Path Compression and Making the Inverse Ackermann Function Appear Natural(ly)

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Bob Tarjan 1975

Theorem:

Any sequence of m Union, Find operations in a universe of n elements that uses linking by rank and path compression takes time at most

$$O(\, m \cdot \alpha(m,n) + n \,)$$

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Theorem:

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$$O(\, m \cdot \alpha(m,n) + n \,)$$

where $\alpha(m,n)$ is the "Functional Inverse" of the Ackermann Function.

What is this $\alpha(m,n)$??

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What is this $\alpha(m,n)$??

Why does this $\alpha(m,n)$ appear in the analysis of path compression ??

What is this $\alpha(m,n)$??

Ackermann function - Wikipedia, the free encyclopedia - Mozilla Firefox

Datei Bearbeiten Ansicht Gehe Lesezeichen Extras Hilfe

http://en.wikipedia.org/wiki/Ackerman's_function Go

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A two-parameter variation of the inverse Ackermann function can be defined as follows:

$$\alpha(m,n) = \min\{i \geq 1 : A(i, \lfloor m/n \rfloor) \geq \log_2 n\}.$$

This function arises in more precise analyses of the algorithms mentioned above, and gives a more refined time bound. In the disjoint-set data structure, m represents the number of operations while n represents the number of elements; in the minimum spanning tree algorithm, m represents the number of edges while n represents the number of vertices. Several slightly different definitions of $\alpha(m, n)$ exist; for example, $\log_2 n$ is sometimes replaced by n, and the floor function is sometimes replaced by a ceiling.

Fertig

Ackermann function - Wikipedia, the free encyclopedia - Mozilla Firefox

http://en.wikipedia.org/wiki/Ackerman's_function

Definition and properties

[edit]

The Ackermann function is defined recursively for non-negative integers *m* and *n* as follows:

$$A(m,n) = \begin{cases} n+1 & \text{if } m = 0 \\ A(m-1, 1) & \text{if } m > 0 \text{ and } n = 0 \\ A(m-1, A(m, n-1)) & \text{if } m > 0 \text{ and } n > 0. \end{cases}$$

The Ackermann function can be calculated by a simple function based directly on the definition:

Fertig

This definition of $\alpha(m,n)$ is not particularly enlightening.

Why does this $\alpha(m,n)$ appear in the analysis of path compression ??

Union Find with Path Compressions

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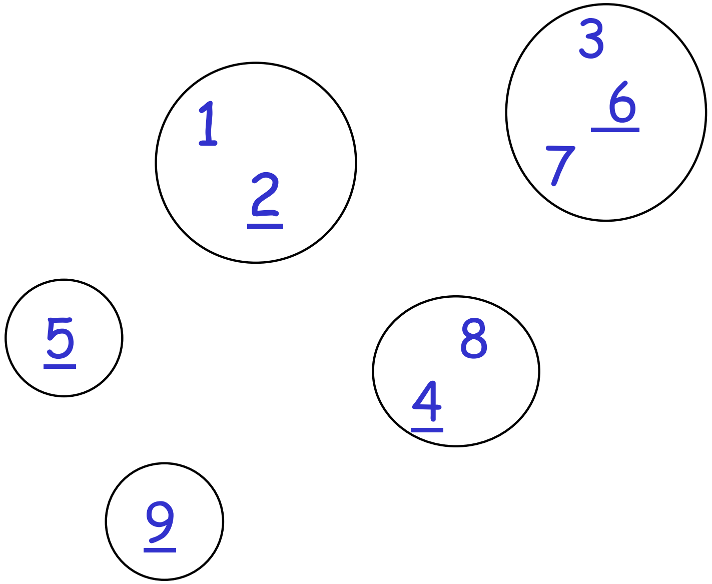
Maintain partition of $S = \{1, 2, \cdots, n\}$

under operations



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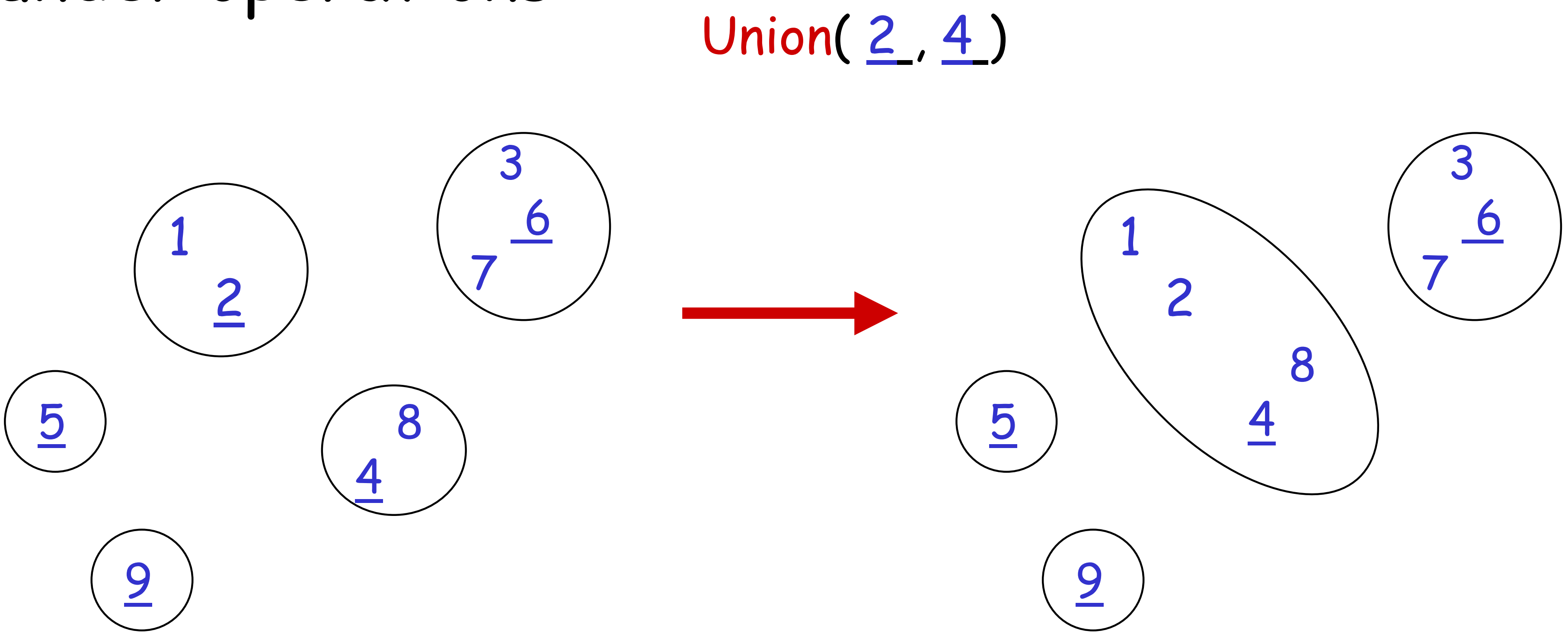

Union Find with Path Compressions

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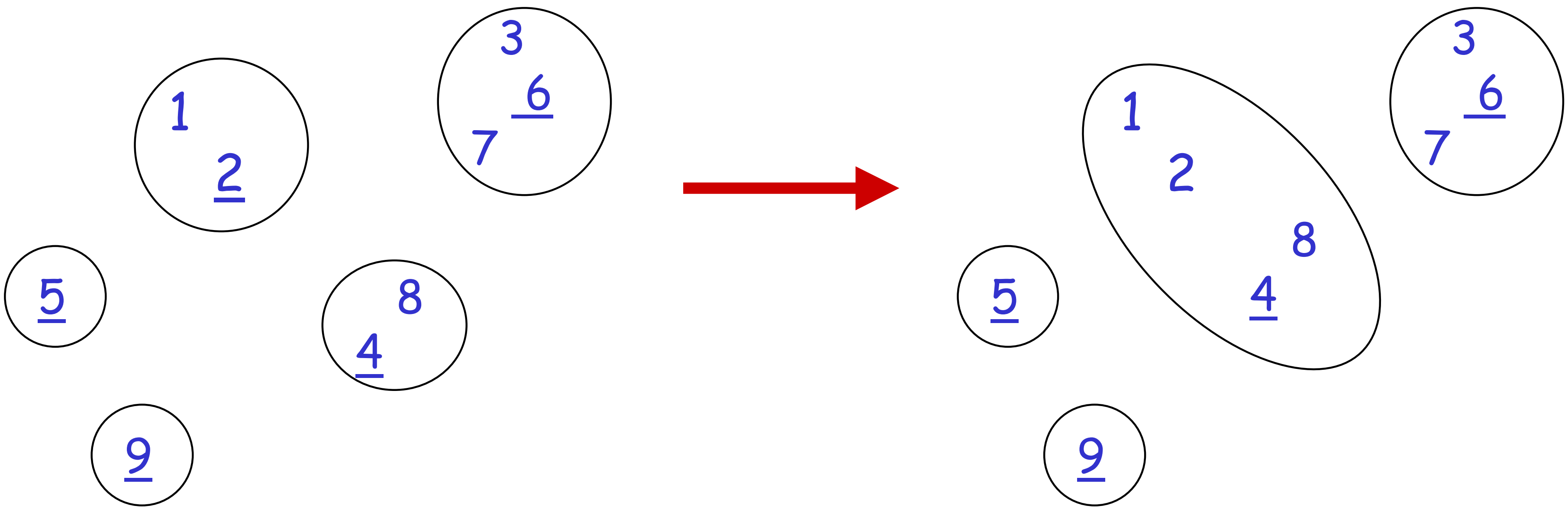
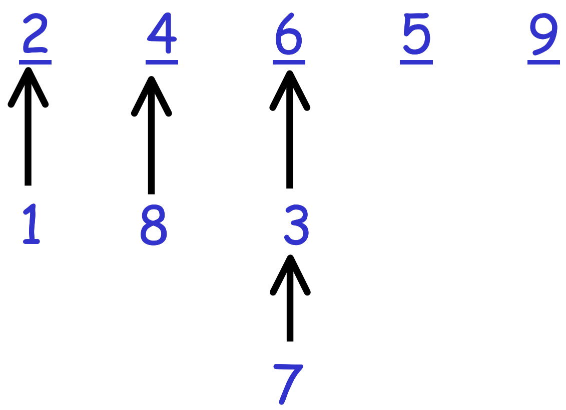
Union(2 , 4)



