Evaluating formulas with a quantum computer

Andrew Childs (Waterloo)

Andris Ambainis (Waterloo & Latvia)

Ben Reichardt (Waterloo)

Robert Špalek (Google)

Shengyu Zhang (Chinese U. of Hong Kong)

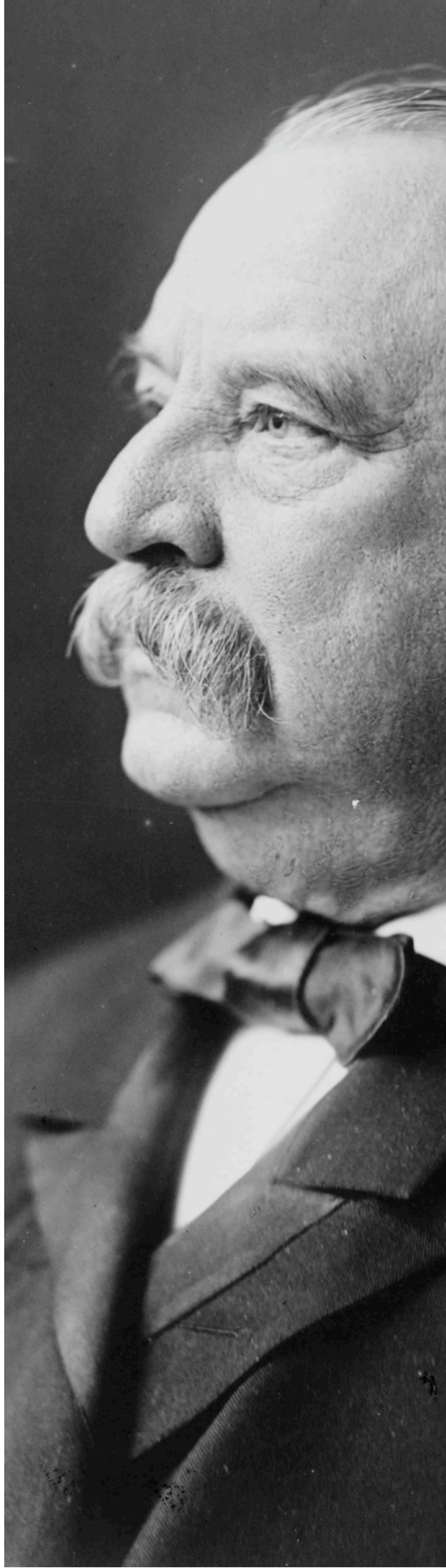
quant-ph/0703015

FOCS 2007

OR

How fast can we compute the OR of n bits?

Evaluate formula: x_1 OR x_2 OR ... OR x_n



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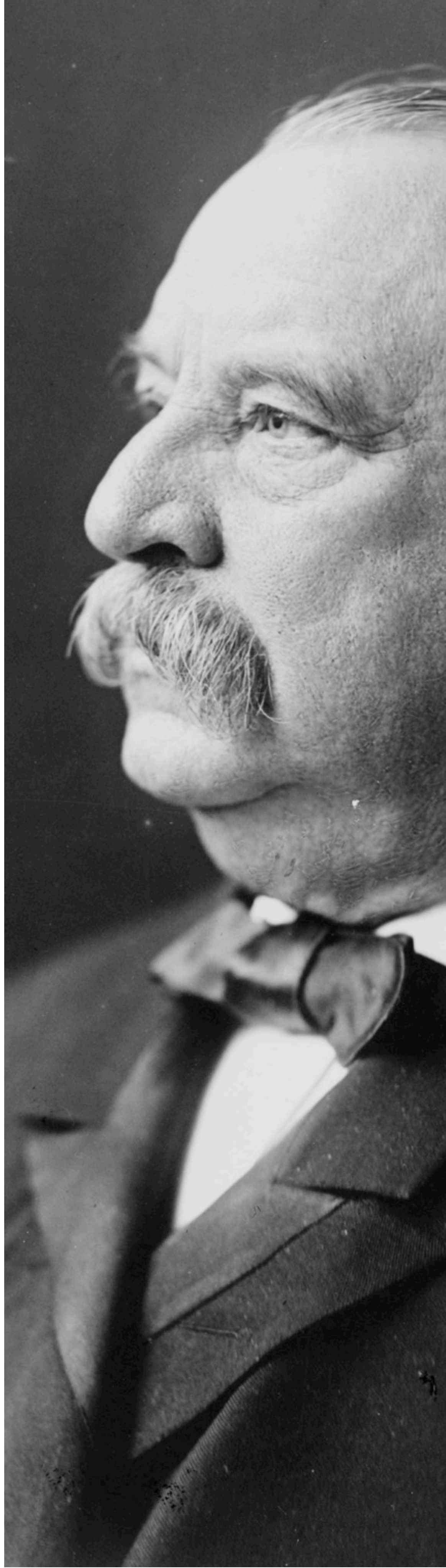

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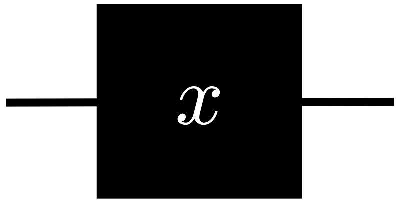

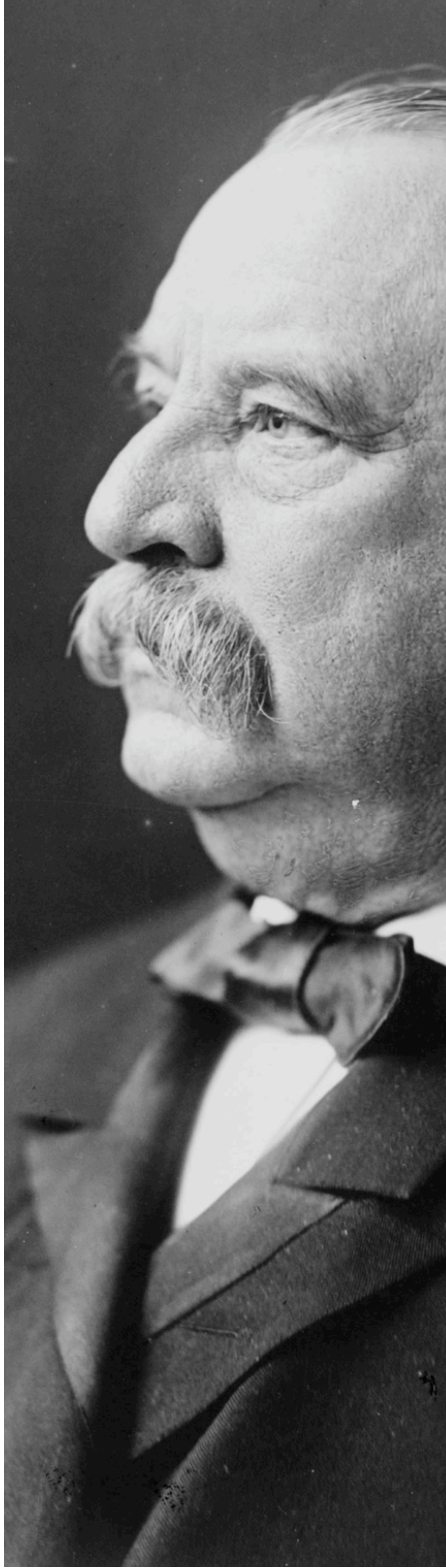

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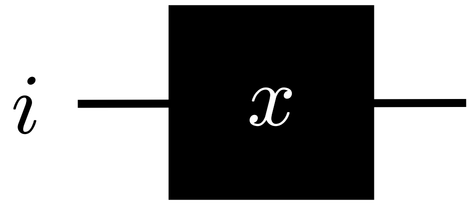

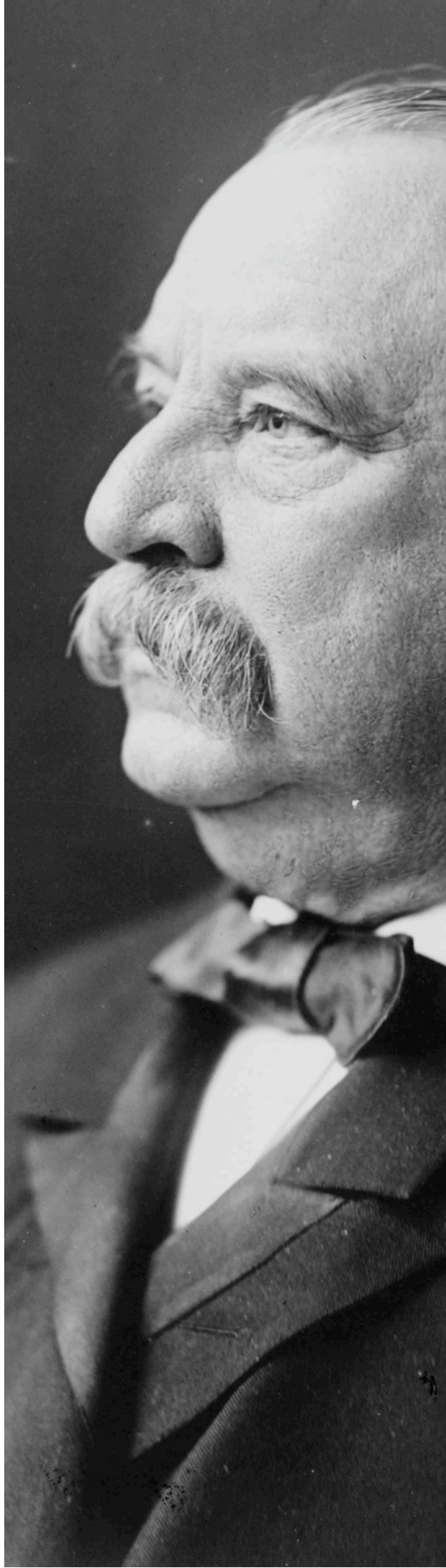

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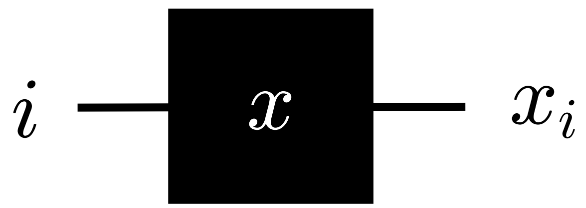

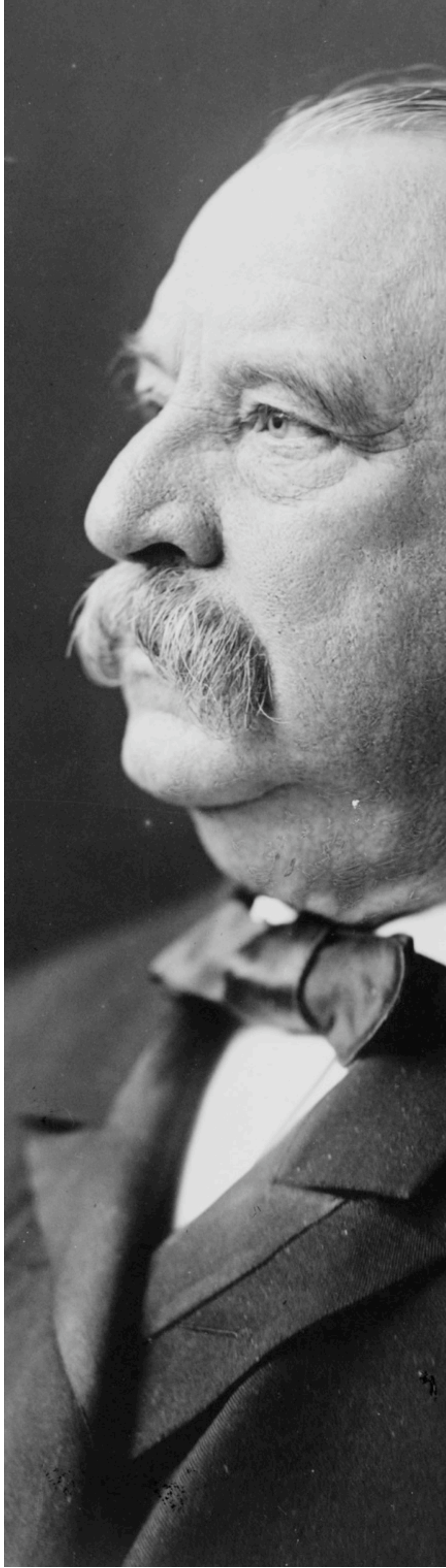

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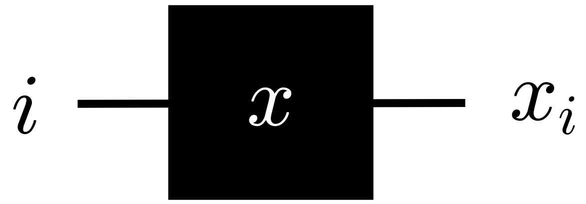

