03-0: **Algorithm Analysis**

```
for (i=1; i<=n*n; i++)
  for (j=0; j<i; j++)
    sum++;
```

03-1: **Algorithm Analysis**

```
for (i=1; i<=n*n; i++)   Executed n*n times
  for (j=0; j<i; j++)     Executed <= n*n times
    sum++;                 O(1)
```

Running Time: $O(n^4)$ 03-2: **Algorithm Analysis**

```
for (i=1; i<=n*n; i++)
  for (j=0; j<i; j++)
    sum++;
```

Exact # of times `sum++` is executed:

$$\begin{aligned}\sum_{i=1}^{n^2} i &= \frac{n^2(n^2+1)}{2} \\ &= \frac{n^4+n^2}{2} \\ &\in \Theta(n^4)\end{aligned}$$

03-3: **Recursive Functions**

```
long power(long x, long n) {
  if (n == 0)
    return 1;
  else
    return x * power(x, n-1);
}
```

03-4: **Recurrence Relations**

$T(n)$ = Time required to solve a problem of size n

Recurrence relations are used to determine the running time of recursive programs – recurrence relations themselves are recursive

$T(0) =$ time to solve problem of size 0
– Base Case
$T(n) =$ time to solve problem of size n
– Recursive Case

03-5: **Recurrence Relations**

```
long power(long x, long n) {
  if (n == 0)
    return 1;
  else
    return x * power(x, n-1);
}
```

$T(0) = c_1$ for some constant c_1
$T(n) = c_2 + T(n-1)$ for some constant c_2

03-6: **Solving Recurrence Relations**

$T(0) = c_1$
$T(n) = T(n-1) + c_2$

If we knew $T(n-1)$, we could solve $T(n)$.

$T(n) = T(n-1) + c_2$

03-7: **Solving Recurrence Relations**

$T(0) = c_1$
$T(n) = T(n-1) + c_2$

If we knew $T(n-1)$, we could solve $T(n)$.

$$\begin{aligned} T(n) &= T(n-1) + c_2 & T(n-1) = T(n-2) + c_2 \\ &= T(n-2) + c_2 + c_2 \\ &= T(n-2) + 2c_2 \end{aligned}$$

03-8: **Solving Recurrence Relations**

$T(0) = c_1$
$T(n) = T(n-1) + c_2$

If we knew $T(n-1)$, we could solve $T(n)$.

$$\begin{aligned} T(n) &= T(n-1) + c_2 & T(n-1) = T(n-2) + c_2 \\ &= T(n-2) + c_2 + c_2 \\ &= T(n-2) + 2c_2 & T(n-2) = T(n-3) + c_2 \\ &= T(n-3) + c_2 + 2c_2 \\ &= T(n-3) + 3c_2 \end{aligned}$$

03-9: **Solving Recurrence Relations**

$T(0) = c_1$
$T(n) = T(n-1) + c_2$

If we knew $T(n-1)$, we could solve $T(n)$.

$$\begin{aligned} T(n) &= T(n-1) + c_2 & T(n-1) = T(n-2) + c_2 \\ &= T(n-2) + c_2 + c_2 \\ &= T(n-2) + 2c_2 & T(n-2) = T(n-3) + c_2 \\ &= T(n-3) + c_2 + 2c_2 \\ &= T(n-3) + 3c_2 & T(n-3) = T(n-4) + c_2 \\ &= T(n-4) + 4c_2 \end{aligned}$$

03-10: **Solving Recurrence Relations**

$T(0) = c_1$
$T(n) = T(n-1) + c_2$

If we knew $T(n-1)$, we could solve $T(n)$.

$$\begin{aligned} T(n) &= T(n-1) + c_2 & T(n-1) = T(n-2) + c_2 \\ &= T(n-2) + c_2 + c_2 \\ &= T(n-2) + 2c_2 & T(n-2) = T(n-3) + c_2 \\ &= T(n-3) + c_2 + 2c_2 \\ &= T(n-3) + 3c_2 & T(n-3) = T(n-4) + c_2 \\ &= T(n-4) + 4c_2 \\ &= \ldots \\ &= T(n-k) + kc_2 \end{aligned}$$