Find(3) = 6 (representative element)

Implementation

* forest $\mathcal{F}$ of rooted trees with node set S
* one tree for each group in current partition
* root of tree is representative of the group



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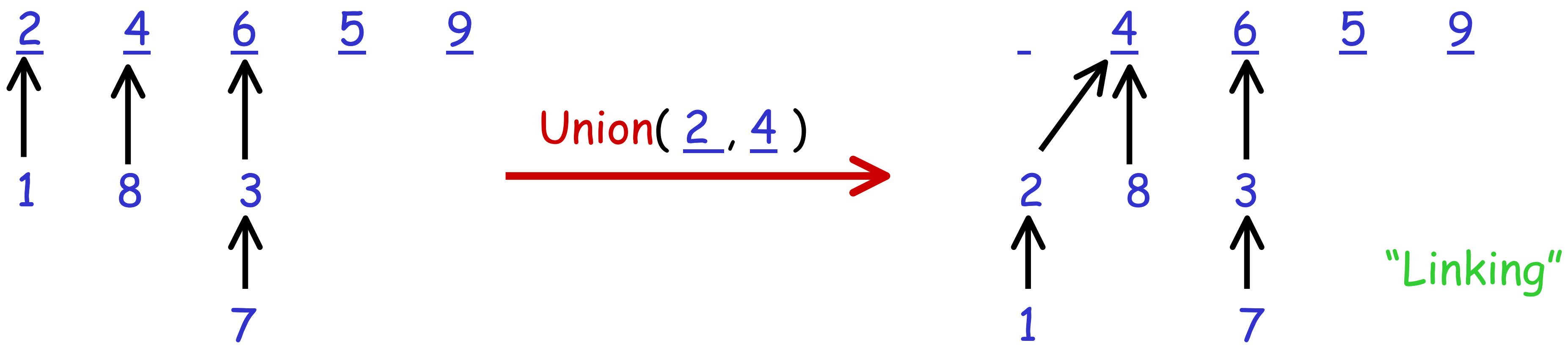

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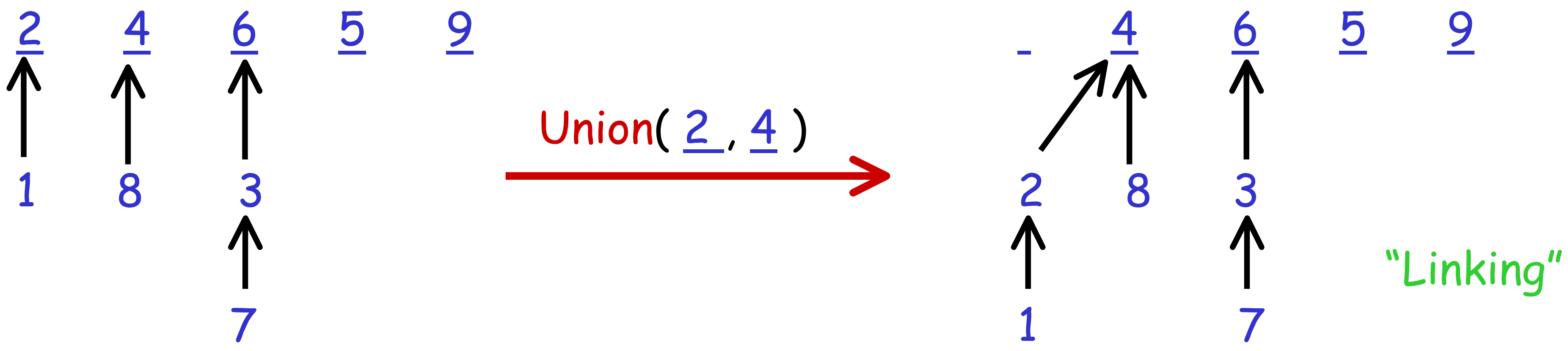
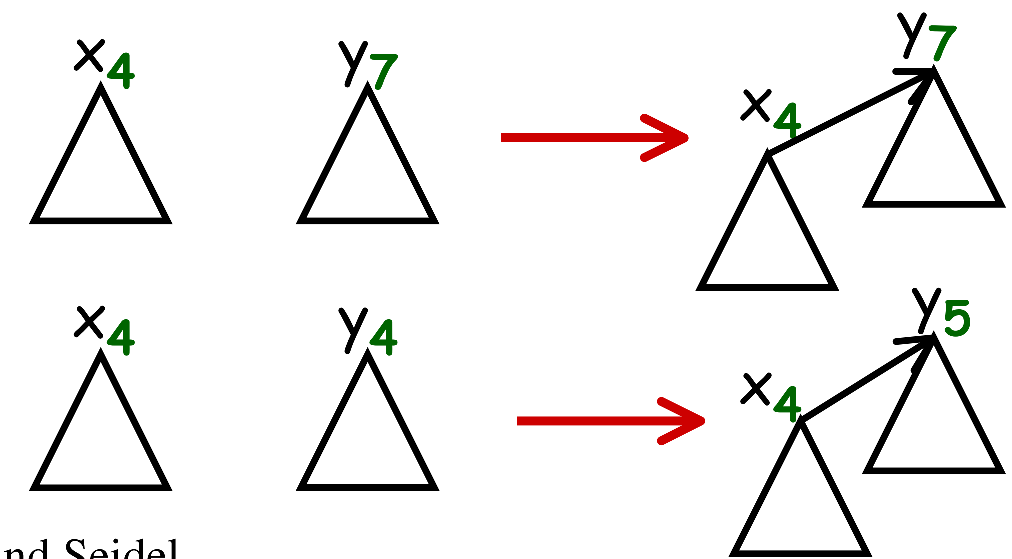


Find(x)   follow path from x to root   "path follwoing"

Heuristic 1: "linking by rank"

- each node x carries integer rk(x)
- initially rk(x) = 0
- as soon as x is NOT a root, rk(x) stays unchanged
- for Union(x , y) make node with smaller rank child of the other
  in case of tie, increment one of the ranks



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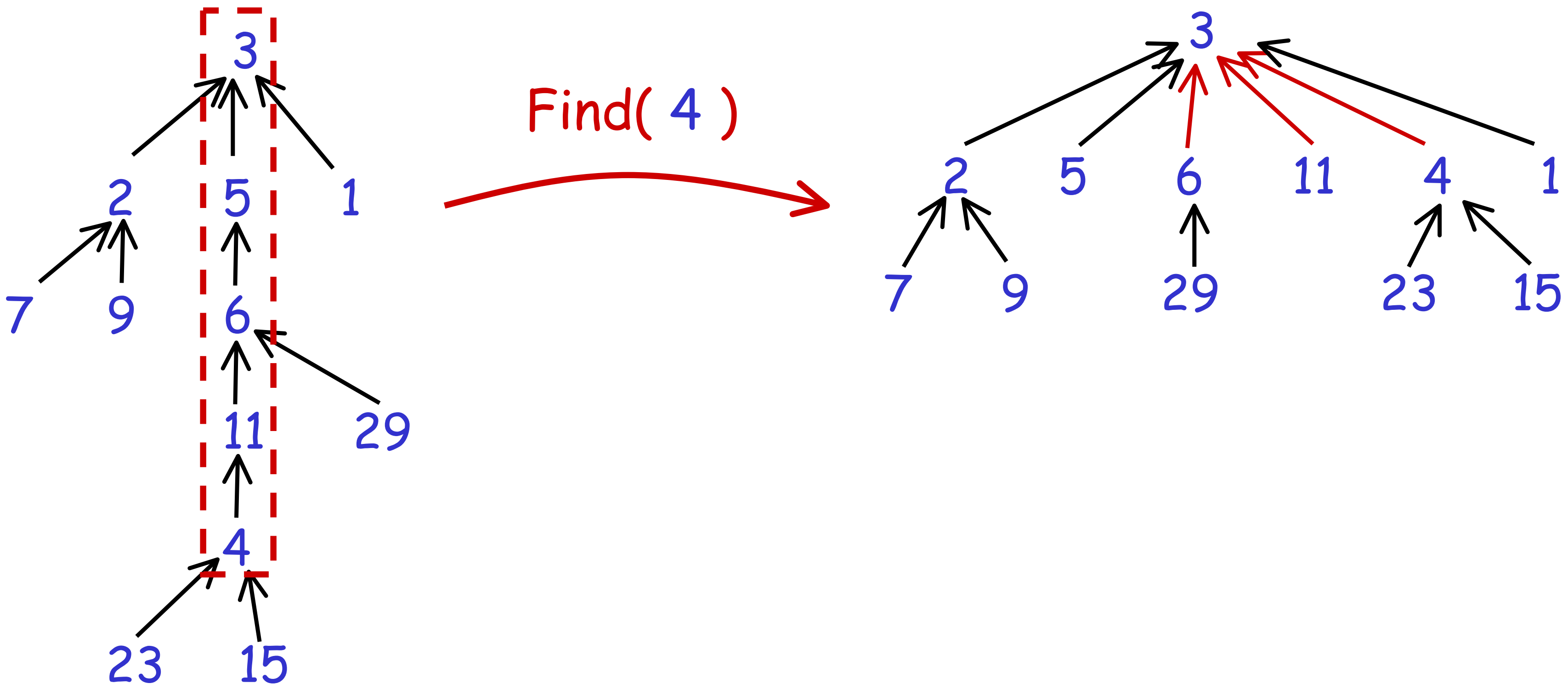
Heuristic 2: Path compression

when performin a Find(x) operation make all nodes in the "findpath" children of the root



