frac{1}{2}-k+1)}{k!} (-4x)^k && \text{Denom. of } \frac{1}{2} \\ &= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(-\frac{1}{2})\cdots(-\frac{2k-3}{2})}{k!} (-1)^k 4^k x^k && \text{Factor } -2\text{'s} \end{aligned}$$

Expansion of $\sqrt{1-4x}$

What is the power series expansion of $\sqrt{1-4x}$?

$$\sqrt{1-4x} = ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k \quad \text{Expand } \binom{1/2}{k}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(\frac{1}{2}-1)\cdots(\frac{1}{2}-k+1)}{k!} (-4x)^k \quad \text{Denom. of } \frac{1}{2}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(-\frac{1}{2})\cdots(-\frac{2k-3}{2})}{k!} (-1)^k 4^k x^k \quad \text{Factor } -2\text{'s}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{(-1)^{k-1}(1)\cdots(2k-3)}{k!2^k} (-1)^k 4^k x^k \quad \text{Simplify; rewrite prod.}$$

Expansion of $\sqrt{1-4x}$

What is the power series expansion of $\sqrt{1-4x}$?

$$\sqrt{1-4x} = ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k \quad \text{Expand } \binom{1/2}{k}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(\frac{1}{2}-1)\cdots(\frac{1}{2}-k+1)}{k!} (-4x)^k \quad \text{Denom. of } \frac{1}{2}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(-\frac{1}{2})\cdots(-\frac{2k-3}{2})}{k!} (-1)^k 4^k x^k \quad \text{Factor } -2\text{'s}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{(-1)^{k-1}(1)\cdots(2k-3)}{k!2^k} (-1)^k 4^k x^k \quad \text{Simplify; rewrite prod.}$$

$$= 1 + \sum_{k=1}^{\infty} -\frac{1\cdot 2\cdot 3\cdot 4\cdots(2k-3)\cdot(2k-2)}{k!\cdot 2\cdot 4\cdots(2k-2)} 2^k x^k \quad \text{Write as factorials}$$

Expansion of $\sqrt{1-4x}$

What is the power series expansion of $\sqrt{1-4x}$?

$$\sqrt{1-4x} = ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k$$

Expand $\binom{1/2}{k}$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(\frac{1}{2}-1)\cdots(\frac{1}{2}-k+1)}{k!} (-4x)^k$$

Denom. of $\frac{1}{2}$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(-\frac{1}{2})\cdots(-\frac{2k-3}{2})}{k!} (-1)^k 4^k x^k$$

Factor -2 's

$$= 1 + \sum_{k=1}^{\infty} \frac{(-1)^{k-1}(1)\cdots(2k-3)}{k!2^k} (-1)^k 4^k x^k$$

Simplify; rewrite prod.

$$= 1 + \sum_{k=1}^{\infty} -\frac{1\cdot 2\cdot 3\cdot 4\cdots(2k-3)\cdot(2k-2)}{k!\cdot 2\cdot 4\cdots(2k-2)} 2^k x^k$$

Write as factorials

$$= 1 + \sum_{k=1}^{\infty} -\frac{(2k-2)!}{k!(2^{k-1})1\cdot 2\cdots(k-1)} 2^k x^k$$

Expansion of $\sqrt{1-4x}$

What is the power series expansion of $\sqrt{1-4x}$?

$$\sqrt{1-4x} = ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k \quad \text{Expand } \binom{1/2}{k}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(\frac{1}{2}-1)\cdots(\frac{1}{2}-k+1)}{k!} (-4x)^k \quad \text{Denom. of } \frac{1}{2}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(-\frac{1}{2})\cdots(-\frac{2k-3}{2})}{k!} (-1)^k 4^k x^k \quad \text{Factor } -2\text{'s}$$

$$= 1 + \sum_{k=1}^{\infty} \frac{(-1)^{k-1}(1)\cdots(2k-3)}{k!2^k} (-1)^k 4^k x^k \quad \text{Simplify; rewrite prod.}$$

$$= 1 + \sum_{k=1}^{\infty} -\frac{1\cdot 2\cdot 3\cdot 4\cdots(2k-3)\cdot(2k-2)}{k!\cdot 2\cdot 4\cdots(2k-2)} 2^k x^k \quad \text{Write as factorials}$$

$$= 1 + \sum_{k=1}^{\infty} -\frac{(2k-2)!}{k!(2^{k-1})1\cdot 2\cdots(k-1)} 2^k x^k$$

$$= 1 + \sum_{k=1}^{\infty} \frac{-2}{k} \frac{(2k-2)!}{(k-1)!(k-1)!} x^k$$

Expansion of $\sqrt{1-4x}$

What is the power series expansion of $\sqrt{1-4x}$?

$$\begin{aligned}
 \sqrt{1-4x} &= ((-4x) + 1)^{1/2} = \sum_{k=0}^{\infty} \binom{1/2}{k} (-4x)^k && \text{Expand } \binom{1/2}{k} \\
 &= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(\frac{1}{2}-1)\cdots(\frac{1}{2}-k+1)}{k!} (-4x)^k && \text{Denom. of } \frac{1}{2} \\
 &= 1 + \sum_{k=1}^{\infty} \frac{\frac{1}{2}(-\frac{1}{2})\cdots(-\frac{2k-3}{2})}{k!} (-1)^k 4^k x^k && \text{Factor } -2\text{'s} \\
 &= 1 + \sum_{k=1}^{\infty} \frac{(-1)^{k-1}(1)\cdots(2k-3)}{k!2^k} (-1)^k 4^k x^k && \text{Simplify; rewrite prod.} \\
 &= 1 + \sum_{k=1}^{\infty} -\frac{1\cdot 2\cdot 3\cdot 4\cdots(2k-3)\cdot(2k-2)}{k!\cdot 2\cdot 4\cdots(2k-2)} 2^k x^k && \text{Write as factorials} \\
 &= 1 + \sum_{k=1}^{\infty} -\frac{(2k-2)!}{k!(2^{k-1})1\cdot 2\cdots(k-1)} 2^k x^k \\
 &= 1 + \sum_{k=1}^{\infty} \frac{-2}{k} \frac{(2k-2)!}{(k-1)!(k-1)!} x^k \\
 &= 1 + \sum_{k=1}^{\infty} \frac{-2}{k} \binom{2(k-1)}{k-1} x^k
 \end{aligned}$$