03-11: **Solving Recurrence Relations**

$T(0) = c_1$
$T(n) = T(n-k) + k * c_2$ for all k

If we set $k = n$, we have:

$$\begin{aligned} T(n) &= T(n-n) + nc_2 \\ &= T(0) + nc_2 \\ &= c_1 + nc_2 \\ &\in \Theta(n) \end{aligned}$$

03-12: **Building a Better** `Power`

```
long power(long x, long n) {
  if (n==0) return 1;
  if (n==1) return x;
  if ((n % 2) == 0)
    return power(x*x, n/2);
  else
    return power(x*x, n/2) * x;
}
```

03-13: **Building a Better** `Power`

```
long power(long x, long n) {
  if (n==0) return 1;
  if (n==1) return x;
  if ((n % 2) == 0)
    return power(x*x, n/2);
  else
    return power(x*x, n/2) * x;
}
```

$T(0) = c_1$
$T(1) = c_2$
$T(n) = T(n/2) + c_3$
(Assume n is a power of 2)

03-14: **Solving Recurrence Relations**

$T(n) = T(n/2) + c_3$

03-15: **Solving Recurrence Relations**

$$\begin{aligned} T(n) &= T(n/2) + c_3 & T(n/2) = T(n/4) + c_3 \\ &= T(n/4) + c_3 + c_3 \\ &= T(n/4) 2c_3 \end{aligned}$$

03-16: **Solving Recurrence Relations**

$$\begin{aligned} T(n) &= T(n/2) + c_3 & T(n/2) = T(n/4) + c_3 \\ &= T(n/4) + c_3 + c_3 \\ &= T(n/4) 2c_3 & T(n/4) = T(n/8) + c_3 \\ &= T(n/8) + c_3 + 2c_3 \\ &= T(n/8) 3c_3 \end{aligned}$$

03-17: **Solving Recurrence Relations**

$T(n)$	$= T(n/2) + c_3$	$T(n/2) = T(n/4) + c_3$
	$= T(n/4) + c_3 + c_3$	
	$= T(n/4) 2c_3$	$T(n/4) = T(n/8) + c_3$
	$= T(n/8) + c_3 + 2c_3$	
	$= T(n/8) 3c_3$	$T(n/8) = T(n/16) + c_3$
	$= T(n/16) + c_3 + 3c_3$	
	$= T(n/16) + 4c_3$	

03-18: **Solving Recurrence Relations**

$T(n)$	$= T(n/2) + c_3$	$T(n/2) = T(n/4) + c_3$
	$= T(n/4) + c_3 + c_3$	
	$= T(n/4) 2c_3$	$T(n/4) = T(n/8) + c_3$
	$= T(n/8) + c_3 + 2c_3$	
	$= T(n/8) 3c_3$	$T(n/8) = T(n/16) + c_3$
	$= T(n/16) + c_3 + 3c_3$	
	$= T(n/16) + 4c_3$	$T(n/16) = T(n/32) + c_3$
	$= T(n/32) + c_3 + 4c_3$	
	$= T(n/32) + 5c_3$	

03-19: **Solving Recurrence Relations**

$T(n)$	$= T(n/2) + c_3$	$T(n/2) = T(n/4) + c_3$
	$= T(n/4) + c_3 + c_3$	
	$= T(n/4) 2c_3$	$T(n/4) = T(n/8) + c_3$
	$= T(n/8) + c_3 + 2c_3$	
	$= T(n/8) 3c_3$	$T(n/8) = T(n/16) + c_3$
	$= T(n/16) + c_3 + 3c_3$	
	$= T(n/16) + 4c_3$	$T(n/16) = T(n/32) + c_3$
	$= T(n/32) + c_3 + 4c_3$	
	$= T(n/32) + 5c_3$	
	$= \ldots$	
	$= T(n/2^k) + kc_3$	