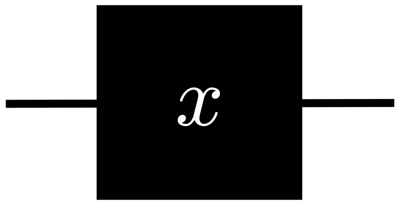

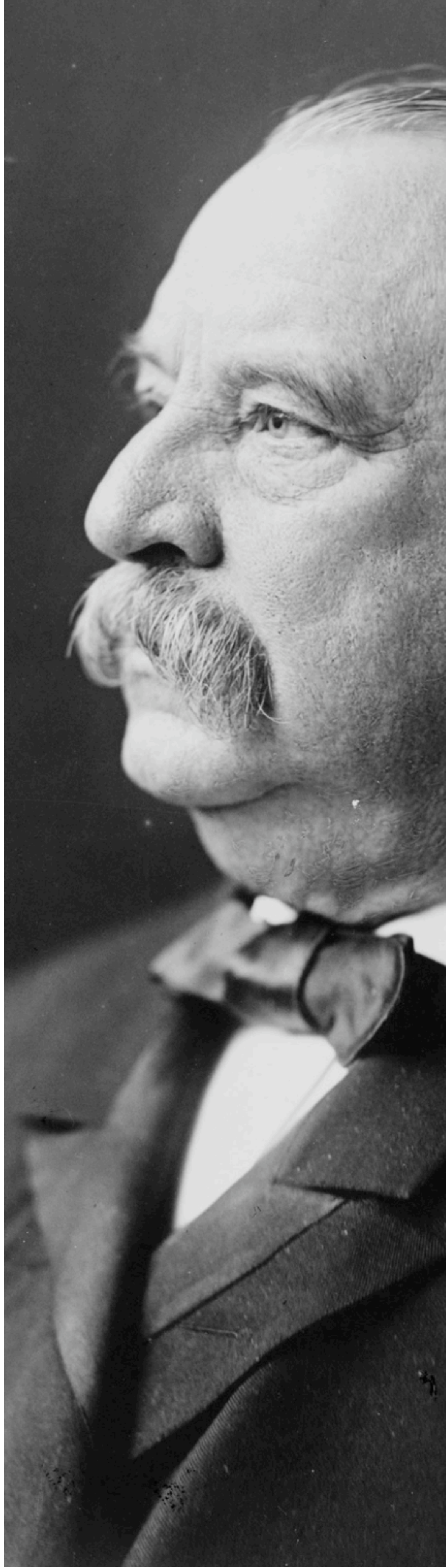

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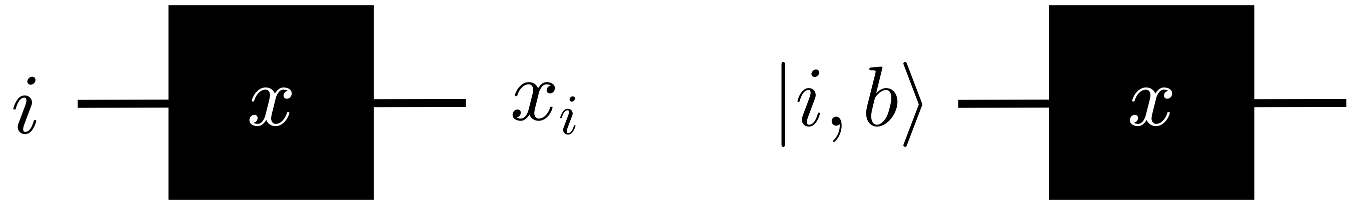

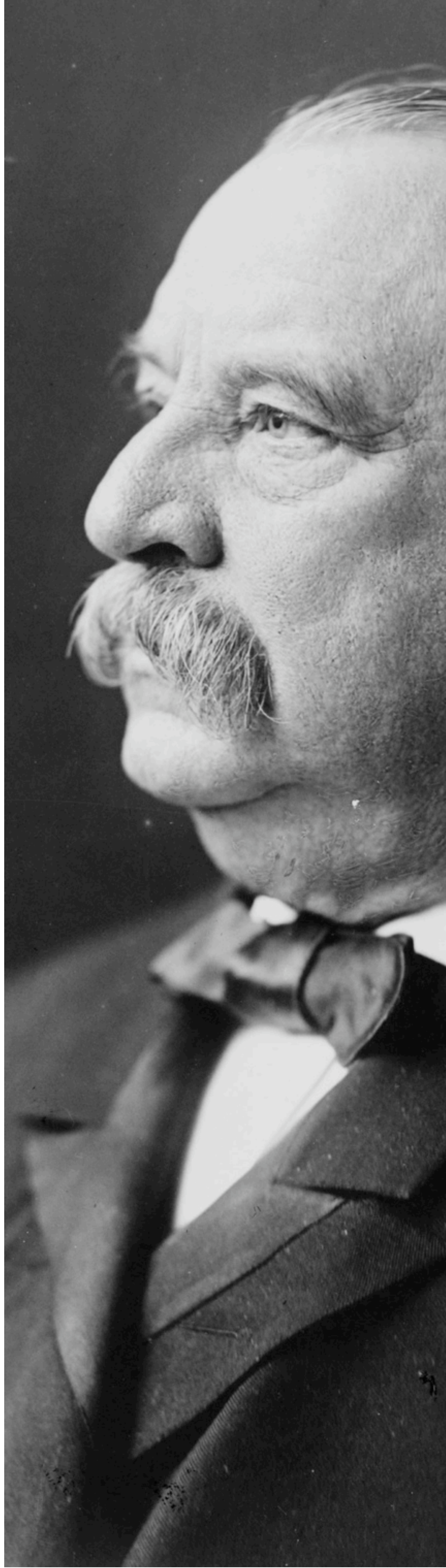

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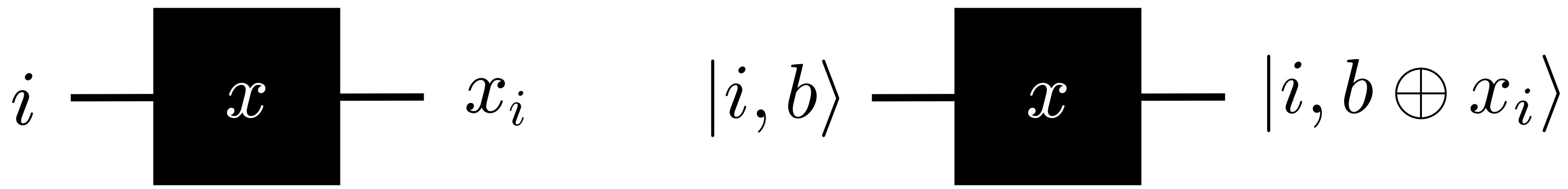

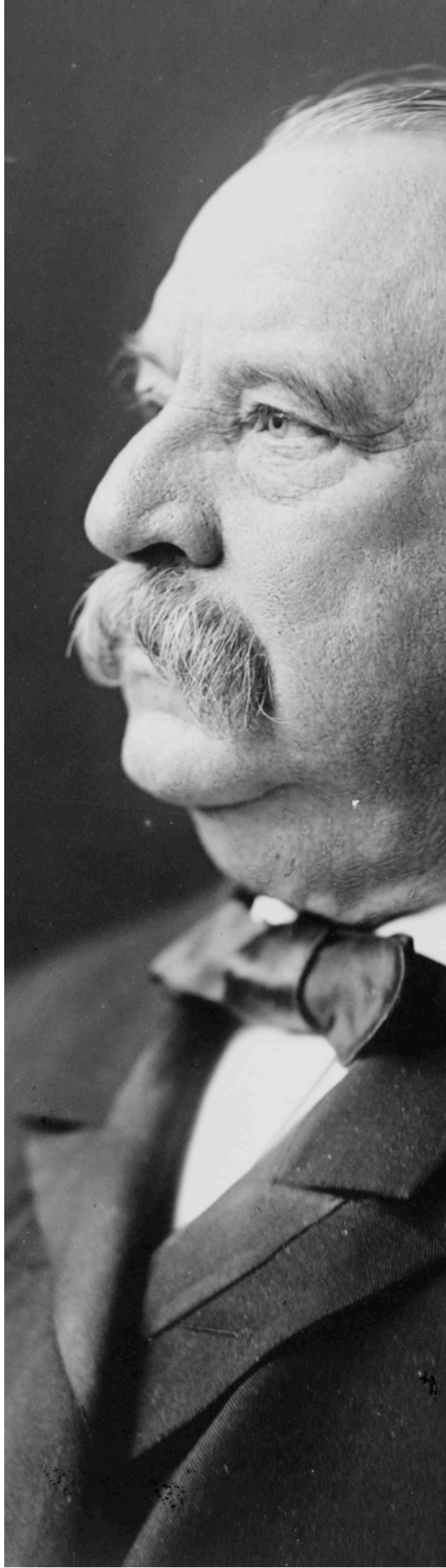

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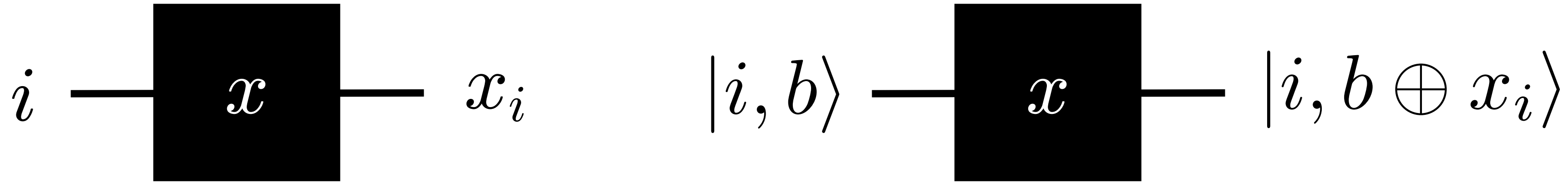
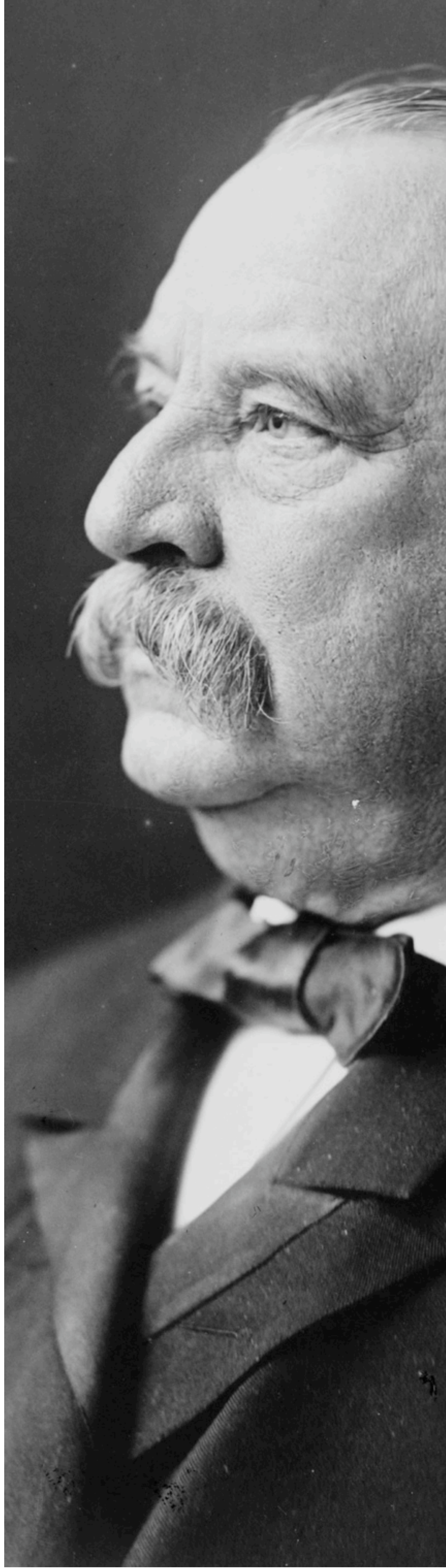


How many queries are required to evaluate OR?

Classical complexity: $\Theta(n)$

Quantum algorithm [Grover 1996]: $O(\sqrt{n})$

Quantum lower bound [BBBV 1996]: $\Omega(\sqrt{n})$



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How many queries must we make to determine who wins the game (assuming the players play optimally)?

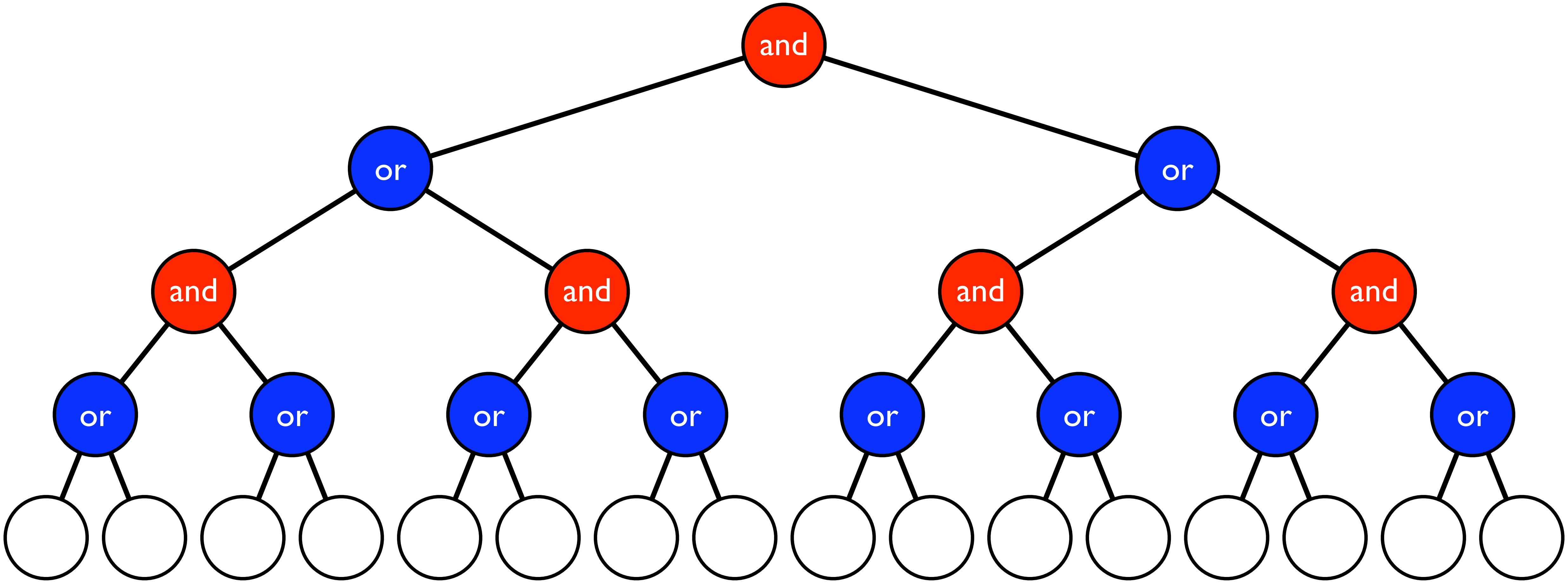
We must evaluate a formula involving AND and OR gates:

Andrea wins if she can make any move that gives 0
i.e., she only loses if all of her moves give 1 (AND)

Orlando wins if he can make any move that gives 1 (OR)