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sequence of Union and Find operation

Explicit cost model:

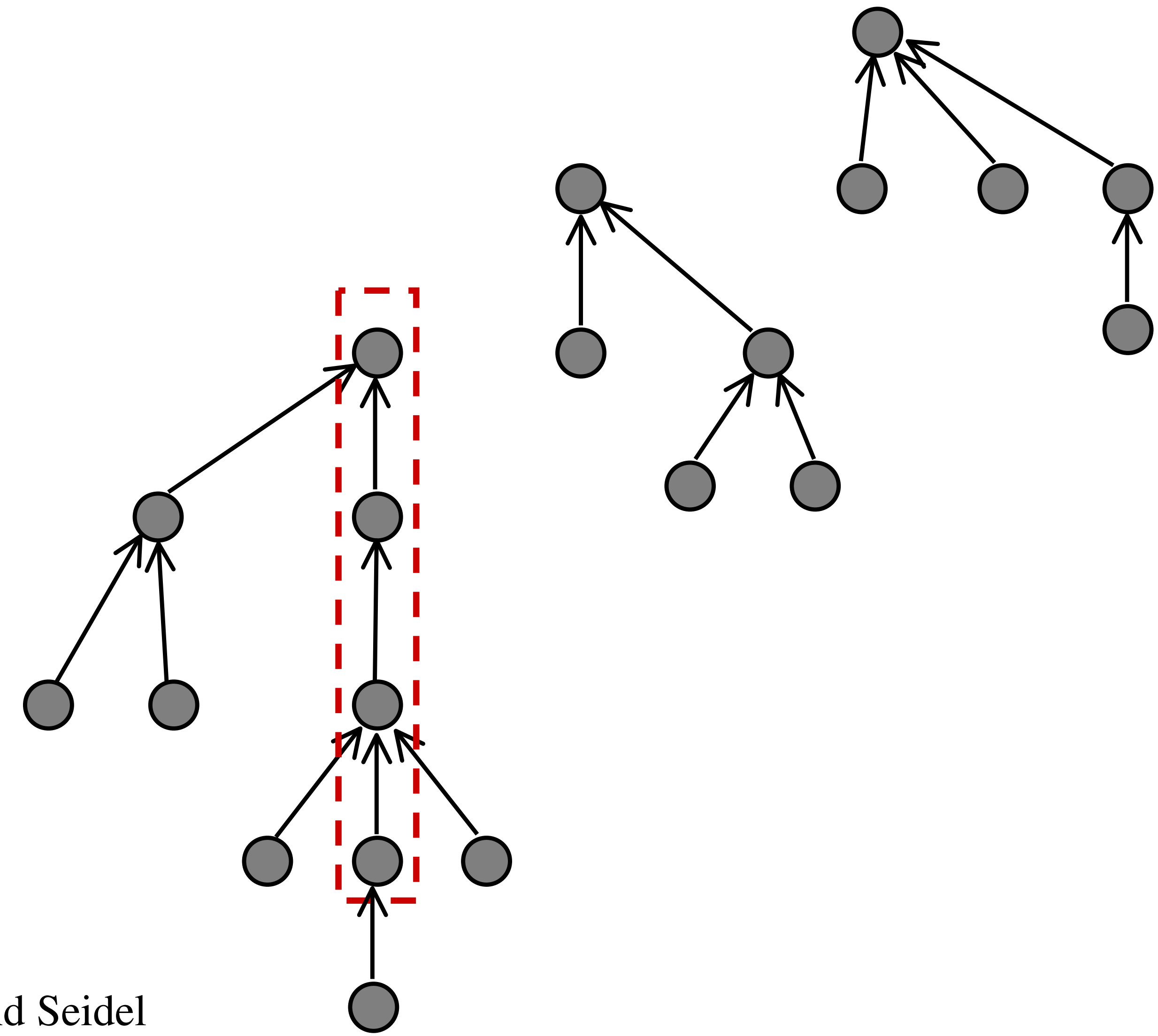
cost(op) = # times some node gets a new parent

Time for Union(x , y) = O(1) = O(cost(Union(x,y)))

Time for Find(x) = O(# of nodes on findpath)

= O(2 + cost(Find(x)))

For analysis assume all Unions are performed first, but Find-paths are only followed (and compressed) to correct node.



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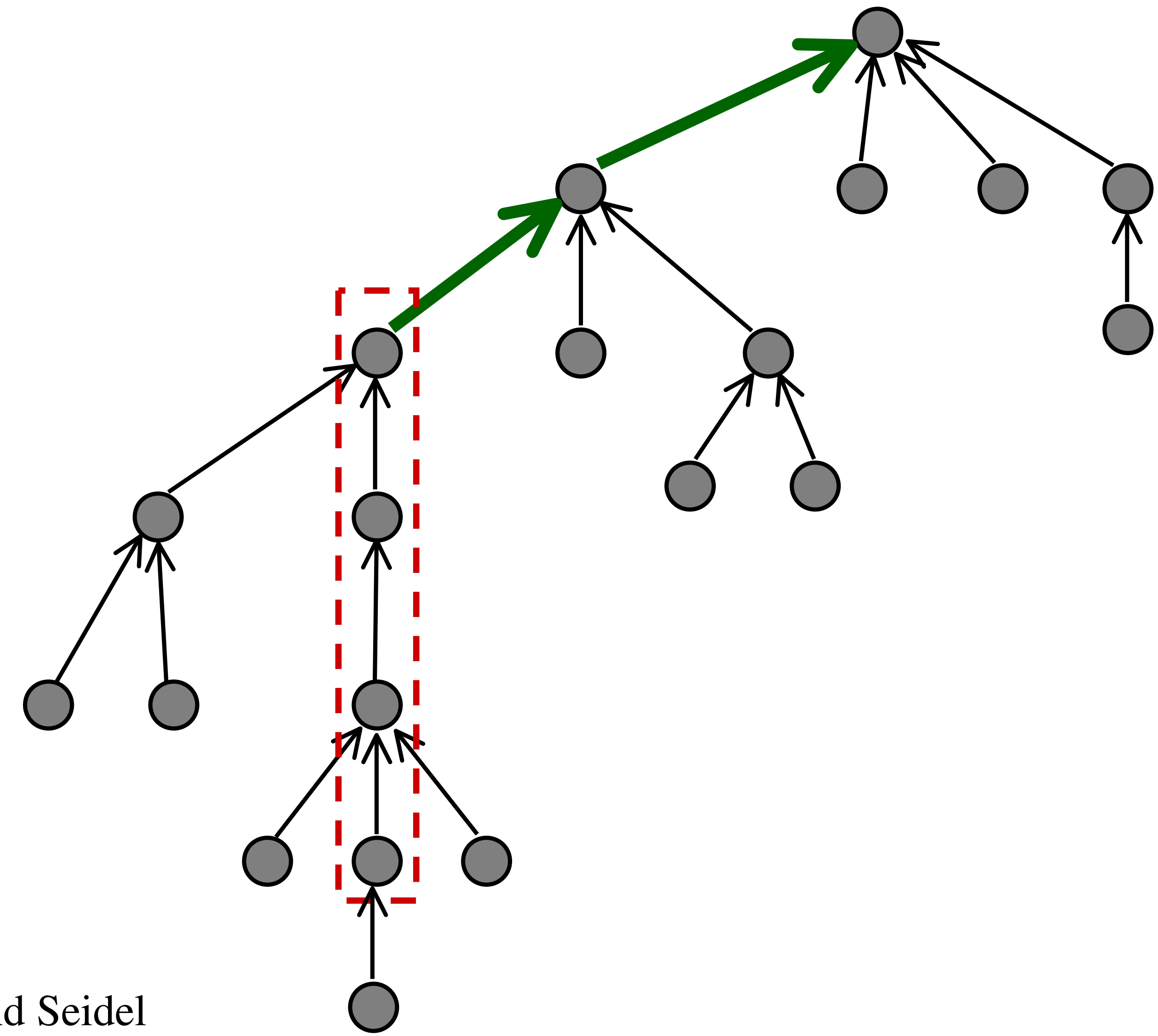