03-20: **Solving Recurrence Relations**

$T(0) = c_1$
$T(1) = c_2$
$T(n) = T(n/2) + c_3$

$T(n) = T(n/2^k) + kc_3$

We want to get rid of $T(n/2^k)$. Since we know $T(1)$ ...

$$\begin{aligned} n/2^k &= 1 \\ n &= 2^k \\ \lg n &= k \end{aligned}$$

$$\begin{aligned} T(n) &= T(n/2^{\lg n}) + \lg n c_3 \\ &= T(1) + c_3 \lg n \\ &= c_2 + c_3 \lg n \\ &\in \Theta(\lg n) \end{aligned}$$

03-21: **Solving Recurrence Relations**

$T(1) = c_2$
$T(n) = T(n/2^k) + kc_3$

Set $k = \lg n$:

$$\begin{aligned} T(n) &= T(n/2^{\lg n}) + (\lg n)c_3 \\ &= T(n/n) + c_3 \lg n \\ &= T(1) + c_3 \lg n \\ &= c_2 + c_3 \lg n \\ &\in \Theta(\lg n) \end{aligned}$$

03-22: `Power` **Modifications**

```
long power(long x, long n) {
  if (n==0) return 1;
  if (n==1) return x;
  if ((n % 2) == 0)
    return power(x*x, n/2);
  else
    return power(x*x, n/2) * x;
}
```

03-23: `Power` **Modifications**

```
long power(long x, long n) {
  if (n==0) return 1;
  if (n==1) return x;
  if ((n % 2) == 0)
    return power(power(x,2), n/2);
  else
    return power(power(x,2), n/2) * x;
}
```

This version of power will not work. Why?

03-24: `Power` **Modifications**

```
long power(long x, long n) {
  if (n==0) return 1;
  if (n==1) return x;
  if ((n % 2) == 0)
    return power(power(x,n/2), 2);
  else
    return power(power(x,n/2), 2) * x;
}
```

This version of power also will not work. Why?

03-25: `Power` **Modifications**

```
long power(long x, long n) {
  if (n==0) return 1;
  if (n==1) return x;
  if ((n % 2) == 0)
    return power(x,n/2) * power(x,n/2);
  else
    return power(x,n/2) * power(x,n/2) * x;
}
```

This version of power does work.

What is the recurrence relation that describes its running time?

03-26: `Power` **Modifications**

```
long power(long x, long n) {
  if (n==0) return 1;
  if (n==1) return x;
  if ((n % 2) == 0)
    return power(x,n/2) * power(x,n/2);
  else
    return power(x,n/2) * power(x,n/2) * x;
}
```

$$\begin{aligned} T(0) &= c_1 \\ T(1) &= c_2 \\ T(n) &= T(n/2) + T(n/2) + c_3 \\ &= 2T(n/2) + c_3 \end{aligned}$$

(Again, assume n is a power of 2)

03-27: **Solving Recurrence Relations**

$$\begin{aligned} T(n) &= 2T(n/2) + c_3 & T(n/2) = 2T(n/4) + c_3 \\ &= 2[2T(n/4) + c_3]c_3 \\ &= 4T(n/4) + 3c_3 & T(n/4) = 2T(n/8) + c_3 \\ &= 4[2T(n/8) + c_3] + 3c_3 \\ &= 8T(n/8) + 7c_3 \\ &= 8[2T(n/16) + c_3] + 7c_3 \\ &= 16T(n/16) + 15c_3 \\ &= 32T(n/32) + 31c_3 \\ &\ldots \\ &= 2^k T(n/2^k) + (2^k - 1)c_3 \end{aligned}$$

03-28: **Solving Recurrence Relations**

$T(0) = c_1$
$T(1) = c_2$
$T(n) = 2^k T(n/2^k) + (2^k - 1)c_3$

Pick a value for k such that $n/2^k = 1$:

$$\begin{aligned} n/2^k &= 1 \\ n &= 2^k \\ \lg n &= k \\ T(n) &= 2^{\lg n} T(n/2^{\lg n}) + (2^{\lg n} - 1)c_3 \\ &= nT(n/n) + (n-1)c_3 \\ &= nT(1) + (n-1)c_3 \\ &= nc_2 + (n-1)c_3 \\ &\in \Theta(n) \end{aligned}$$