Game trees

Example: $d = 2, k = 4$



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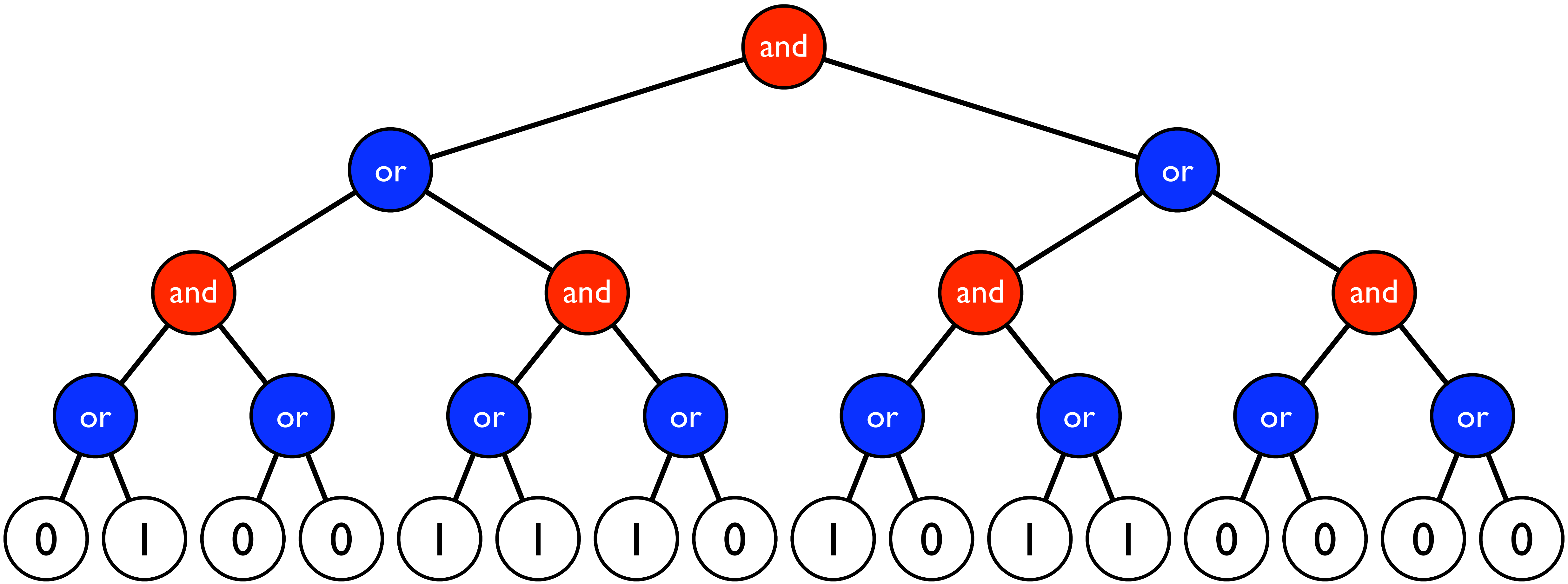

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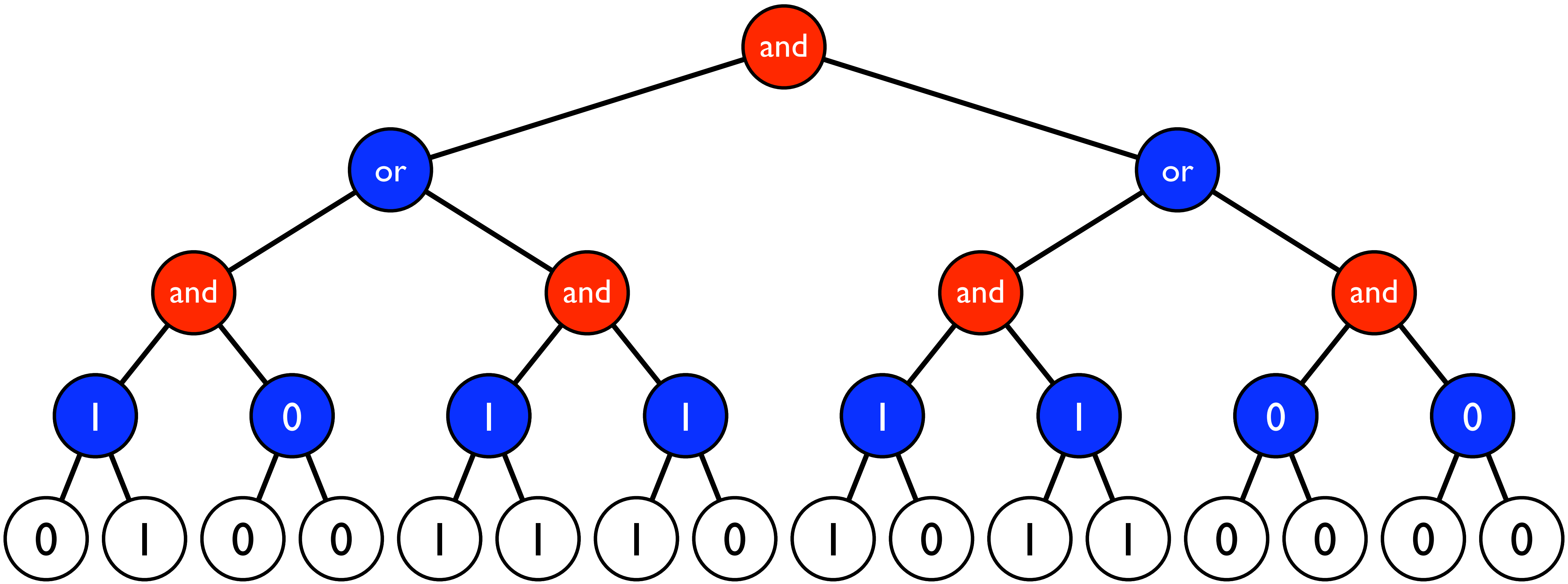

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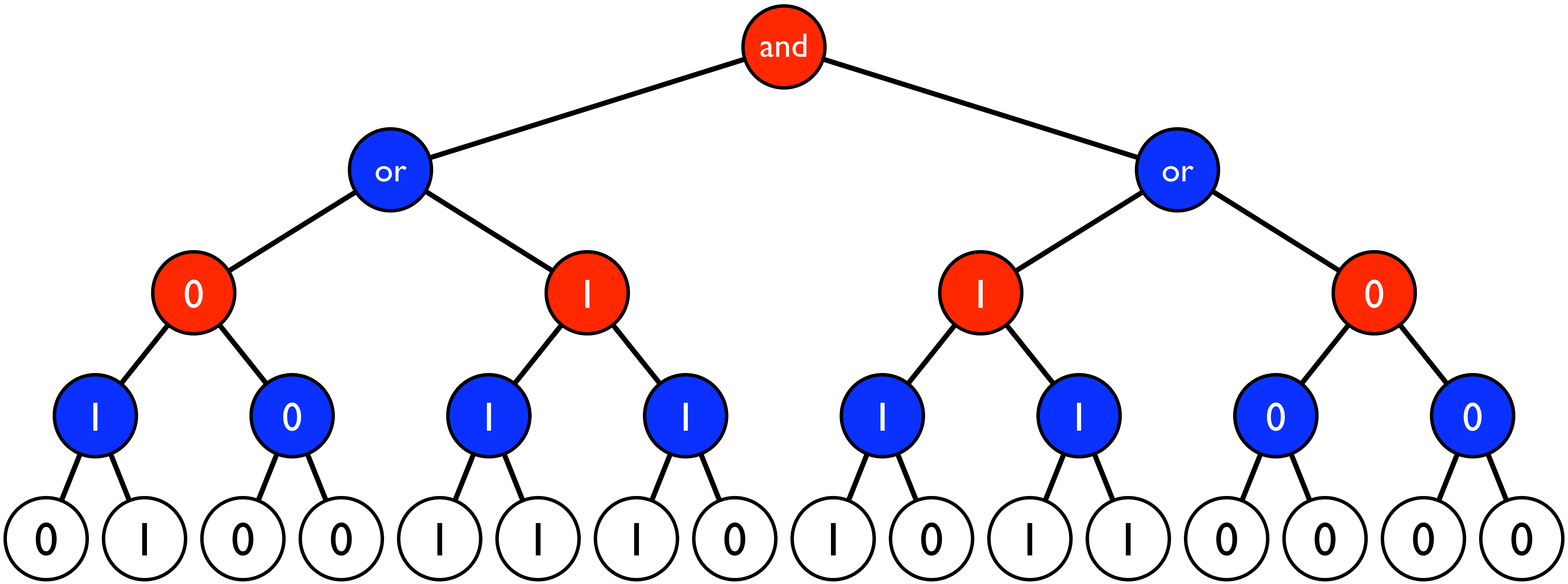

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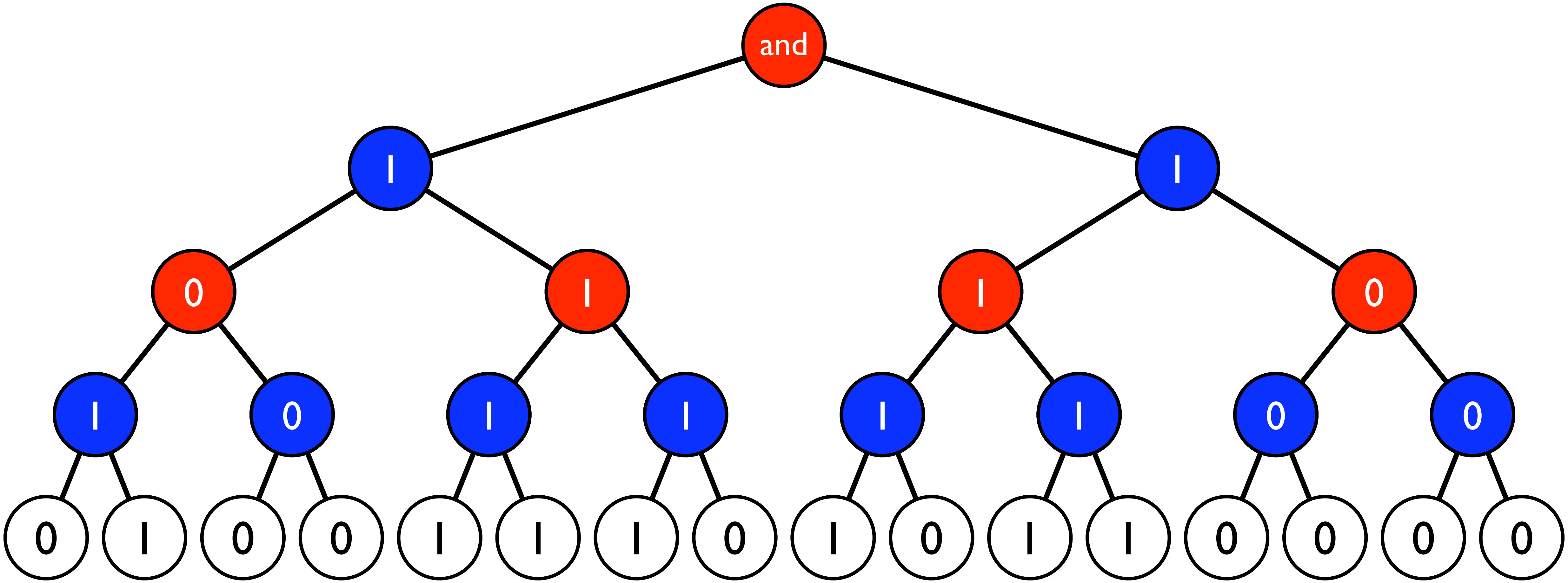

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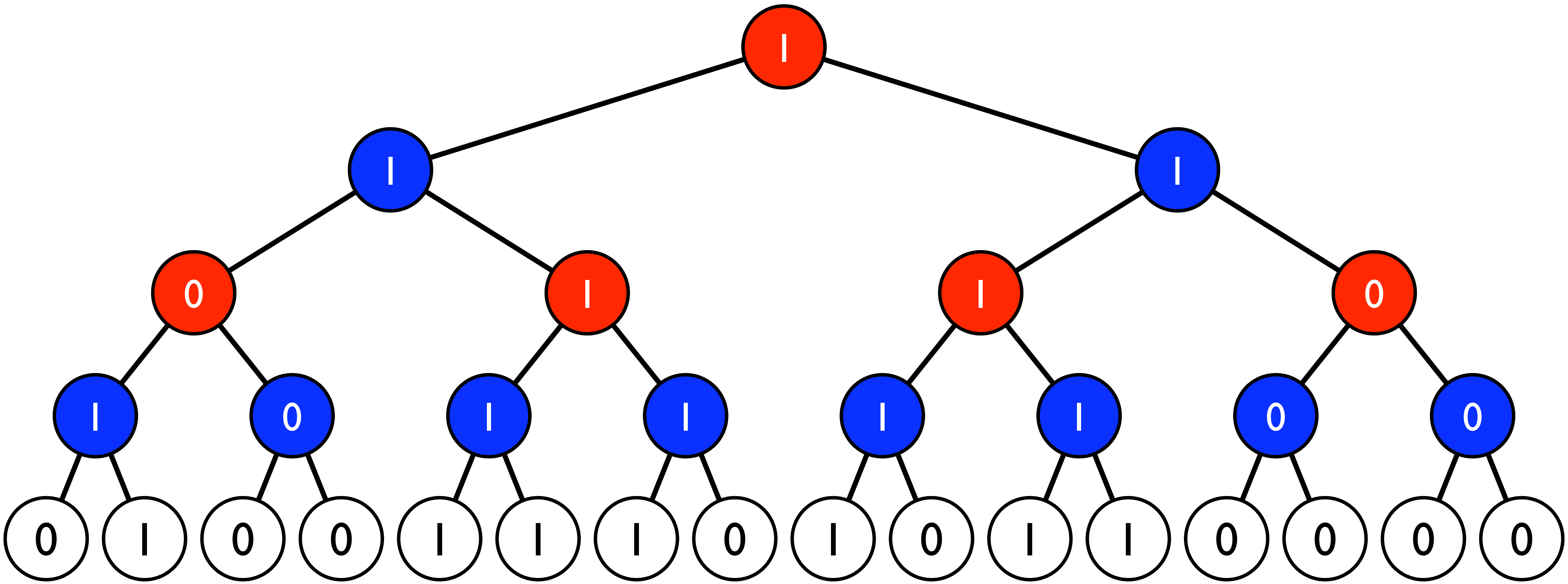

Evaluating game trees

Classical complexity: $\Theta\left(n^{\log_d \frac{d-1+\sqrt{d^2+14d+1}}{4}}\right)$ $\quad$ ($d=2$: $\Theta(n^{0.753})$)

[Snir 85; Saks, Wigderson 86; Santha 95]