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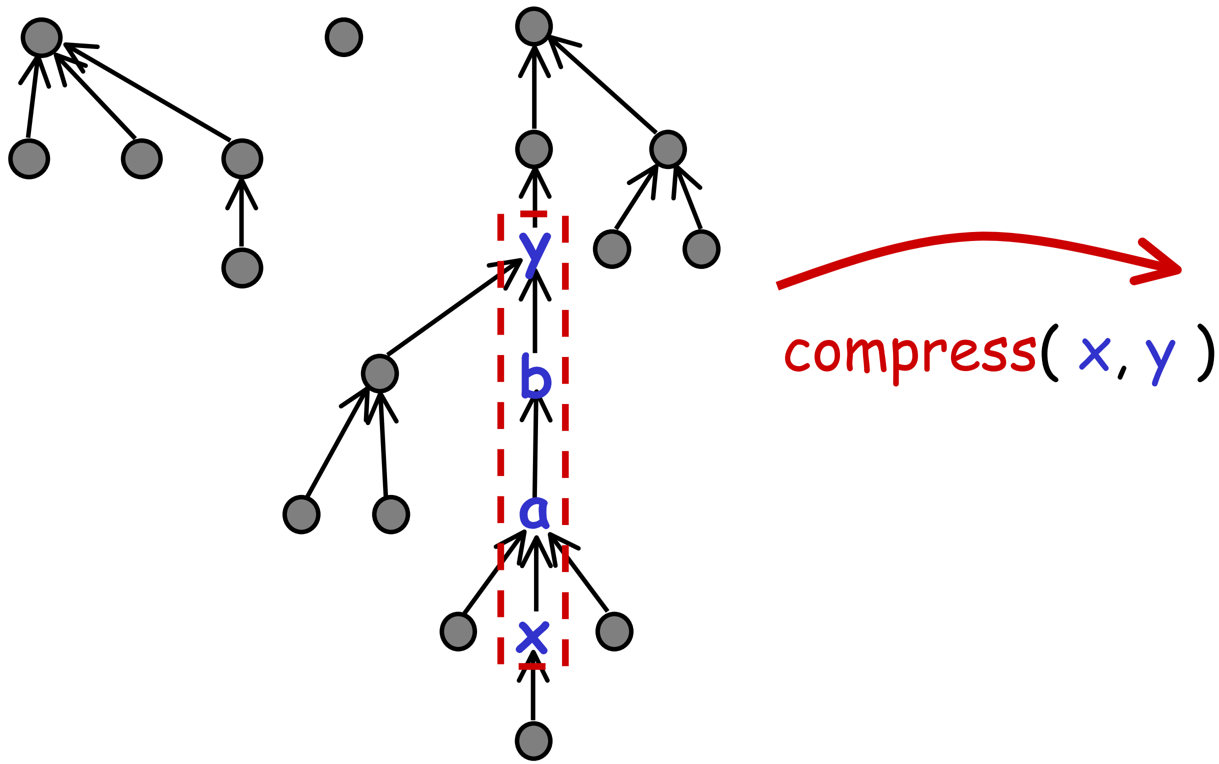
General path compression in forest $\mathcal{F}$



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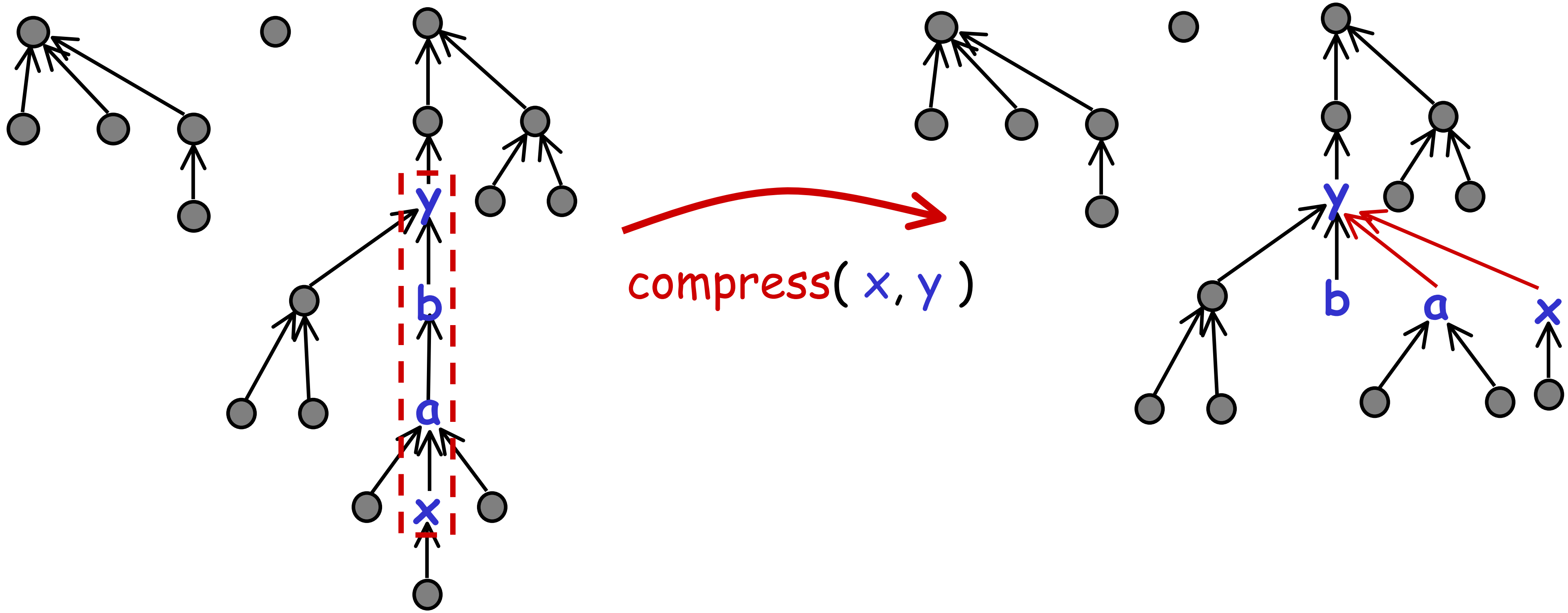

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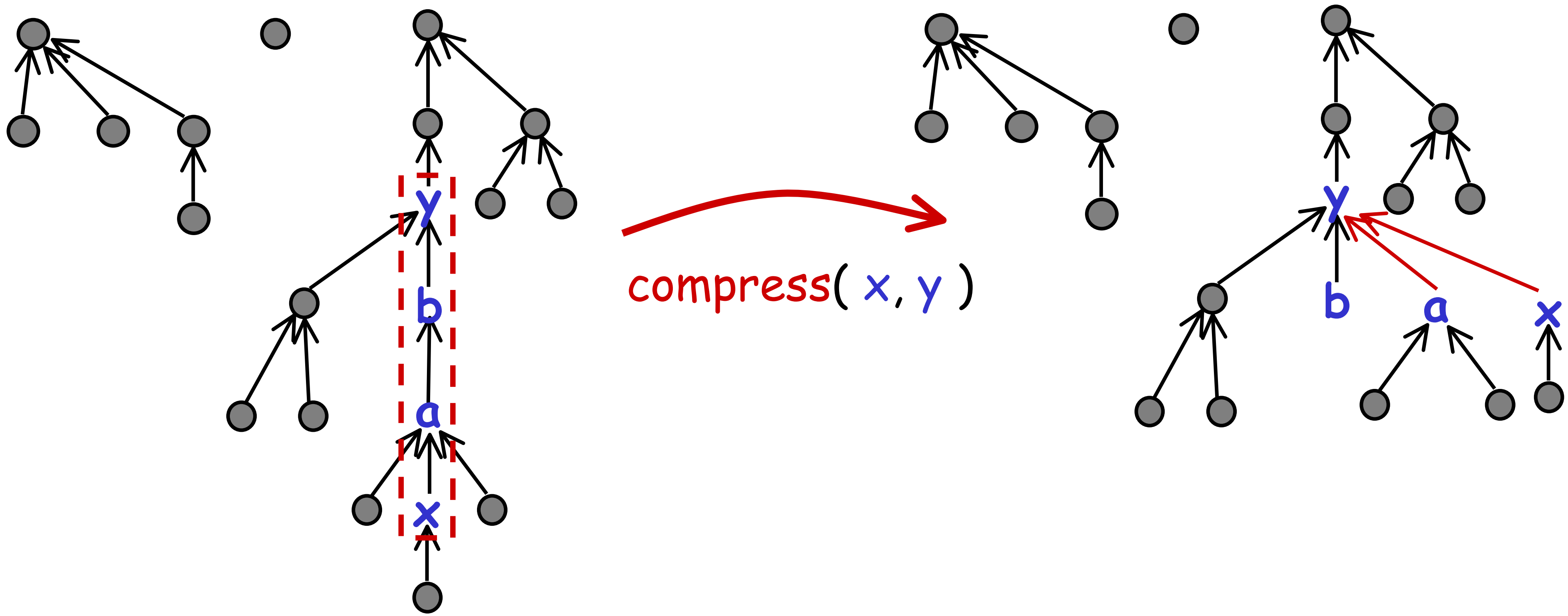

cost(compress(x,y)) = # of nodes that get a new parent

Problem formulation

$\mathcal{F}$ forest on node set X

C sequence of compress operations on $\mathcal{F}$

$|C|$ = # of true compress operations in C

cost(C) = $\sum$(cost of individual operations)

How large can cost(C) be at most,
in terms of $|X|$ and $|C|$?

Idea:

For the analysis try *"divide and conquer."*

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Question:

How do you *"divide"*?