03-29: **Recursion Trees**

- We can also do this substitution visually, leads to Recursion Trees
- Consider:

$$\begin{aligned} T(n) &= 2T(n/2) + Cn \\ T(1) &= C_2 \\ T(0) &= C_2 \end{aligned}$$

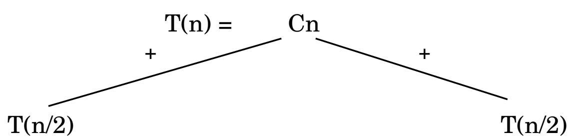
03-30: **Recursion Trees**

- Start with the recursive definition

$$T(n) = Cn + 2T(n/2)$$

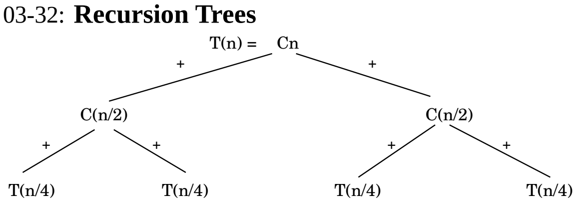
03-31: **Recursion Trees**

- Move the equation around a bit to get:



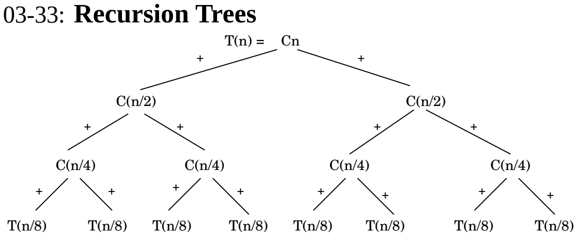
- Repalce each occurance of $T(n/2)$ with $T(n/4) + T(n/4) + C(n/2)$

03-32: **Recursion Trees**



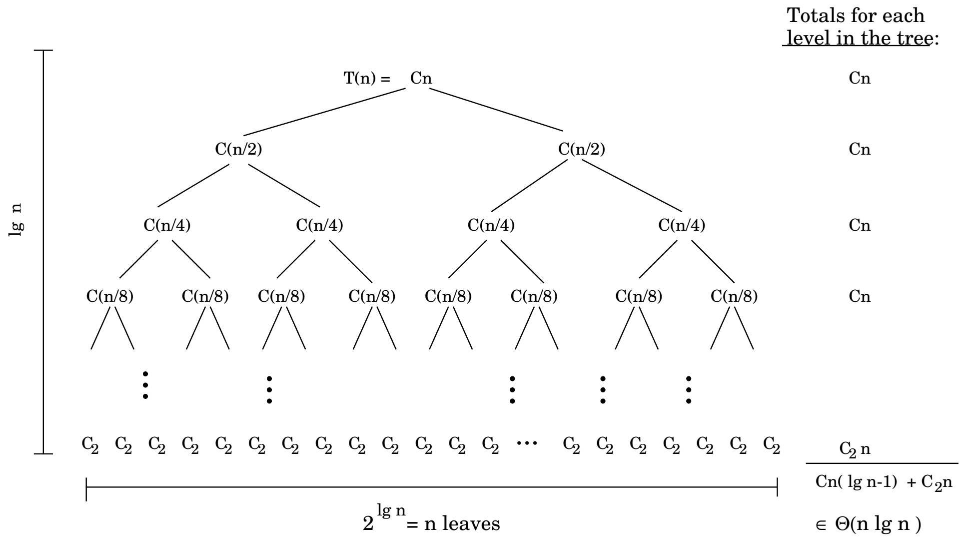
- Replace again, using $T(n) = 2T(n/2) + Cn$

03-33: **Recursion Trees**



- If we continue replacing ...