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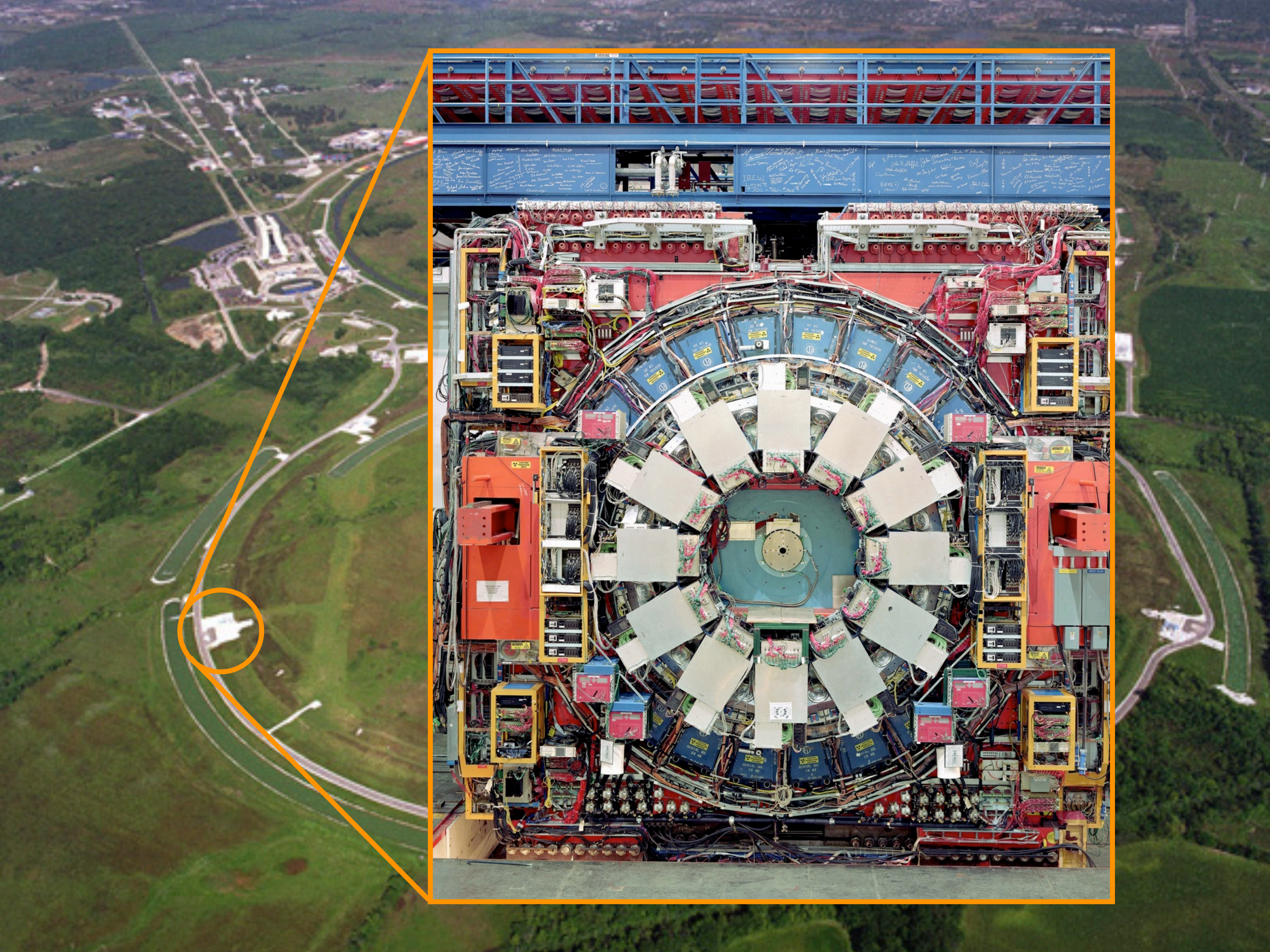
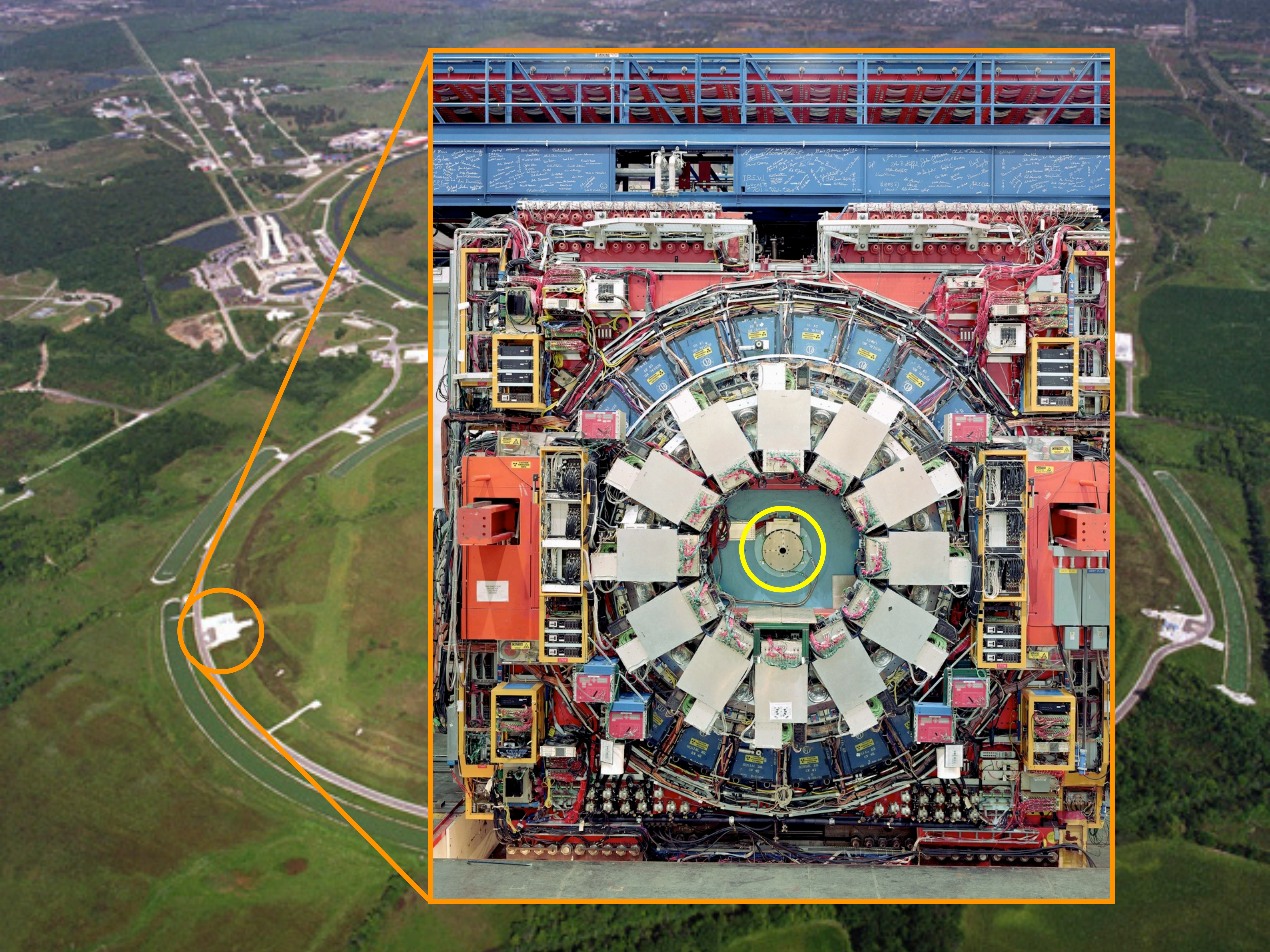
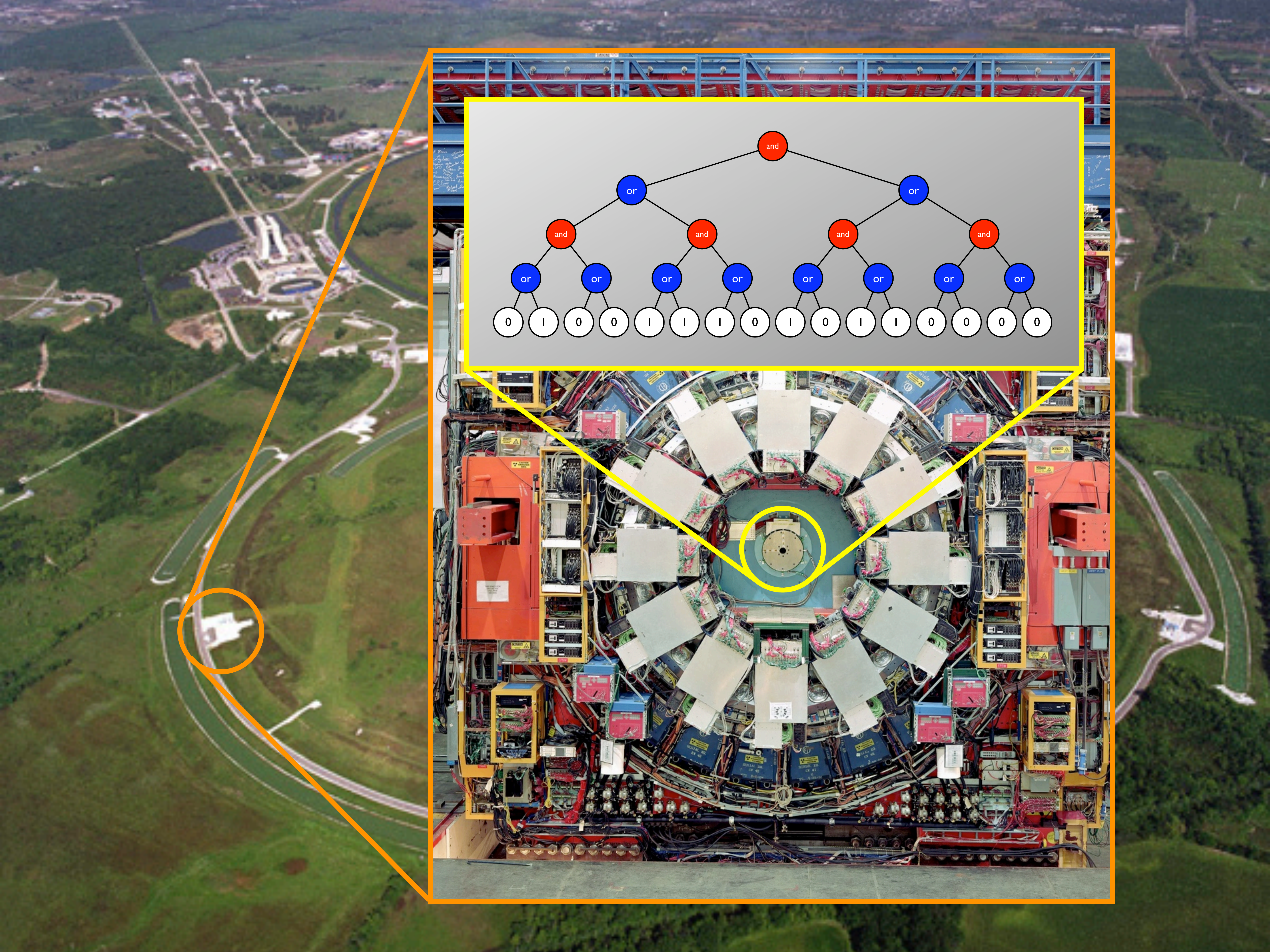
But these algorithms are only close to tight for k constant.

And for low degree (e.g., $d=2$), nothing better than classical was known until very recently!



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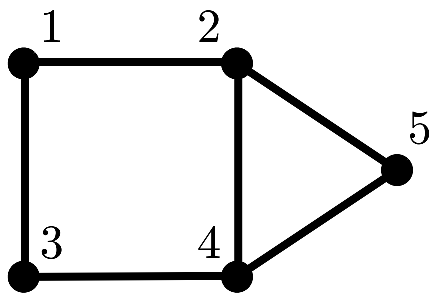
Continuous-time quantum walk

Graph G:



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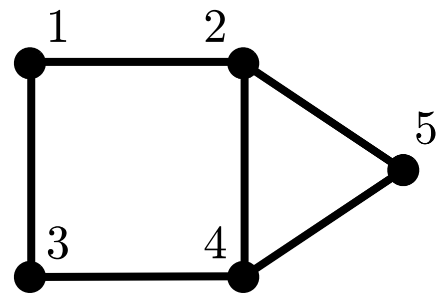

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adjacency matrix

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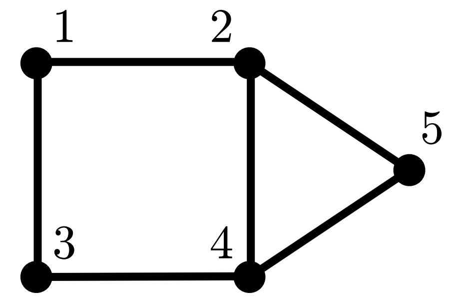

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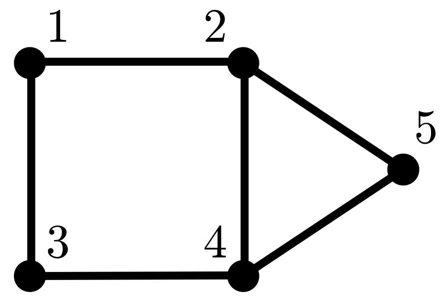
Graph G: 

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State: Probability $p_j(t)$ of being at vertex j at time t

Dynamics: $\frac{\mathrm{d}}{\mathrm{d}t}\vec{p} = -\gamma L \vec{p}$

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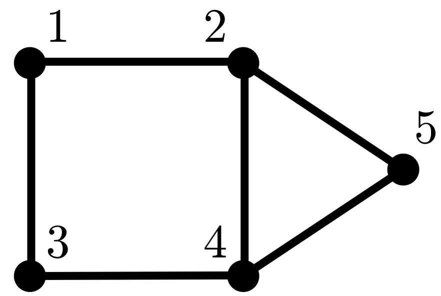

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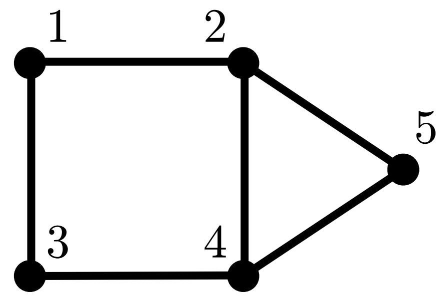
Graph G: 

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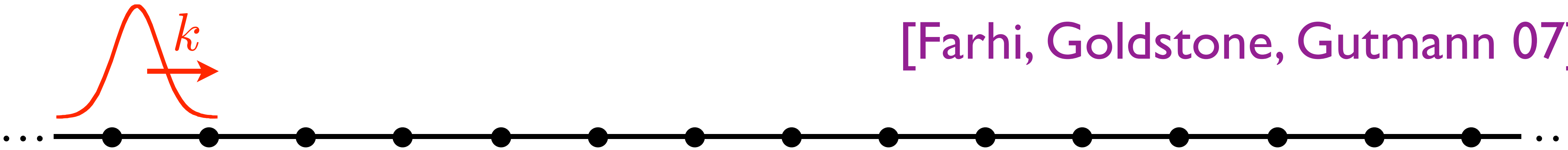
Evaluating AND-OR trees by scattering