Dissection of a forest $\mathcal{F}$ with node set X :

partition of X into "top part" X_t
and "bottom part" X_b

so that top part X_t is "upwards closed",

i.e. $x \in X_t \Rightarrow$ every ancestor of x is in X_t also

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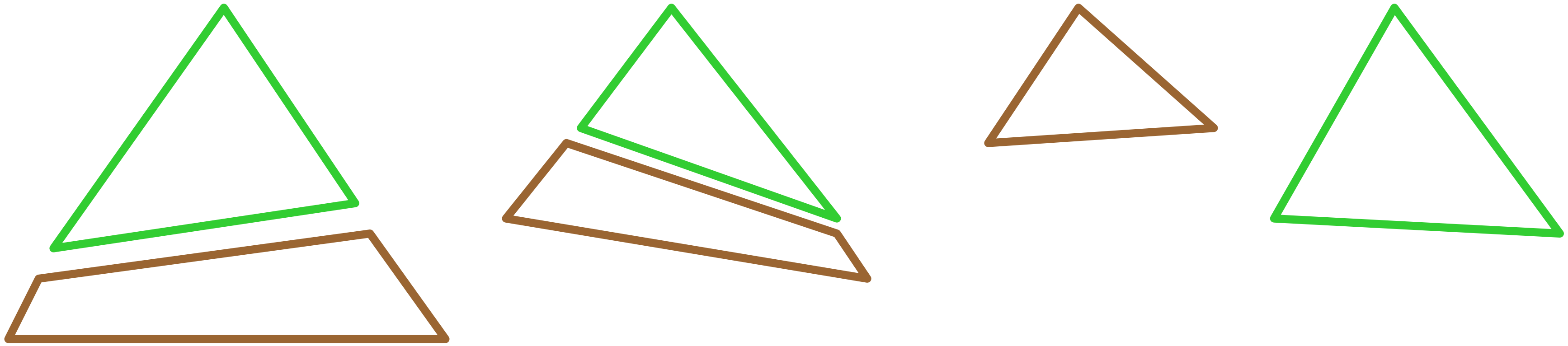

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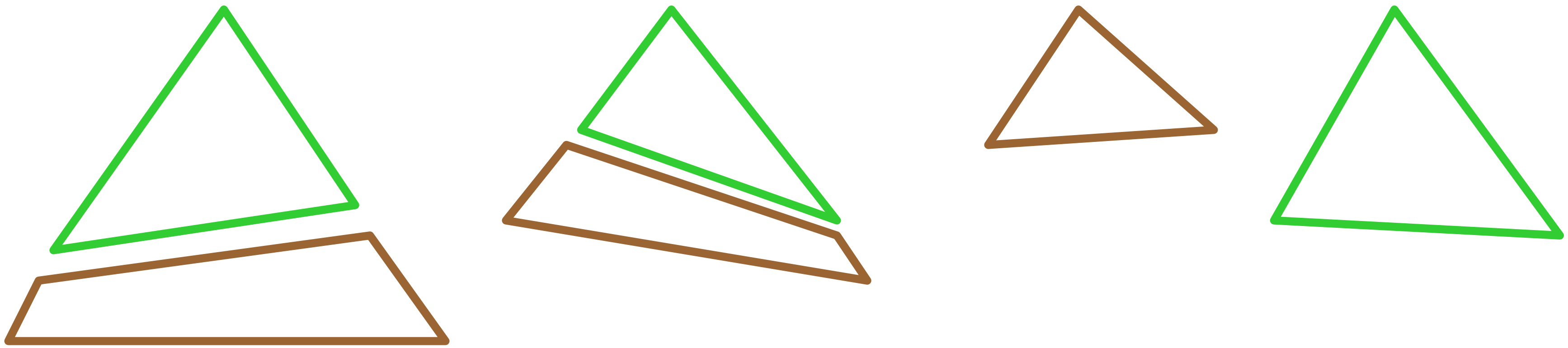

Note: X_t, X_b dissection for $\mathcal{F}$
$\mathcal{F}'$ obtained from $\mathcal{F}$ by sequence of path compressions
$\Rightarrow$ X_t, X_b is dissection for $\mathcal{F}'$

Main Lemma:

$\mathcal{C}$ ... sequence of operations on $\mathcal{F}$ with node set X

X_t, X_b dissection for $\mathcal{F}$ inducing subforests $\mathcal{F}_t$, $\mathcal{F}_b$

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$\Rightarrow$ $\exists$ compression sequences C_b for $\mathcal{F}_b$ and C_t for $\mathcal{F}_t$ with

$$|C_b| + |C_t| \leq |C|$$

and

$$\text{cost}(C) \leq \text{cost}(C_b) + \text{cost}(C_t) + |X_b| + |C_t|$$

Proof: 1) How to get C_b and C_t from C:

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compression paths from C

case 1:   into C_t

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case 2:   into C_b

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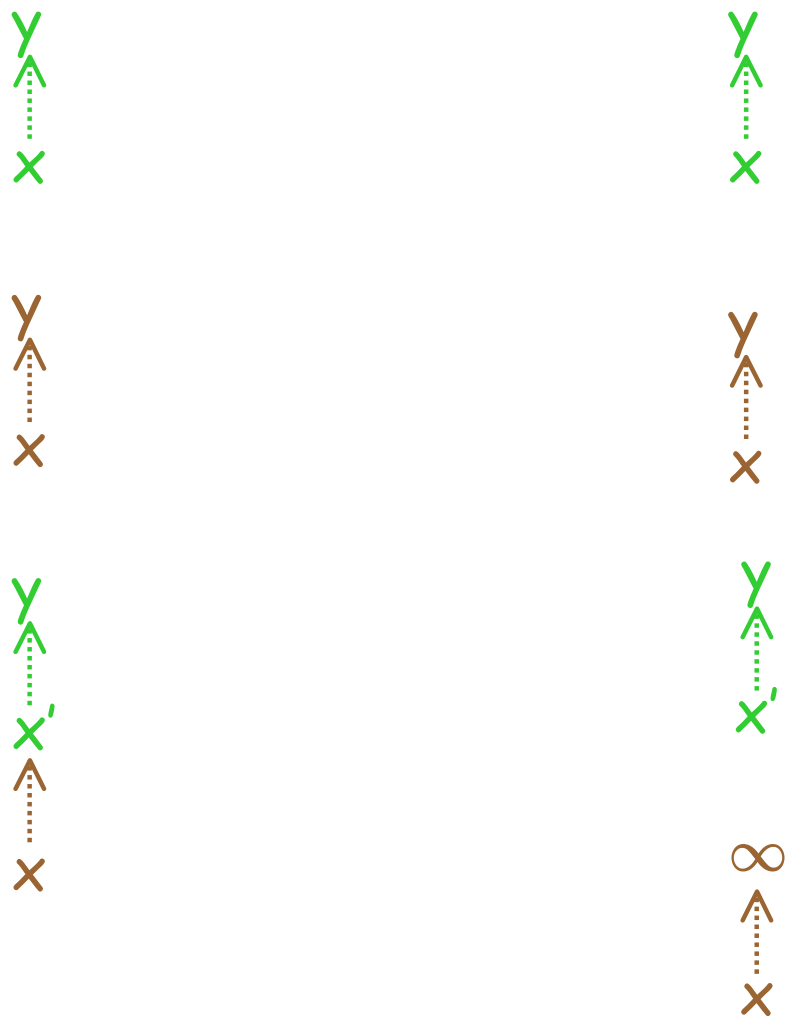
compression paths from C

case 1: into C_t

case 2: into C_b

case 3: into C_t, into C_b



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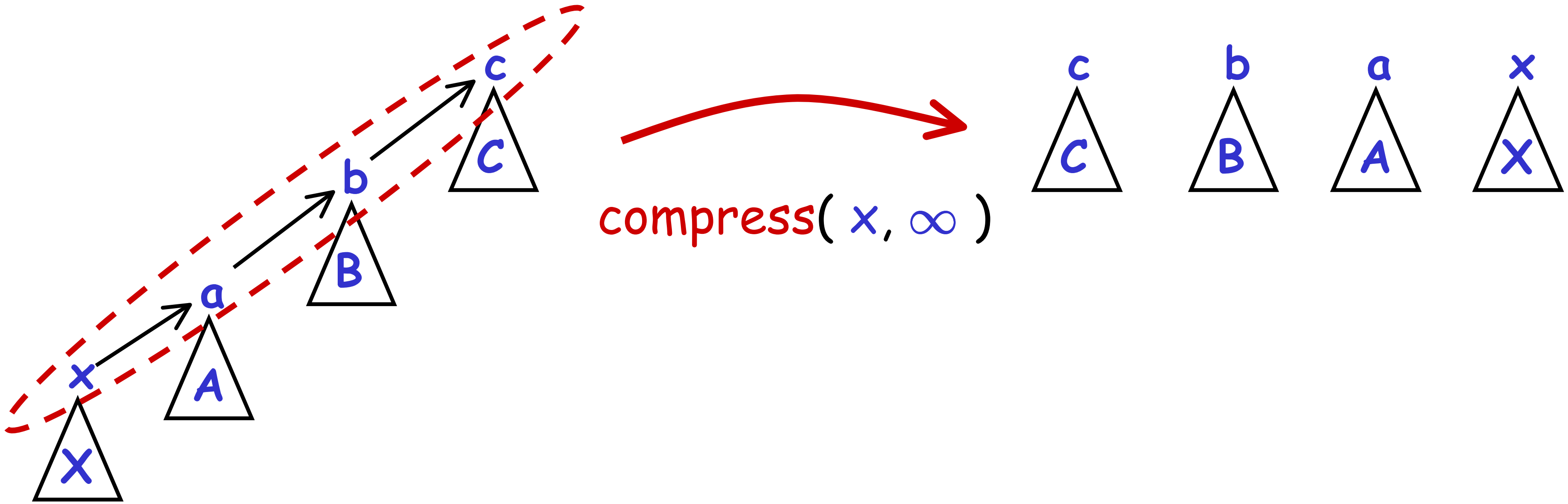
"rootpath compress"