03-34: **Recursion Trees**



03-35: **Recursion Trees**

$$
\begin{aligned}
T(1) &= C_1 \\
T(n) &= T(n-1) + C_2
\end{aligned}
$$

03-36: **Recursion Trees**

$$
\begin{aligned}
T(0) &= C_1 \\
T(1) &= C_1 \\
T(n) &= T(n/2) + C_2
\end{aligned}
$$

03-37: **Substitution Method**

- We can prove that a bound is correct using induction, this is the substituion method

$$
\begin{aligned}
T(1) &= C_1 \\
T(n) &= T(n-1) + C_2
\end{aligned}
$$

Show: $T(n) \in O(\ ?\ )$

03-38: **Substitution Method**

- We can prove that a bound is correct using induction, this is the substituion method

$$
\begin{aligned}
T(1) &= C_1 \\
T(n) &= T(n-1) + C_2
\end{aligned}
$$

Show: $T(n) \in O(n)$, that is:
$T(n) \leq C * n$ for all $n > n_0$,
for some pair of constants C, n_0

03-39: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in O(n)$, that is, $T(n) \leq C * n$

- Base case: $T(1) = C_1 \leq C * 1$ for some constant C

  This is true as long as $C \geq C_1$.

03-40: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in O(n)$, that is, $T(n) \leq C * n$

- Recursive case:

$$\begin{array}{rcll} T(n) & = & T(n-1) + C_2 & \text{Recurrence definition} \end{array}$$

03-41: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in O(n)$, that is, $T(n) \leq C * n$

- Recursive case:

$$\begin{array}{rcll} T(n) & = & T(n-1) + C_2 & \text{Recurrence definition} \\ & \leq & C(n-1) + C_2 & \text{Inductive hypothesis} \end{array}$$

03-42: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in O(n)$, that is, $T(n) \leq C * n$

- Recursive case:

$$\begin{array}{rcll} T(n) & = & T(n-1) + C_2 & \text{Recurrence definition} \\ & \leq & C(n-1) + C_2 & \text{Inductive hypothesis} \\ & \leq & Cn + (C_2 - C) & \text{Algebra} \\ & \leq & Cn & \text{If } C > C_2 \end{array}$$

This is true as long as $C \geq C_1$.

03-43: **Substitution Method**

- We can prove that a bound is correct using induction, this is the substituion method

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in \Omega(n)$

$T(n) \geq C * n$ for all $n > n_0$,
for some pair of constants C, n_0

03-44: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in \Omega(n)$, that is, $T(n) \geq C * n$

- Base case: $T(1) = C_1 \geq C * 1$ for some constant C

  This is true as long as $C \leq C_1$.

03-45: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in \Omega(n)$, that is, $T(n) \geq C * n$

- Recursive case:

$$\begin{array}{rcll} T(n) & = & T(n-1) + C_2 & \text{Recurrence definition} \end{array}$$

03-46: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in \Omega(n)$, that is, $T(n) \geq C * n$

- Recursive case:

$$\begin{array}{rcll} T(n) & = & T(n-1) + C_2 & \text{Recurrence definition} \\ & \geq & C(n-1) + C_2 & \text{Inductive hypothesis} \end{array}$$

03-47: **Substitution Method**

$$\begin{array}{rcl} T(1) & = & C_1 \\ T(n) & = & T(n-1) + C_2 \end{array}$$

Show: $T(n) \in \Omega(n)$, that is, $T(n) \geq C * n$

- Recursive case:

$$\begin{array}{rcll} T(n) & = & T(n-1) + C_2 & \text{Recurrence definition} \\ & \geq & C(n-1) + C_2 & \text{Inductive hypothesis} \\ & \geq & Cn + (C_2 - C) & \text{Algebra} \\ & \geq & Cn & \text{If } C \leq C_2 \end{array}$$

This is true as long as $C \leq C_1$.

03-48: **Substitution Method**

$$\begin{array}{rcl} T(0) & = & C_2 \\ T(1) & = & C_2 \\ T(n) & = & 2T(n/2) + C_1 n \end{array}$$

Show: $T(n) \in O(n \lg n)$, that is, $T(n) \leq C * n \lg n$

03-49: **Substitution Method**

$$\begin{array}{rcl} T(0) & = & C_2 \\ T(1) & = & C_2 \\ T(n) & = & 2T(n/2) + C_1 n \end{array}$$

Show: $T(n) \in O(n \lg n)$, that is, $T(n) \leq C * n \lg n$

- Base cases:
  - $T(0) = C_1 \leq C * 0 \lg 0$ for some constant C
  - $T(1) = C_1 \leq C * 1 \lg 1$ for some constant C
-

Hmmm....