[Farhi, Goldstone, Gutmann 07]



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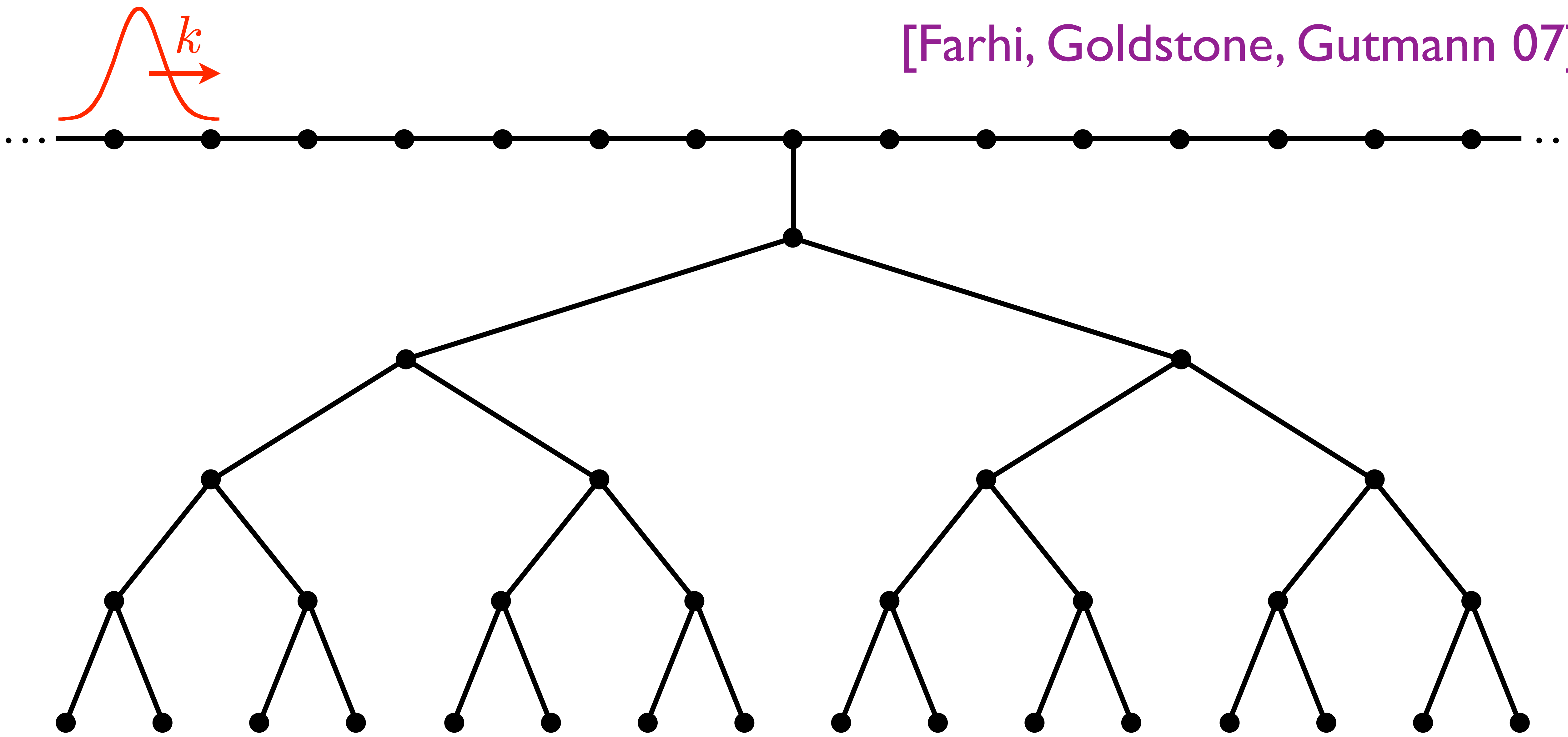

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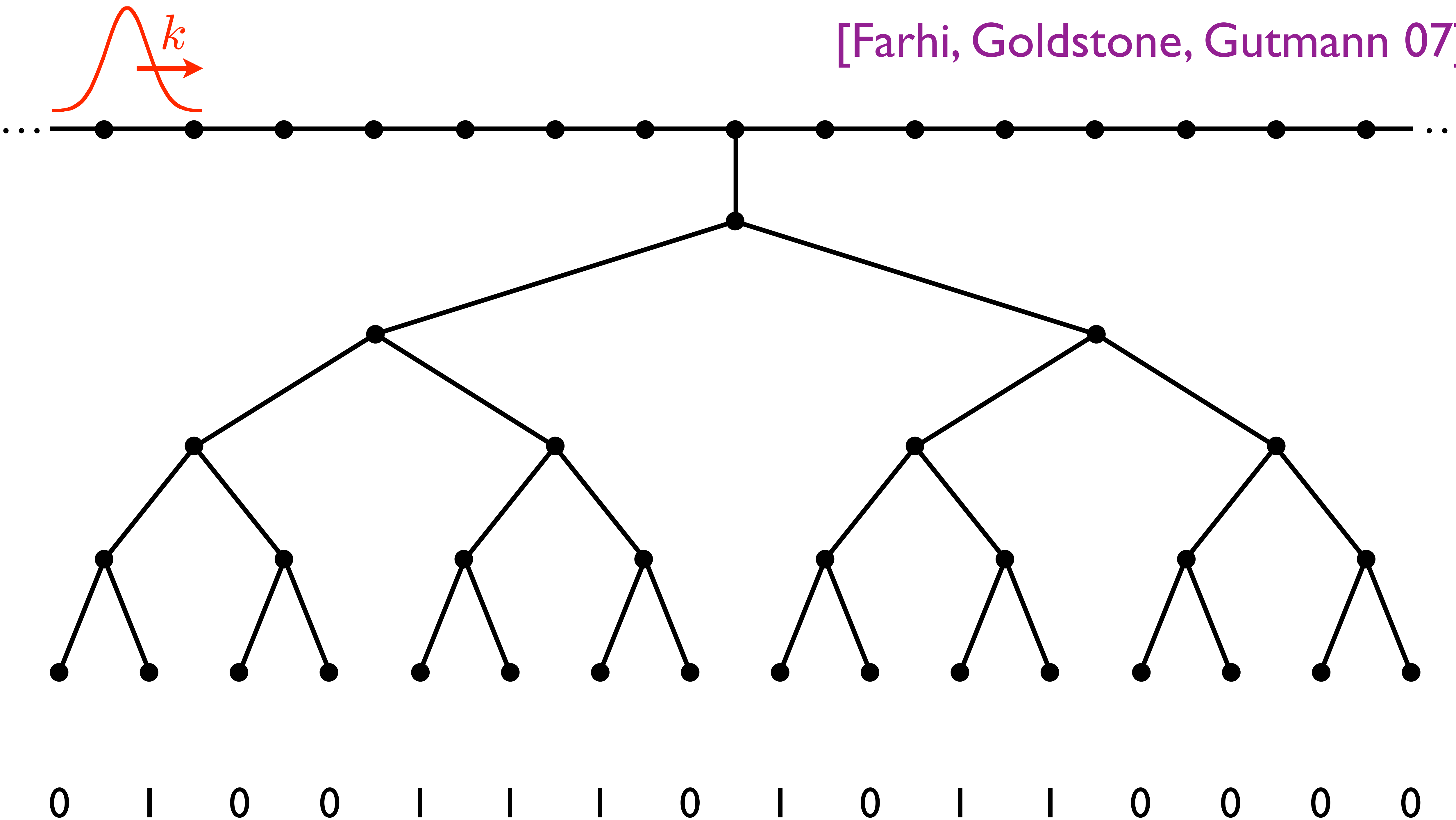

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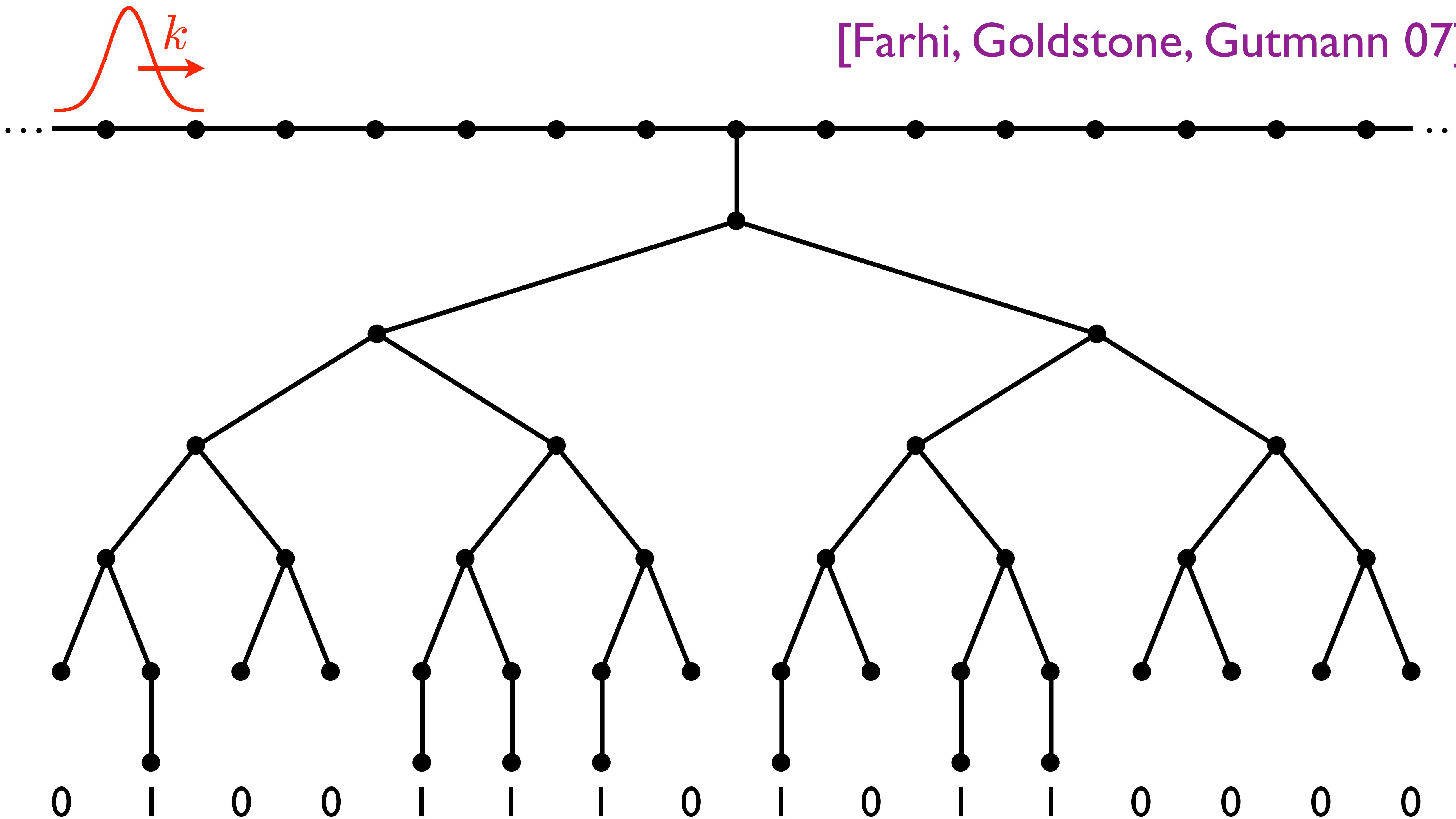

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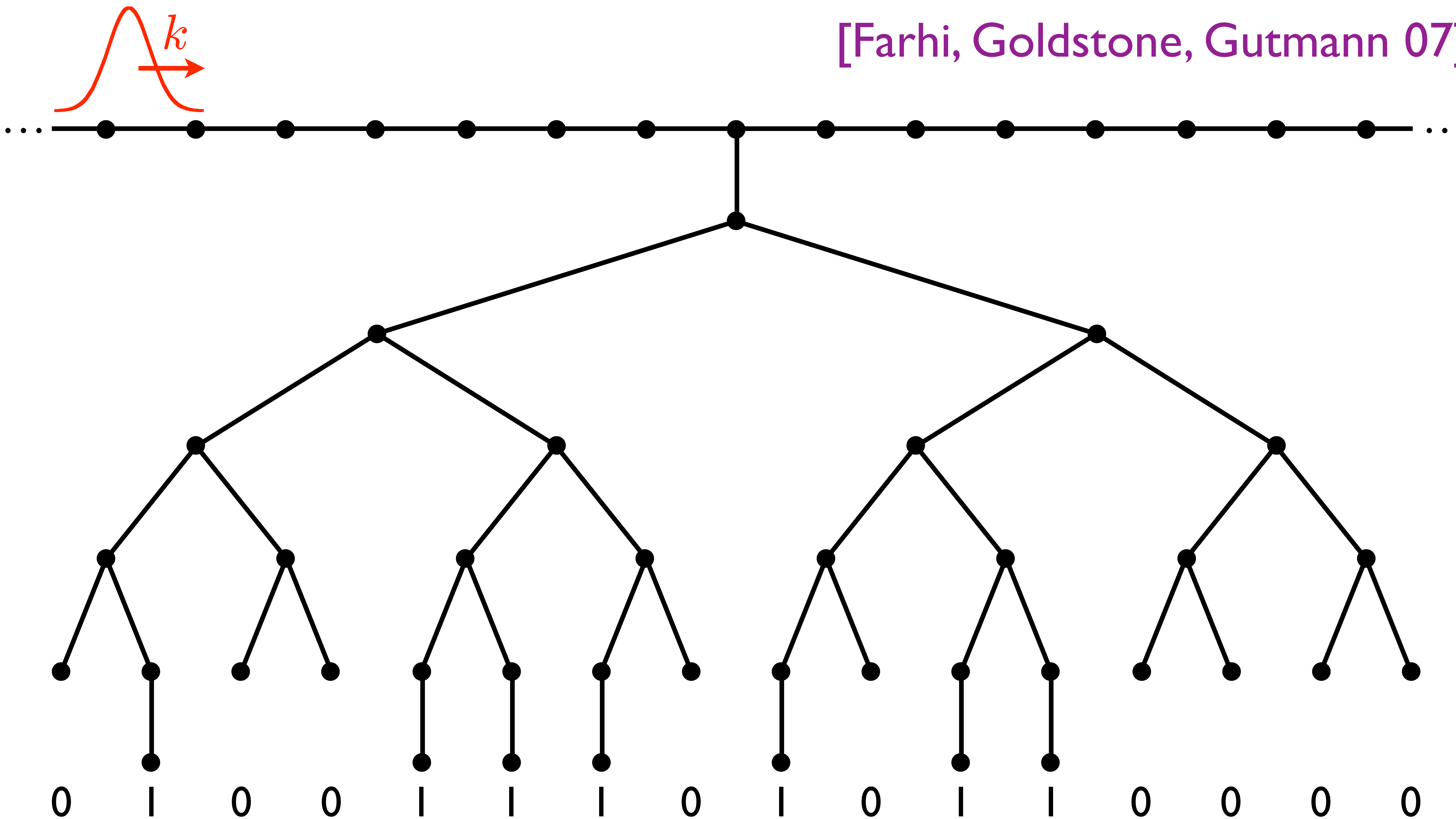

Claim: For small k, the wave is transmitted if the formula (translated into NAND gates) evaluates to 0, and reflected if it evaluates to 1.