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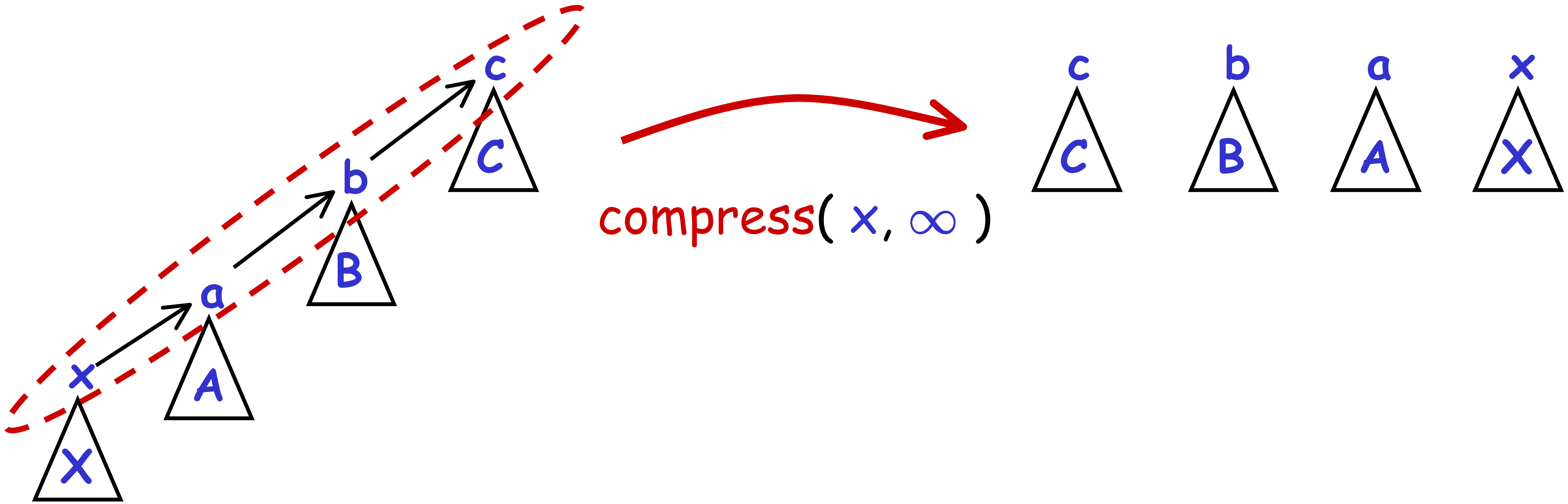


cost(compress(x, ∞)) = # of nodes that get a new parent

= 0

Proof:

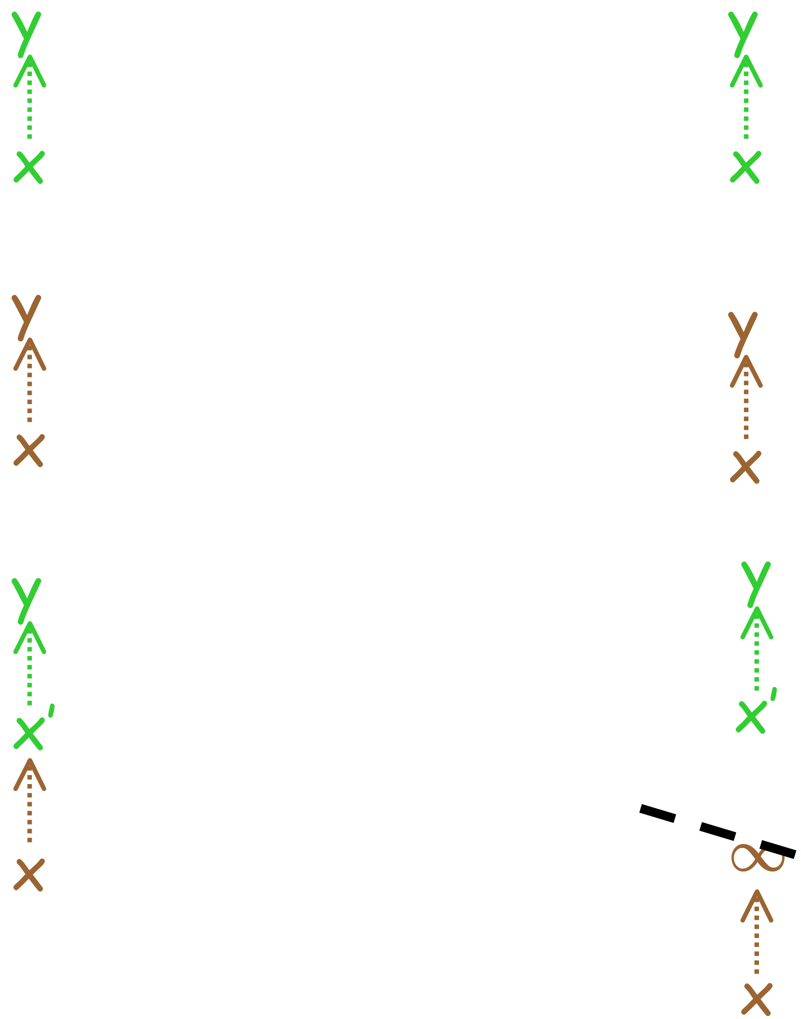
$$|C_b| + |C_t| \le |C|$$

compression paths from C

case 1:

case 2:

case 3:



into C_t

into C_b

into C_t

~~into C_b~~

$$\text{cost}(C) \leq \text{cost}(C_b) + \text{cost}(C_t) + |X_b| + |C_t|$$

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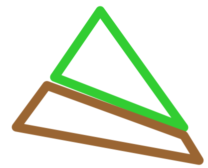
$\mathrm{cost}(\,C\,)$



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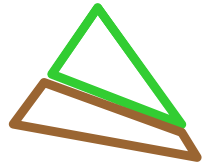

cost(C)

green node gets new green parent: | accounted by $\text{cost}(C_t)$

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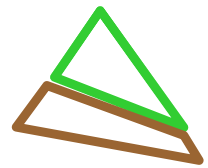

cost(C)

green node gets new green parent: accounted by cost(C_t)

brown node gets new brown parent: accounted by cost(C_b)

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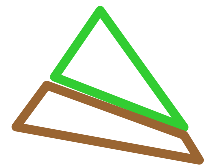

cost(C)

green node gets new green parent:	accounted by $\text{cost}(C_t)$
brown node gets new brown parent:	accounted by $\text{cost}(C_b)$
brown node gets new green parent: for the first time	accounted by $\lvert X_b \rvert$

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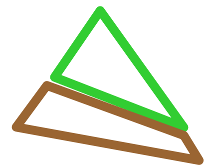
$\text{cost}(\,C\,) \leq \text{cost}(\,C_b\,) + \text{cost}(\,C_t\,) + |X_b| + |C_t|$



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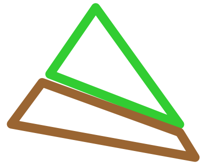

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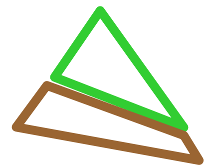

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brown node gets new green parent: again	accounted by $|C_t|$

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Main Lemma':

C ... sequence of operations on $\mathcal{F}$ with node set X

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$f(m,n)$ ... maximum cost of any compression sequence C with $|C|=m$ in an arbitrary forest with n nodes.

Claim: $f(m,n) \leq (m+n)\cdot\log_2 n$

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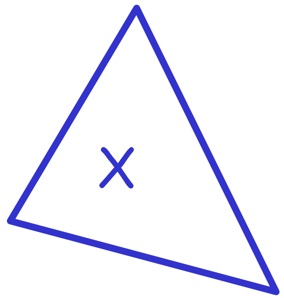
Proof:

forest $\mathcal{F}$



$|X| = n$

C compression sequence $|C| = m$

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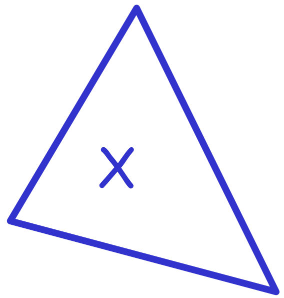
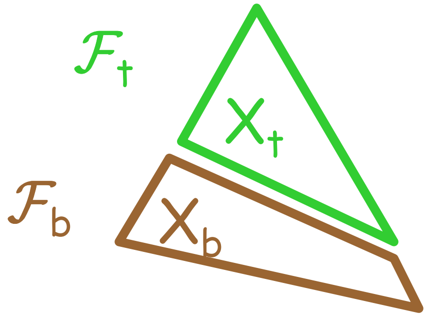


$|X|=n$



$|X_t|=|X_b|=n/2$

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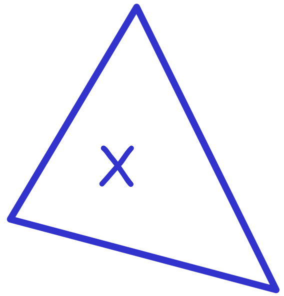