03-50: **Substitution Method**

$$\begin{array}{rcl} T(0) & = & C_2 \\ T(1) & = & C_2 \\ T(n) & = & 2T(n/2) + C_1 n \end{array}$$

Show: $T(n) \in O(n \lg n)$, that is, $T(n) \leq C * n \lg n$

- Only care about $n > n_0$. We can pick 2, 3 as base cases (why?)
  - $T(2) = C_1 \leq C * 2 \lg 2$ for some constant C
  - $T(3) = C_1 \leq C * 3 \lg 3$ for some constant C
-

03-51: **Substitution Method**

$$\begin{array}{rcl} T(0) & = & C_2 \\ T(1) & = & C_2 \\ T(n) & = & 2T(n/2) + C_1 n \end{array}$$

$$\begin{array}{rcll} T(n) & = & 2T(n/2) + C_1 n & \text{Recurrence Definition} \end{array}$$

03-52: **Substitution Method**

$$\begin{array}{rcl} T(0) & = & C_2 \\ T(1) & = & C_2 \\ T(n) & = & 2T(n/2) + C_1 n \end{array}$$

$$\begin{array}{rcll} T(n) & = & 2T(n/2) + C_1 n & \text{Recurrence Definition} \\ & \leq & 2C(n/2)\lg(n/2) + C_1 n & \text{Inductive hypothesis} \end{array}$$

03-53: **Substitution Method**

$$\begin{array}{rcl} T(0) & = & C_2 \\ T(1) & = & C_2 \\ T(n) & = & 2T(n/2) + C_1 n \end{array}$$

$$\begin{array}{rcll} T(n) & = & 2T(n/2) + C_1 n & \text{Recurrence Definition} \\ & \leq & 2C(n/2)\lg(n/2) + C_1 n & \text{Inductive hypothesis} \\ & \leq & Cn \lg n/2 + C_1 n & \text{Algebra} \\ & \leq & Cn \lg n - Cn \lg 2 + C_1 n & \text{Algebra} \\ & \leq & Cn \lg n - Cn + C_1 n & \text{Algebra} \end{array}$$

03-54: **Substitution Method**

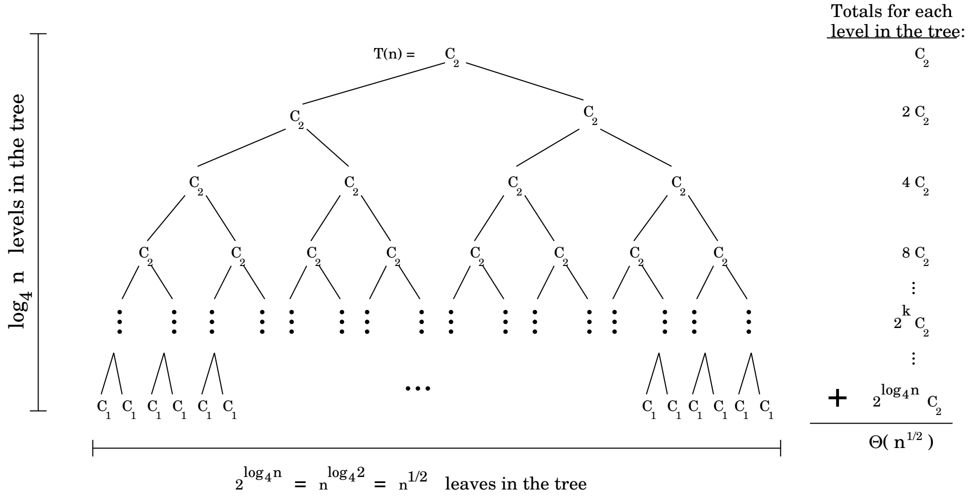
$$\begin{array}{rcl} T(0) & = & C_2 \\ T(1) & = & C_2 \\ T(n) & = & 2T(n/2) + C_1 n \end{array}$$