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{AND, OR, NOT} equivalent to {NAND}

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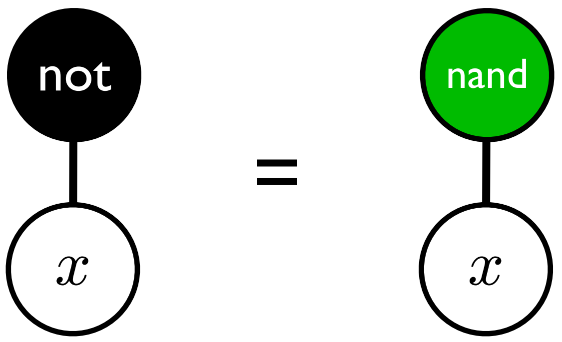

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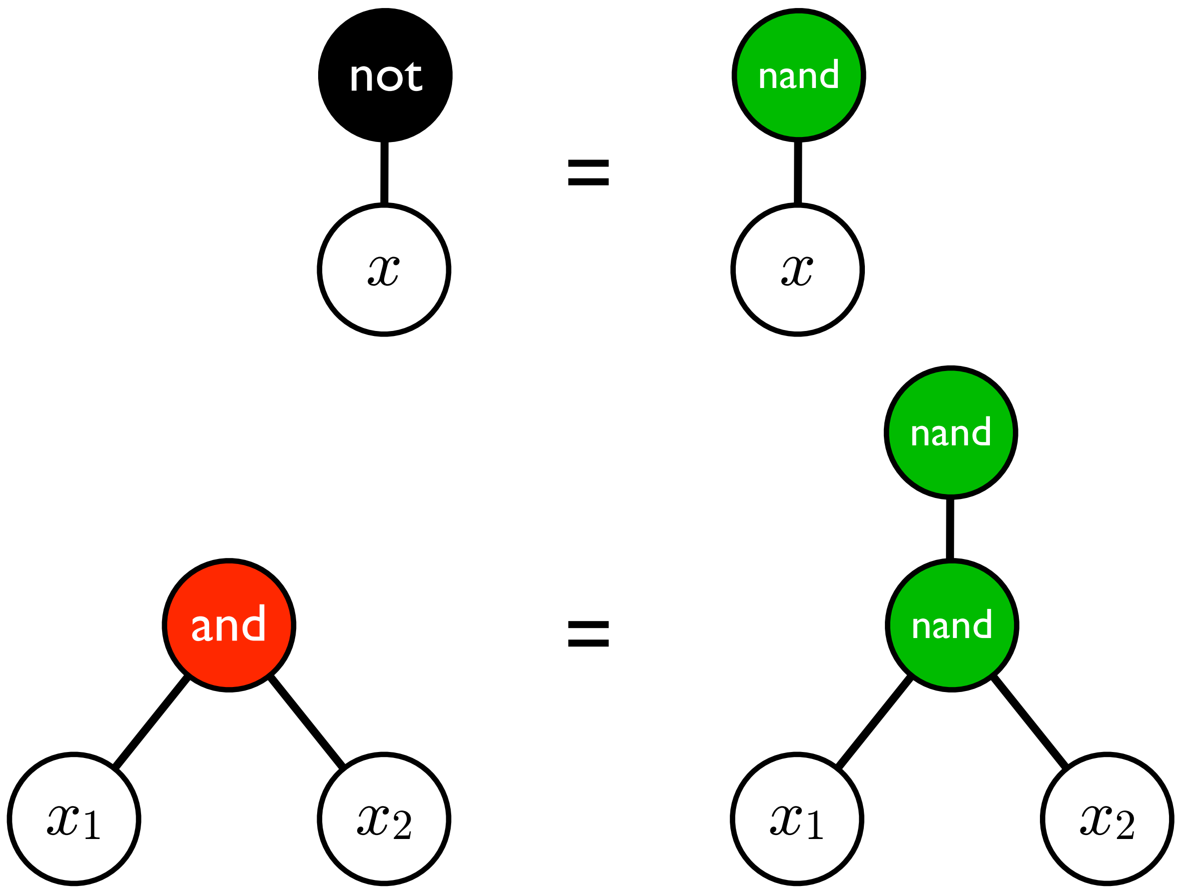

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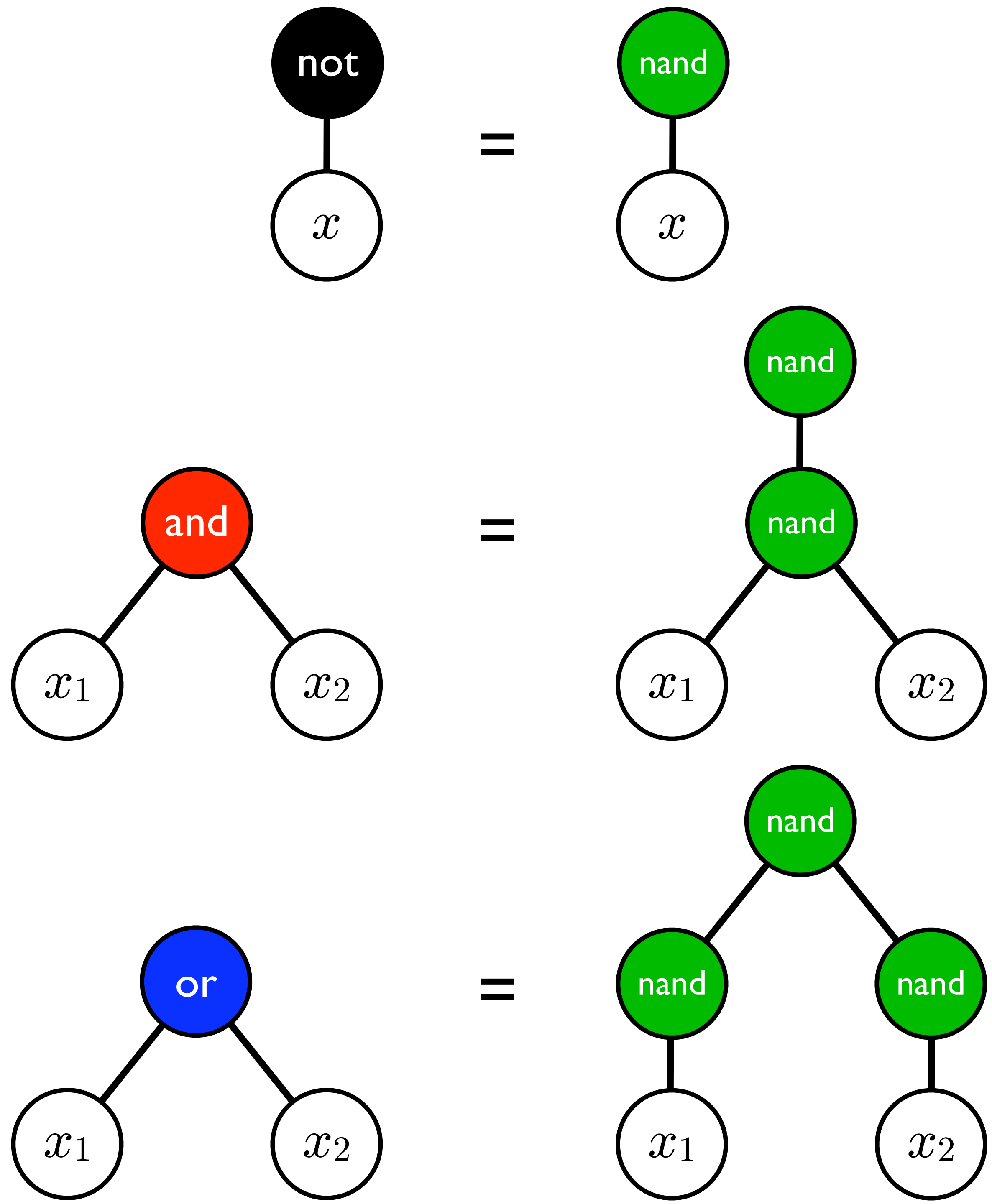
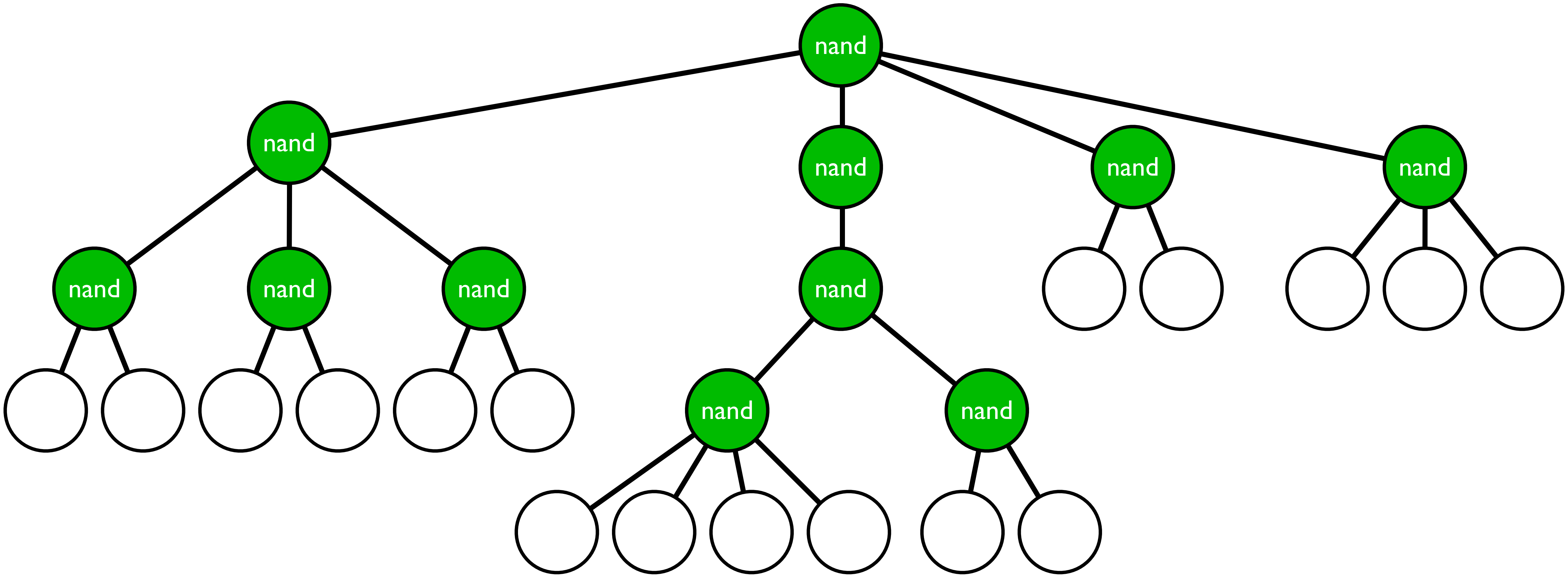


General formulas



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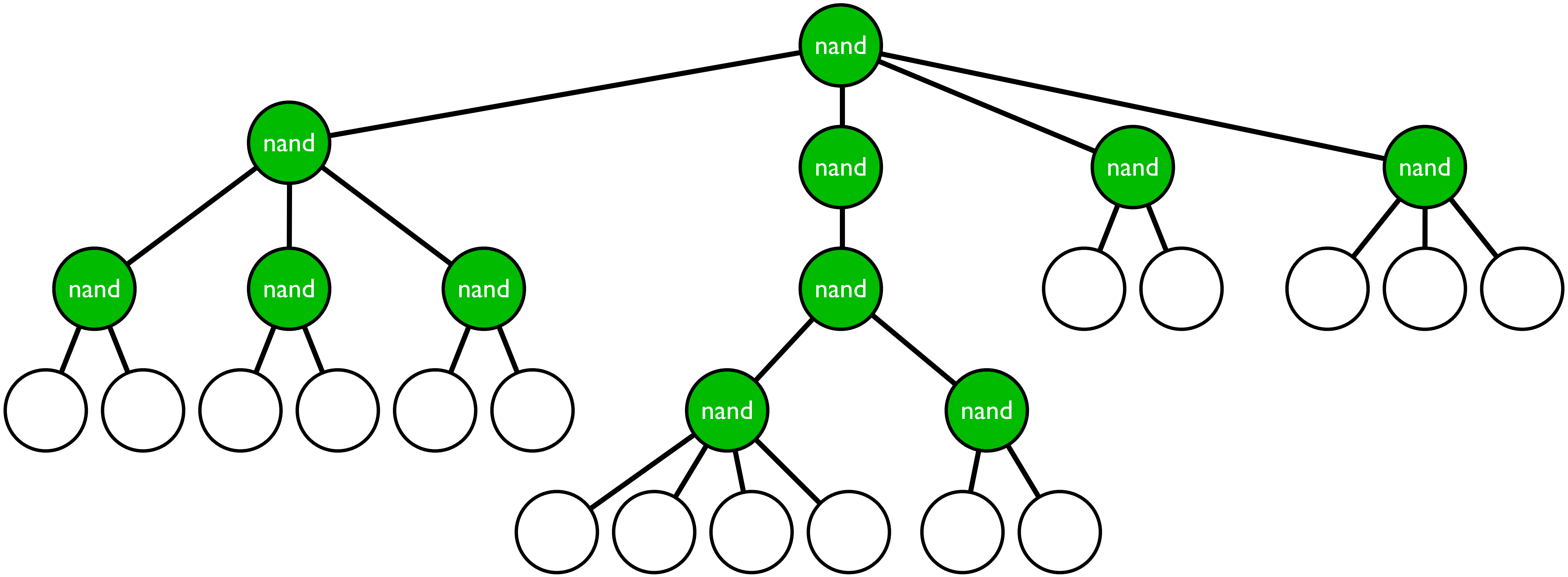

In a *formula* (instead of a *circuit*), the fanout of every gate is 1 (so the graph is a tree).