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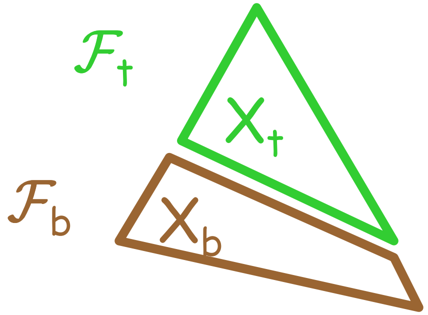

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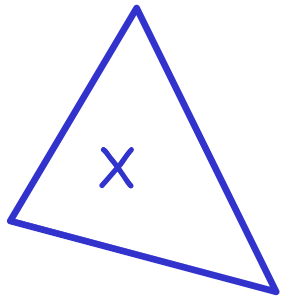

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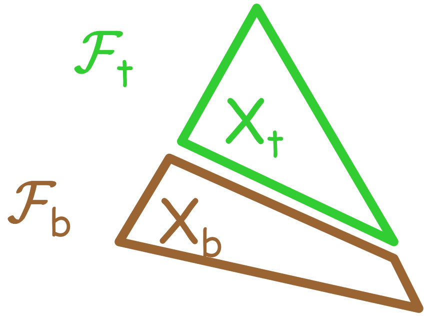

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Induction: $\le (m_b+n/2)\log n/2 + (m_t+n/2)\log n/2 + n/2 + m_t$

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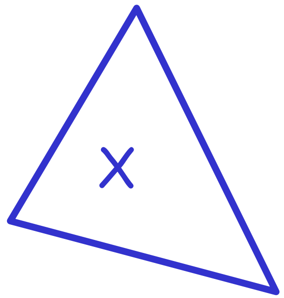

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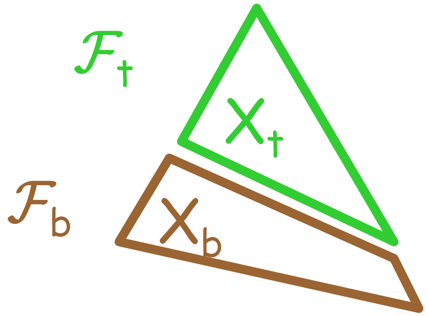

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$$\leq (m_b+m_t+n/2+n/2)\log n/2 + n + m$$

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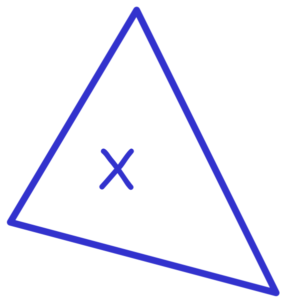

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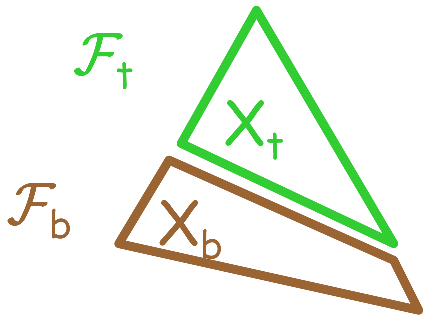

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Induction:

$$\le (m_b+n/2)\log n/2 + (m_t+n/2)\log n/2 + n/2 + m_t$$

$$\le (m_b+m_t+n/2+n/2)\log n/2 + n + m$$

$$\le (m+n)\cdot\log_2 n/2 + (m+n) = (m+n)\cdot\log_2 n$$

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Corollary:

Any sequence of m Union, Find operations in a universe of n elements that uses arbitrary linking and path compression takes time at most

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Proof: exercise

Path compression and union by rank

$f : \mathbb{N} \to \mathbb{R}$

Brief digression

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$$f^*(n) = \begin{cases} 0 & \text{if } n \leq 1 \\ 1 + f^*(\, f(n)\,) & \text{if } n > 1 \end{cases}$$

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Properties: f a "nice" compaction, i.e. $f(n) < n-1$

$\Rightarrow$ f^* a "nice" compaction and

f^* "much smaller" than f

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Brief digression

Examples for f^* :

$f(n)$	$f^*(n)$
$n-1$	$n-1$
$n-2$	$n/2$
$n-c$	n/c
$n/2$	$\log_2 n$
n/c	$\log_c n$
$\sqrt{n}$	$\log \log n$
$\log n$	$\log^* n$

Path compression and union by rank

Def: $\mathcal{F}$ forest, x node in $\mathcal{F}$

$r(x)$ = height of subtree rooted at x

($r(\text{leaf}) = 0$)

$\mathcal{F}$ is a **rank forest**, if

for every node x

for every i with $0 \leq i < r(x)$,

there is a child y_i of x with $r(y_i) = i$.

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Note: Union by rank produces rank forests !

Lemma: $r(x)=r \Rightarrow x$ has at least r children and at least 2^r descendants.

Inheritance Lemma:

$\mathcal{F}$ rank forest with maximum rank r and node set X

$s \in \mathbb{N}$: $X_{>s} = \{ x \in X \mid r(x) > s \}$ $\mathcal{F}_{>s}$

$X_{\leq s} = \{ x \in X \mid r(x) \leq s \}$ $\mathcal{F}_{\leq s}$

induced forests

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induced forests

i) $X_{\leq s}$, $X_{>s}$ is a dissection for $\mathcal{F}$

ii) $\mathcal{F}_{\leq s}$ is a rank forest with maximum rank $\leq s$

iii) $\mathcal{F}_{>s}$ is a rank forest with maximum rank $\leq r-s-1$

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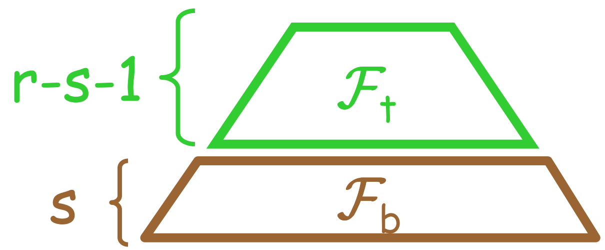

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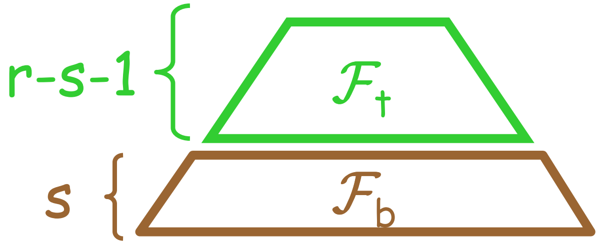

Proofs: exercise

$f(m,n,r)$ = maximum cost of any compression sequence C, with $|C|=m$, in rank forest $\mathcal{F}$ with n nodes and maximum rank r.

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Trivial bounds:

$$f(m,n,r) \leq (r-1)\cdot n$$

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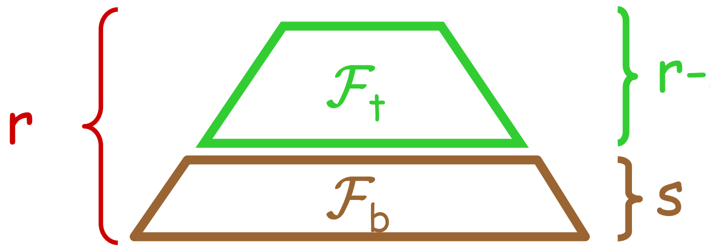
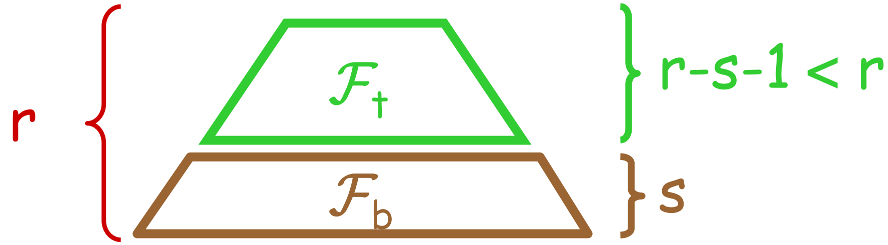


$|X_{>s}| = n_t$ $\quad |C_t| = m_t$

$|X_{\leq s}| = n_b = n - n_t$ $\quad |C_b| = m_b$

$$\text{cost}(\, C\,) \leq \text{cost}(\, C_t\,) + \text{cost}(\, C_b\,) + |X_b| - \#\text{rts}(\mathcal{F}_b) + |C_t|$$



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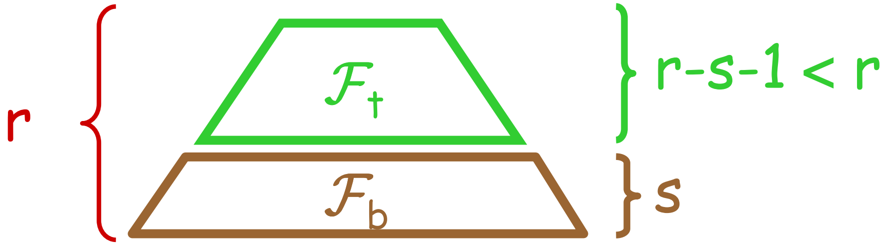

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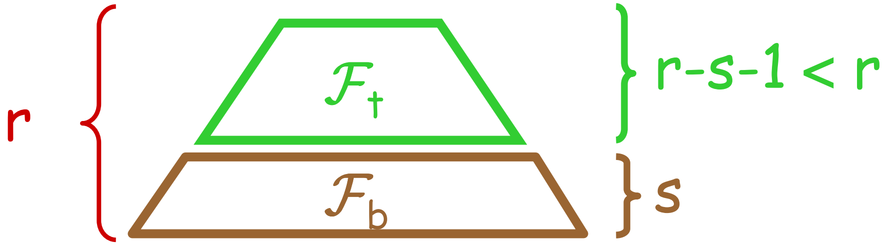
$$\leq f(m_t, n_t, r-s-1) + f(m_b, n_b, s) +$$