$$\begin{array}{rcll} T(n) & = & 2T(n/2) + C_1 n & \text{Recurrence Definition} \\ & \leq & 2C(n/2)\lg(n/2) + C_1 n & \text{Inductive hypothesis} \\ & \leq & Cn \lg n/2 + C_1 n & \text{Algebra} \\ & \leq & Cn \lg n - Cn \lg 2 + C_1 n & \text{Algebra} \\ & \leq & Cn \lg n - Cn + C_1 n & \text{Algebra} \\ & \leq & Cn \lg n & \text{If } C > C_1 \end{array}$$

Recursion Tree for: $T(n) = 2T(n/4) + C_2$

03-55: **Master Method**

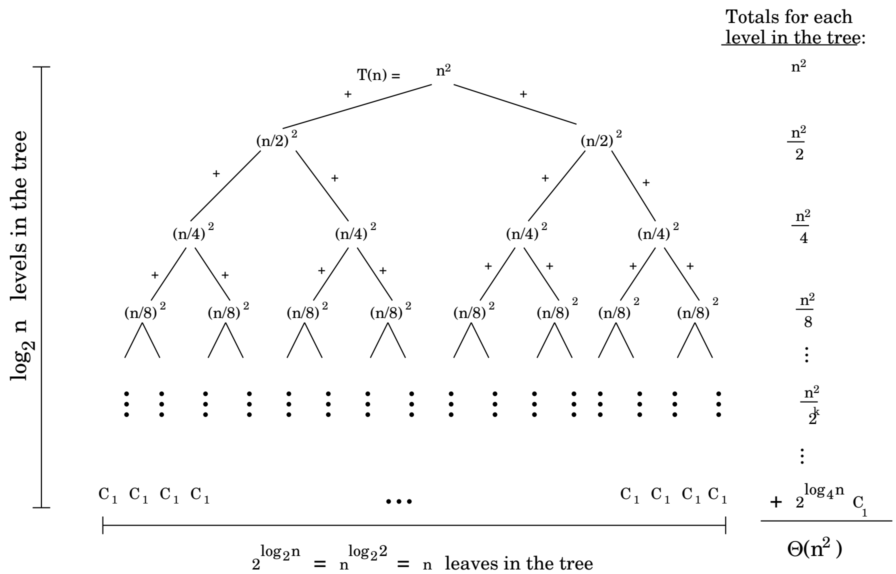
03-56: **Master Method**



03-57: **Master Method**

Recursion Tree for: $T(n) = 2T(n/2) + n^2$

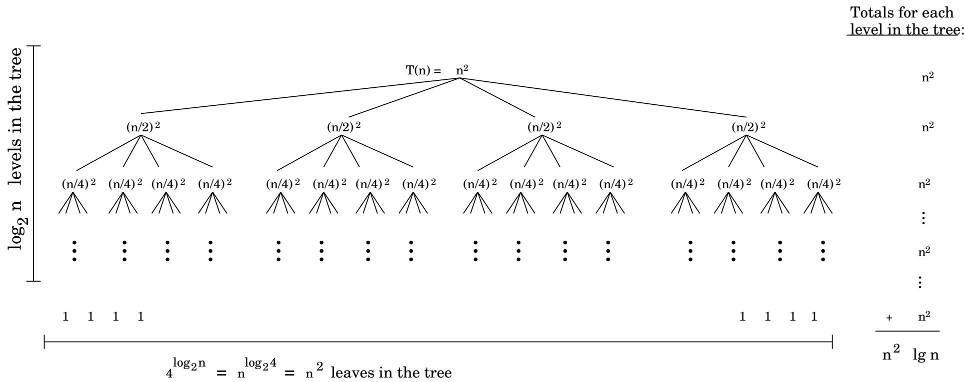
03-58: **Master Method**



03-59: **Master Method**

Recursion Tree for: $T(n) = 4T(n/4) + n^2$

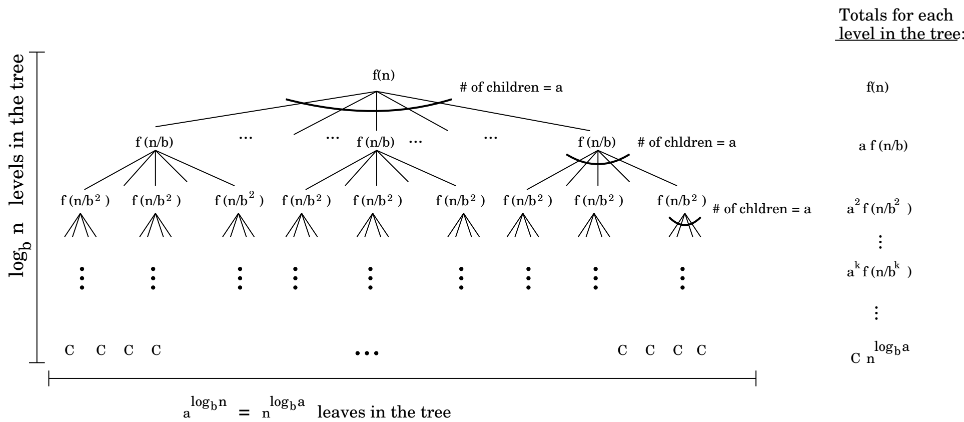
03-60: **Master Method**



03-61: **Master Method**

Recursion Tree for: $T(n) = aT(n/b) + f(n)$

03-62: **Master Method**



03-63: **Master Method**

$$T(n) = aT(n/b) + f(n)$$

1. if $f(n) \in O(n^{\log_b a - \epsilon})$ for some $\epsilon > 0$, then $T(n) \in \Theta(n^{\log_b a})$
2. if $f(n) \in \Theta(n^{\log_b a})$ then $T(n) \in \Theta(n^{\log_b a} * \lg n)$