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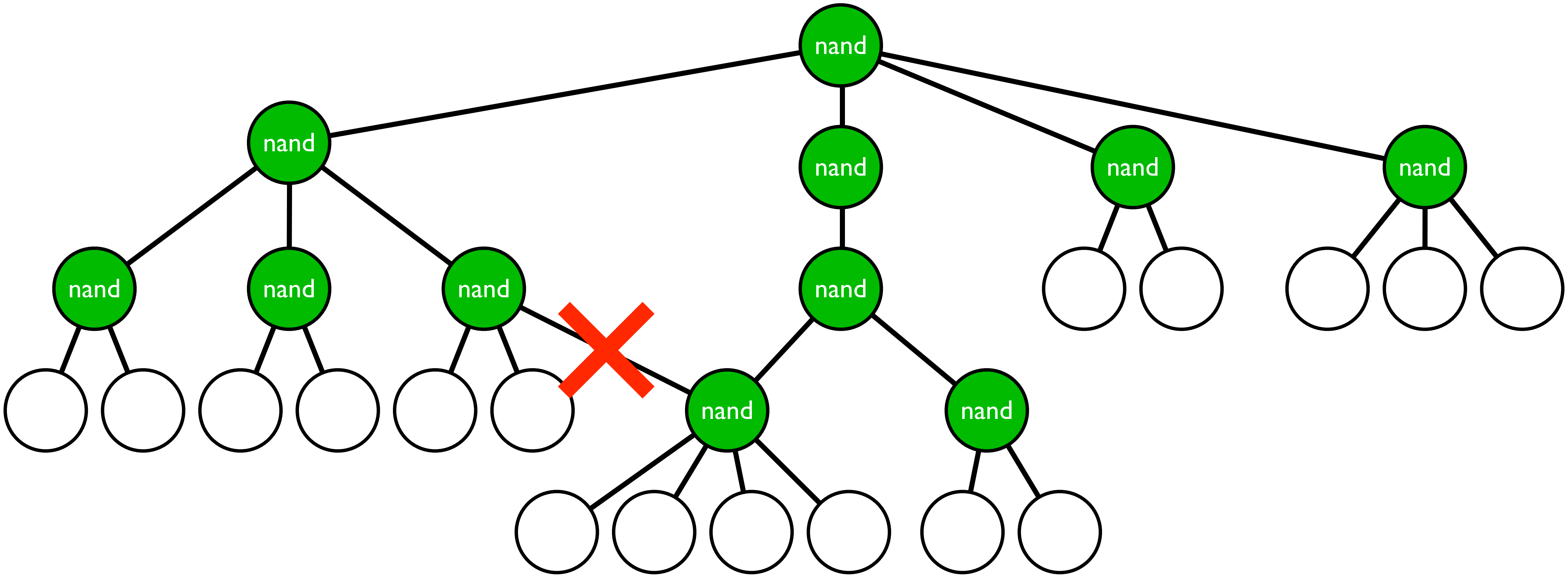

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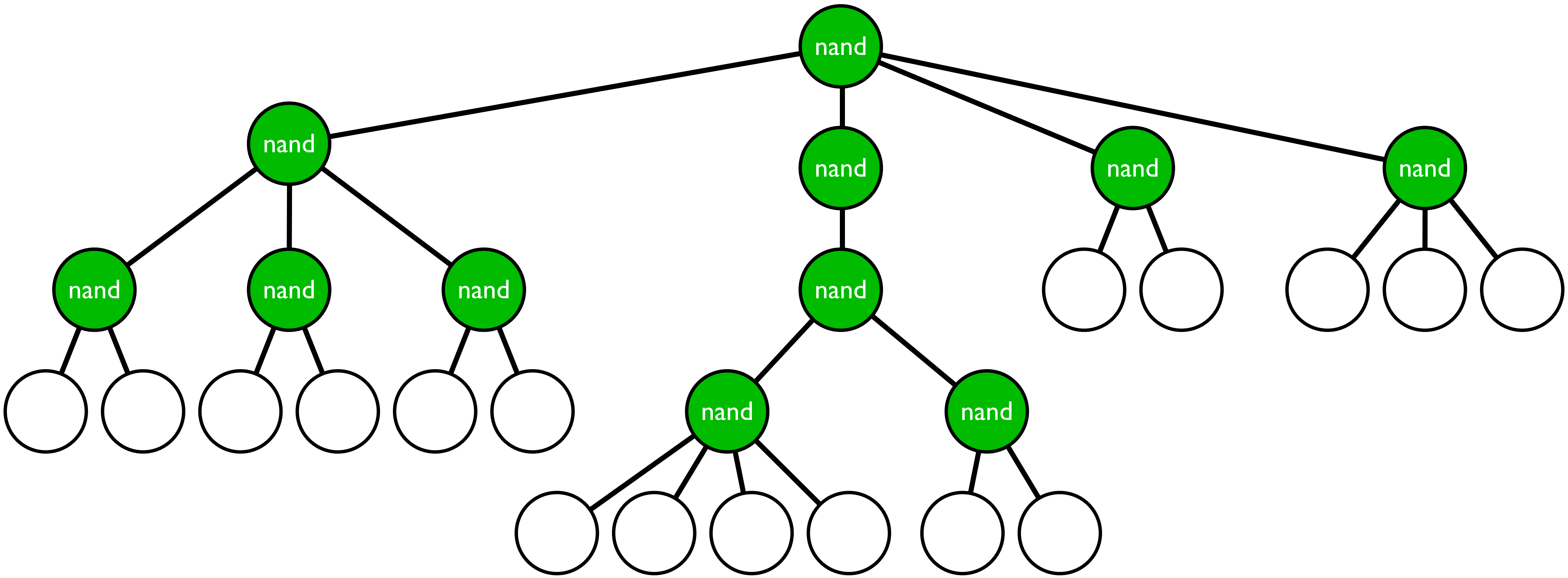

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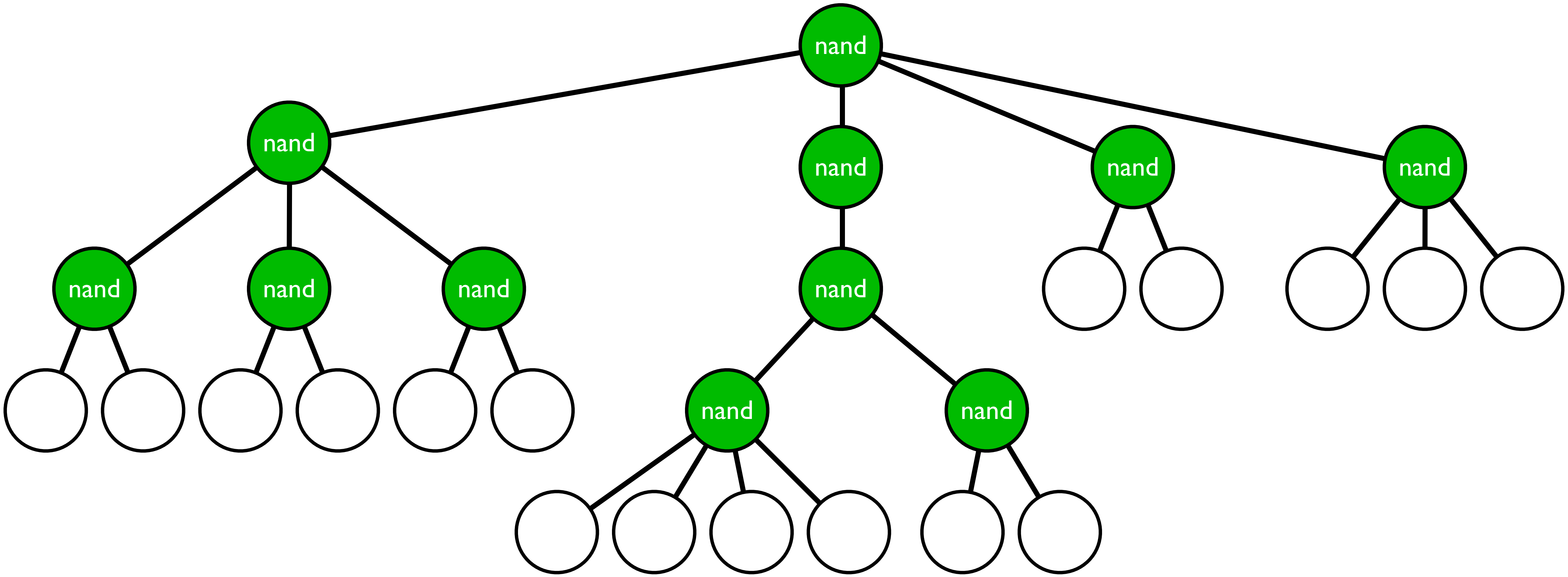

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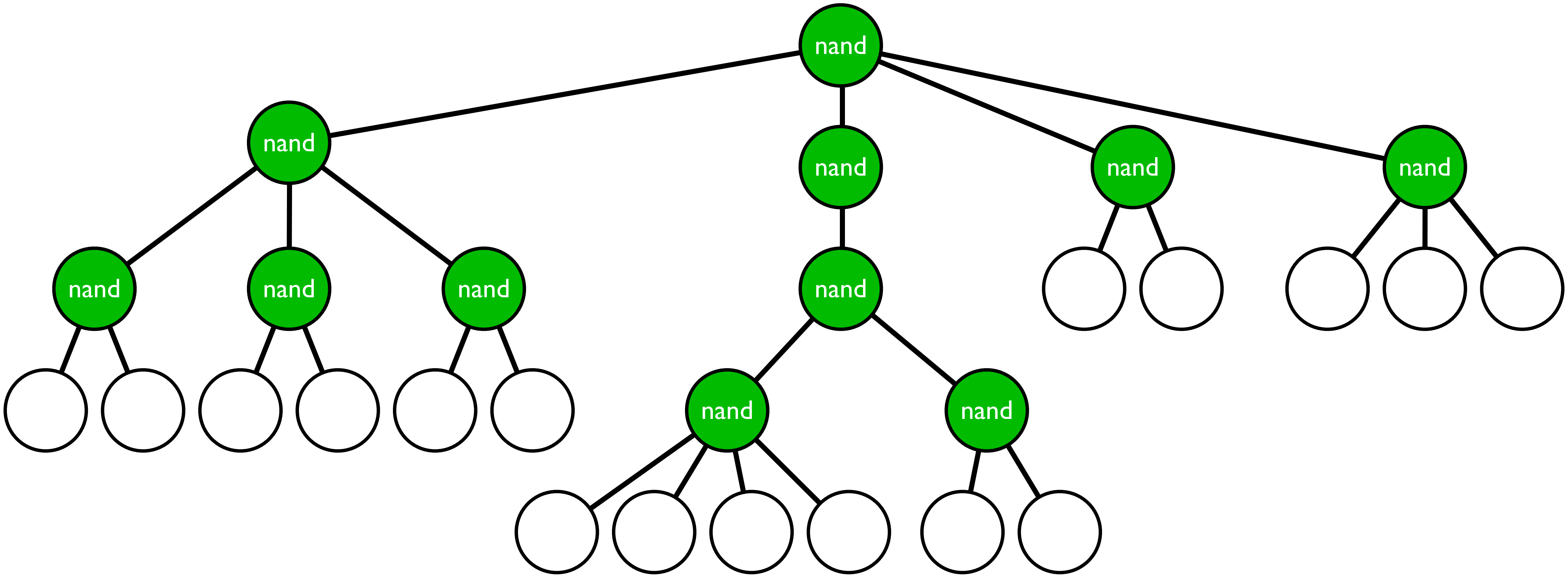

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Quantum lower bound [Barnum-Saks 02]: $\Omega(\sqrt{n})$

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This talk:

- $O(\sqrt{n})$ query quantum algorithm for evaluating "approximately balanced" NAND formulas (optimal!)
- $\sqrt{n^{1+o(1)}}$ time (and query) quantum algorithm for evaluating arbitrary NAND formulas

The algorithm

1. Start at the root of the tree
2. Perform phase estimation with precision $\approx 1/\sqrt{n}$ on a discrete-time quantum walk on the tree
3. If the estimated phase is 0 or π, then output 1; otherwise output 0

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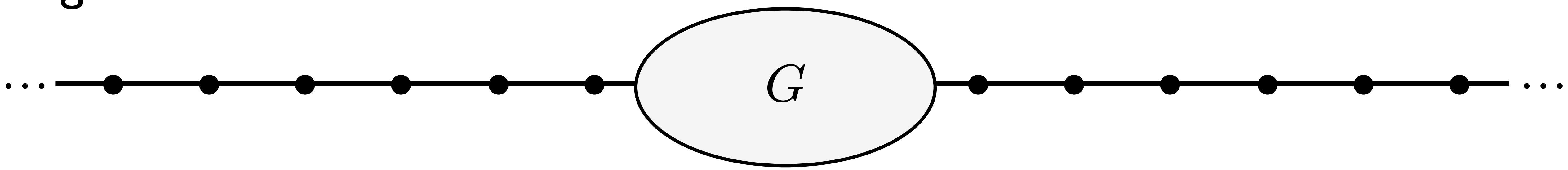
Outline

- Scattering → phase estimation
- Hamiltonian for a continuous-time quantum walk (with non-uniform edge weights)
- Low-energy eigenstates "compute NAND"
- Continuous time → discrete time (gives a small speedup)
- Formula rebalancing

From scattering to phase estimation

To do scattering calculations, we compute a complete basis of eigenstates:



Left:	$e^{ikx} + R(k)\, e^{-ikx}$	$T(k)\, e^{ikx}$
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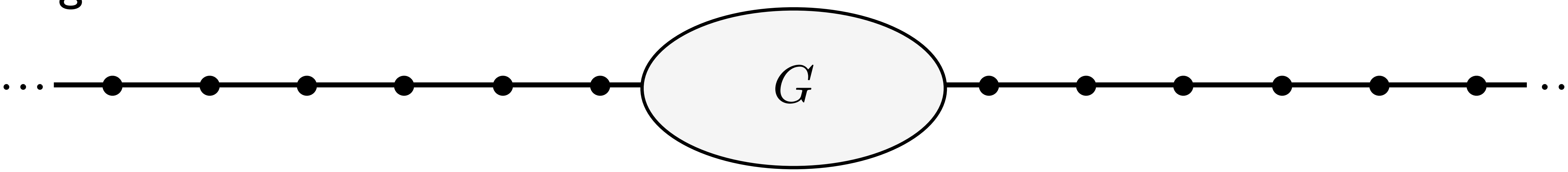

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Instead, we can just look at eigenstates of the graph itself.

Phase estimation: Given U and an eigenstate $|\varphi\rangle$ with $U|\varphi\rangle = e^{i\varphi}|\varphi\rangle$, we can estimate φ to precision δ in $O(1/\delta)$ steps.
(Equivalent to measuring $H = i \log U$.)