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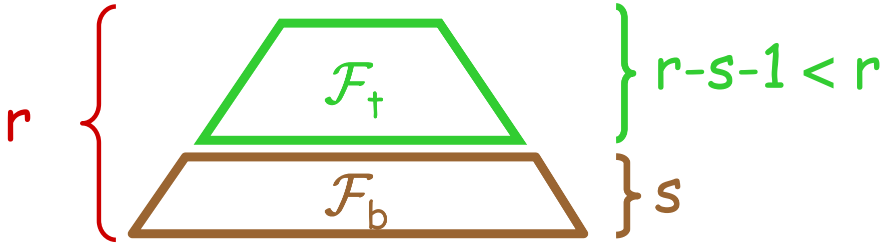

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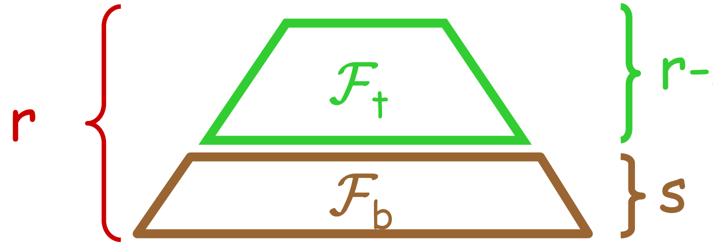

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Each node in $\mathcal{F}_t$ has at least s+1 children in $\mathcal{F}_b$, and they must all be different roots of $\mathcal{F}_b$.

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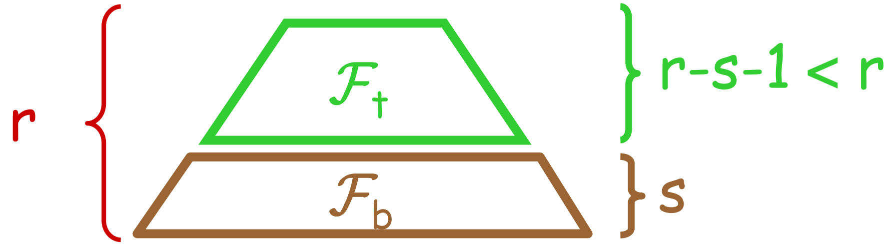

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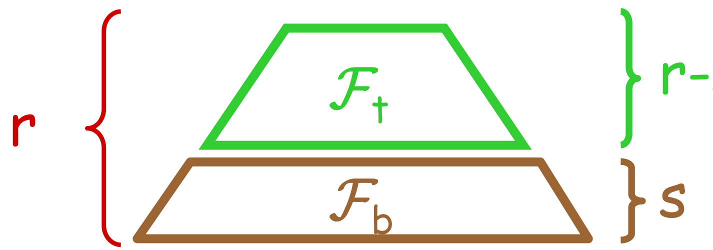

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$$f(m,n,r) \le f(m_t, n_t, r-s-1) + f(m_b, n_b, s) + n - (s+2)\cdot n_t + m_t$$

$$f(m,n,r) \leq f(m_t,n_t,r-s-1) + f(m_b,n_b,s) + n - (s+2)\cdot n_t + m_t$$

$$n_t + n_b = n$$
$$m_t + m_b \leq m$$

$$0 \leq s < r$$

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Assume: $f(M,N,R) \le k\cdot M + N\cdot g(R)$

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choose $s = g(r)$

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$$\le (k+1)\cdot m_t + f(m_b,n,s) + n$$

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$$f(m,n,r) \leq (k+1)\cdot m_t + f(m_b,n,s) + n \quad \Big| \quad -(k+1)\cdot(m_b+m_t)$$

$s = g(r)$

$$f(m,n,r) \leq (k+1)\cdot m_t + f(m_b,n,s) + n \quad \Big| \quad -(k+1)\cdot\overbrace{(m_b+m_t)}^{m}$$

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$$f(m,n,r) - (k+1)\cdot m \le f(m_b,n,s) - (k+1)\cdot m_b + n$$

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$$f(m,n,r) - (k+1)\cdot m \le f(m_b,n,s) - (k+1)\cdot m_b + n$$

$$\phi(m,n,r) \le \phi(m_b,n,g(r)) + n$$

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$$s = g(r)$$

$$f(m,n,r) \leq (k+1)\cdot m_t + f(m_b,n,s) + n \quad \Big| \quad -(k+1)\cdot\overbrace{(m_b+m_t)}^{m}$$

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$$\phi(m,n,r) \leq \phi(m_b,n,g(r)) + n$$

$$\leq (\phi(m_{bb},n,g(g(r))) + n) + n$$

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$$f(m,n,r) - (k+1)\cdot m \leq f(m_b,n,s) - (k+1)\cdot m_b + n$$

$$\begin{aligned}
\phi(m,n,r) &\leq \phi(m_b,n,g(r)) + n \\
&\leq (\phi(m_{bb},n,g(g(r))) + n) + n \\
&\leq ((\phi(m_{bbb},n,g(g(g(r)))) + n) + n) + n
\end{aligned}$$

$s = g(r)$

$$f(m,n,r) \le (k+1)\cdot m_t + f(m_b,n,s) + n \quad \Big| \quad -(k+1)\cdot\overbrace{(m_b+m_t)}^{m}$$

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$$\le ((\phi(m_{bbb},n,g(g(g(r)))) + n) + n) + n$$

$$\phi(m,n,r) \le n \cdot g^*(r)$$

$$s = g(r)$$

$$f(m,n,r) \le (k+1)\cdot m_t + f(m_b,n,s) + n \quad \Big| \quad -(k+1)\cdot\overbrace{(m_b+m_t)}^{m}$$

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$$\phi(m,n,r) \le \phi(m_b,n,g(r)) + n$$

$$\le (\phi(m_{bb},n,g(g(r))) + n) + n$$

$$\le ((\phi(m_{bbb},n,g(g(g(r)))) + n) + n) + n$$

$$\phi(m,n,r) \le n \cdot g^*(r)$$

$$f(m,n,r) \le (k+1)\cdot m + n \cdot g^*(r)$$

Shifting Lemma:

If $f(m,n,r) \leq k \cdot m + n \cdot g(r)$

then also $f(m,n,r) \leq (k+1) \cdot m + n \cdot g^*(r)$

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If $f(m,n,r) \leq k \cdot m + n \cdot g(r)$

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Shifting Corollary:

If $f(m,n,r) \leq k \cdot m + n \cdot g(r)$

then also $f(m,n,r) \leq (k+i) \cdot m + n \cdot g^{\overbrace{**\cdots*}^{i}}(r)$

for any $i \geq 0$

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then also $f(m,n,r) \le (k+i) \cdot m + n \cdot g^{\overbrace{**\cdots*}^{i}}(r)$

for any $i \ge 0$

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Trivial bound: $f(m,n,r) \leq n \cdot (r-1)$

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Trivial bound: $f(m,n,r) \le n \cdot (r-1)$

$= 0 \cdot m + n \cdot (r-1)$

If $f(m,n,r) \leq k \cdot m + n \cdot g(r)$

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$g(r) = r-1$

$g^*(r) = r-1$

If $f(m,n,r) \le k \cdot m + n \cdot g(r)$

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for any $i \ge 0$

Trivial bound: $f(m,n,r) \le m + n \cdot (r-2)$

If $f(m,n,r) \leq k \cdot m + n \cdot g(r)$

then also $f(m,n,r) \leq (k+i) \cdot m + n \cdot g^{\overbrace{**\cdots*}^{i}}(r)$

for any $i \geq 0$

Trivial bound: $f(m,n,r) \leq m + n \cdot (r-2)$

$= 1 \cdot m + n \cdot (r-2)$

If $f(m,n,r) \leq k \cdot m + n \cdot g(r)$

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Therefore for any $i \geq 0$:

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Here is your definition of the Inverse Ackermann Function !!

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Here is a parametrized definition of the Inverse Ackermann Function !!

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For $t \geq 1$ define $\alpha_t(r) = \min\{\, i \mid \log^{\overbrace{**\cdots*}^{i}}(r) \leq t \,\}$

$$f(m,n,r) \leq (3+\alpha_t(r))\cdot m + n\cdot t$$

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Bob Tarjan 1975

Theorem:

Any sequence of m Union, Find operations in a universe of n elements that uses linking by rank and path compression takes time at most

$$O(m \cdot \alpha(m,n) + n)$$

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$$\alpha(m,n) = \alpha_{1+m/n}(\log n)$$

Shifting Lemma:

What to remember:

If $f(m,n,r) \le k \cdot m + n \cdot g(r)$

then also $f(m,n,r) \le (k+1) \cdot m + n \cdot g^{*}(r)$

Shifting Corollary:

If $f(m,n,r) \le k \cdot m + n \cdot g(r)$

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for any $i \ge 0$

Definition of α:

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Actually $f(m,n,r) \leq 1 \cdot m + n \cdot \log^{*} r$ (difficult Exercise)

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(difficult exercises)

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Similar proof for $O(\ m \cdot \alpha(m,n) + n\ )$ bound also works for

* linking by weight and path compression
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Open problem:

simple top-down approach for proving **lower bounds**