3. if $f(n) \in \Omega(n^{\log_b a + \epsilon})$ for some $\epsilon > 0$, and if $af(n/b) \leq cf(n)$ for some $c < 1$ and large n, then $T(n) \in \Theta(f(n))$

03-64: **Master Method**

$$T(n) = 9T(n/3) + n$$

03-65: **Master Method**

$$T(n) = 9T(n/3) + n$$

- $a = 9, b = 3, f(n) = n$
- $n^{\log_b a} = n^{\log_3 9} = n^2$
- $n \in O(n^{2-\epsilon})$

$T(n) = \Theta(n^2)$

03-66: **Master Method**

$$T(n) = T(2n/3) + 1$$

03-67: **Master Method**

$$T(n) = T(2n/3) + 1$$

- $a = 1, b = 3/2, f(n) = 1$
- $n^{\log_b a} = n^{\log_{3/2} 1} = n^0 = 1$
- $1 \in O(1)$

$T(n) = \Theta(1 * \lg n) = \Theta(\lg n)$

03-68: **Master Method**

$$T(n) = 3T(n/4) + n \lg n$$

03-69: **Master Method**

$$T(n) = 3T(n/4) + n \lg n$$

- $a = 3, b = 4, f(n) = n \lg n$
- $n^{\log_b a} = n^{\log_4 3} = n^{0.792}$
- $n \lg n \in \Omega(n^{0.792+\epsilon})$
- $3(n/4) \lg(n/4) \leq c * n \lg n$

$T(n) \in \Theta(n \lg n)$

03-70: **Master Method**

$$T(n) = 2T(n/2) + n \lg n$$

03-71: **Master Method**

$$T(n) = 2T(n/2) + n \lg n$$

- $a = 2, b = 2, f(n) = n \lg n$
- $n^{\log_b a} = n^{\log_2 2} = n^1$

Master method does not apply!
$n^{1+\epsilon}$ grows faster than $n \lg n$ for *any* $\epsilon > 0$
Logs grow *incredibly* slowly! $\lg n \in o(n^\epsilon)$ for any $\epsilon > 0$