The Hamiltonian

Graph: Tree representing the NAND formula, with edges added to 1 inputs (so that all leaves evaluate to 0).

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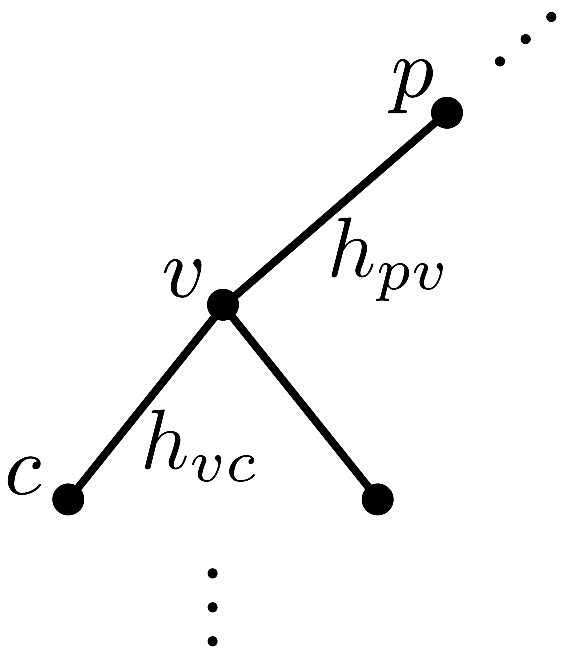
$$H|v\rangle = h_{pv}|p\rangle + \sum_c h_{vc}|c\rangle$$



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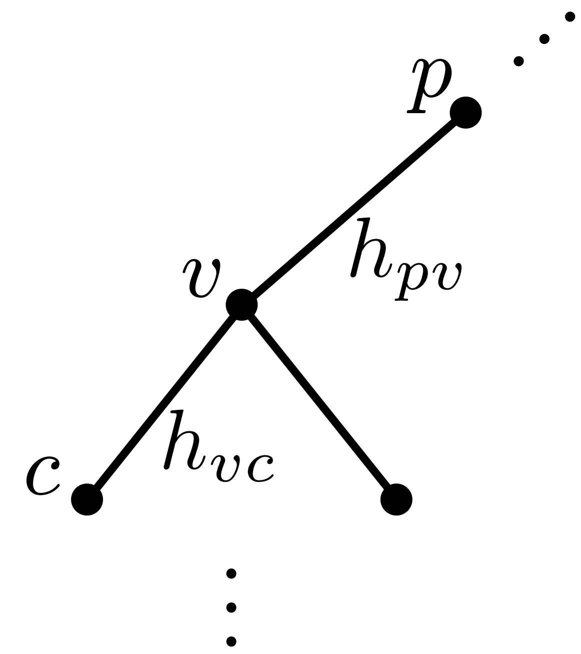

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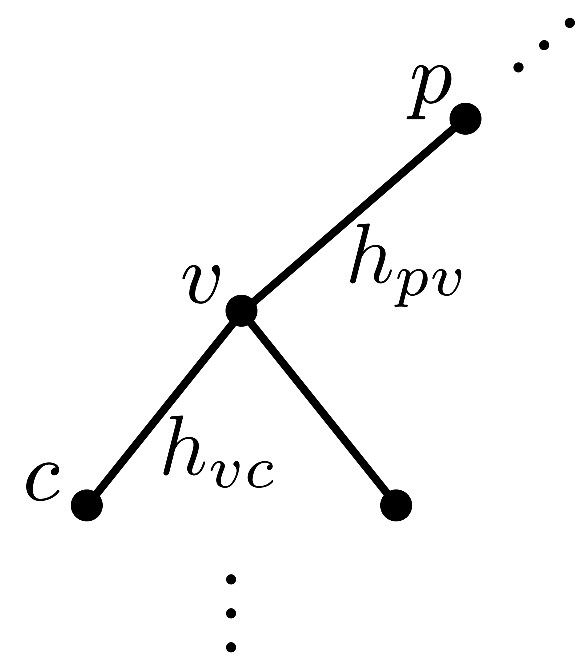

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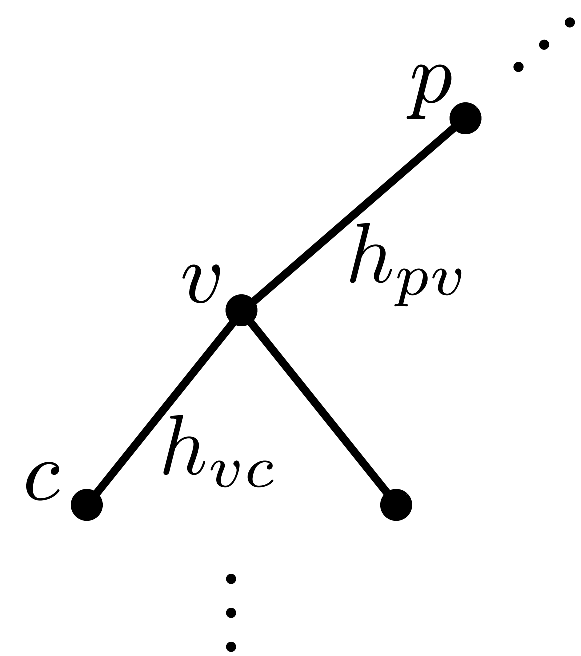

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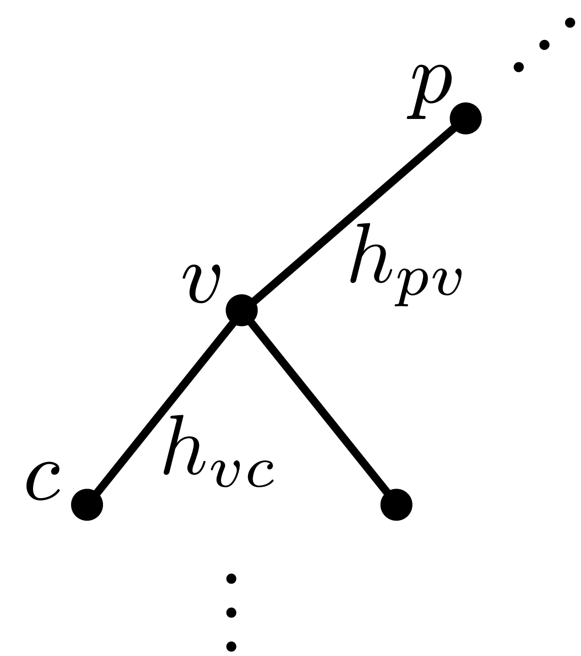

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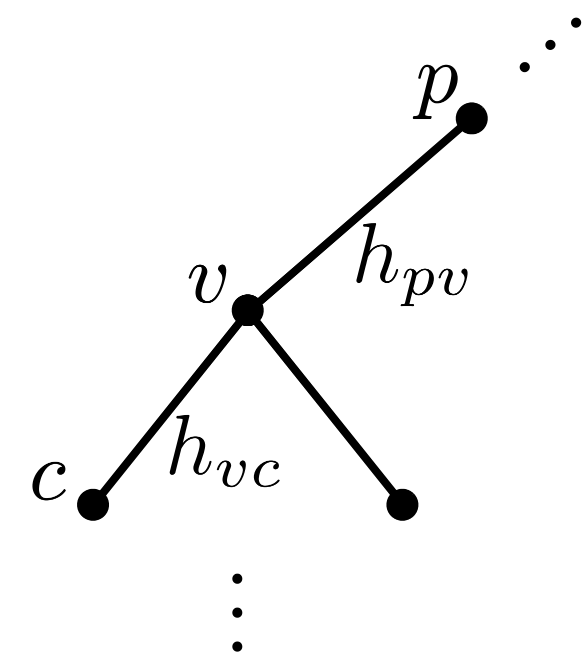

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For $E=0$: $\quad \langle p|\Psi\rangle = -\sum_c \frac{h_{vc}}{h_{pv}}\langle c|\Psi\rangle$

Zero-energy eigenstates evaluate NAND

Let r = root of the tree.

Theorem (qualitative).

If formula $= 0$, then $|\langle r|\Psi\rangle| > 0$ for some $|\Psi\rangle$ with $H|\Psi\rangle = 0$.

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Theorem (quantitative). For approximately balanced formulas:

If formula $= 0$, then $|\langle r|\Psi\rangle| > \Omega(1)$ for some $|\Psi\rangle$ with $H\,|\Psi\rangle = 0$.

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Simulating the quantum walk

[C., Cleve, Jordan, Yeung 07]

We could perform phase estimation directly on the dynamics of this Hamiltonian (i.e., measure the energy).

But this would require *simulating* the dynamics by a sequence of quantum gates, using the black box to simulate the walk near the leaves, and combining that simulation with the input-independent part.

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Instead, we can avoid the $o(1)$ by using a discrete-time quantum walk.

Continuous time → discrete time

Szegedy quantization of classical Markov chains:

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Classical random walk

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Claim: Any symmetric matrix H with positive entries can be factorized as $H = \sqrt{P \circ P^T}$ for some stochastic matrix P. (use Perron vector)

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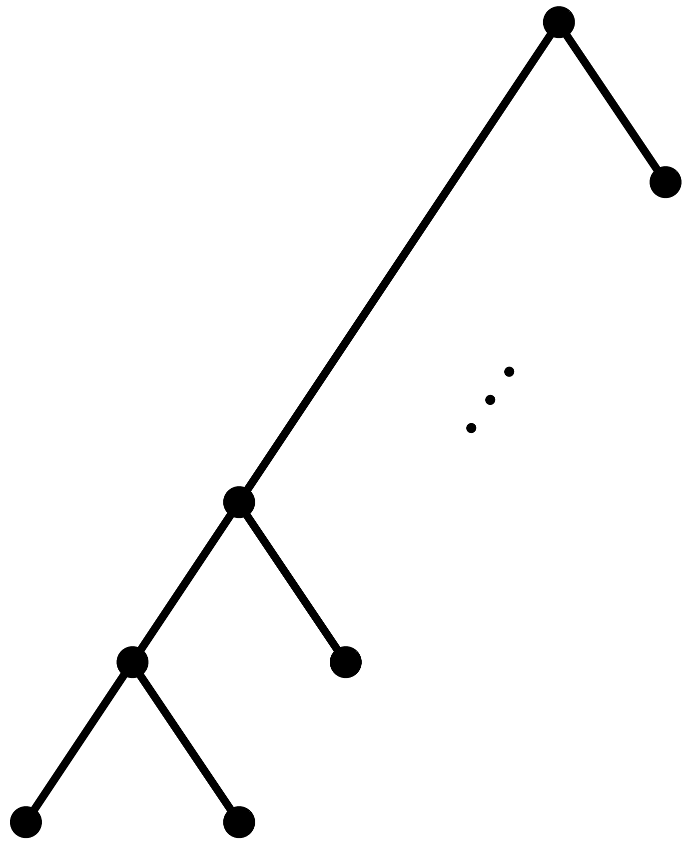
This gives a general way to relate continuous- and discrete-time quantum walk. Small eigenphases of e^{-iH} and U are equal up to third order.

Formula rebalancing

A quantum walk algorithm clearly cannot work for highly unbalanced formulas:



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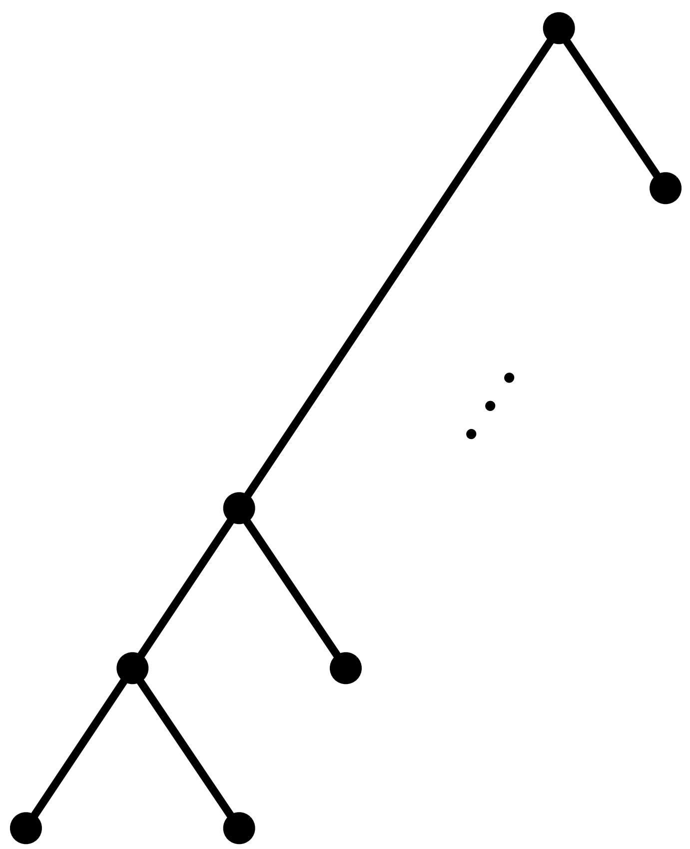

But we can apply

Theorem [Bshouty, Cleve, Eberly 91]: Any NAND formula of size n can be rewritten as an equivalent NAND formula of depth $O(\log n)$ and size $n^{1+o(1)}$.

Applications to recursive functions

Recursive "all equal" function [Ambainis 03]

$$f(x,y,z) = \begin{cases} 1 & x = y = z \\ 0 & \text{otherwise} \end{cases}$$ recurse k times

Polynomial degree: 2^k

Q. query complexity: $\Omega((\frac{3}{\sqrt{2}})^k) = \Omega(2.12^k)$ (adversary method)

$O(\sqrt{6^k}) = O(2.45^k)$ (NAND of 6)

Recursive majority function [Boppana 86]

$$f(x,y,z) = \begin{cases} 1 & x + y + z \geq 2 \\ 0 & \text{otherwise} \end{cases}$$ recurse k times

C. query complexity [JKS 03]: $\Omega((\frac{7}{3})^k) = \Omega(2.33^k)$

$o((\frac{8}{3})^k) = o(2.67^k)$

Q. query complexity: $\Omega(2^k)$ (adversary method)

$O(\sqrt{5^k}) = O(2.24^k)$ (NAND of 5)

Closed problems

This also resolves a conjecture of [O'Donnell-Servedio 03]:

Any NAND formula of size n can be approximated by a polynomial of degree $\sqrt{n^{1+o(1)}}$.

Hence formulas are (classically!) PAC learnable in time $2^{\sqrt{n^{1+o(1)}}}$.

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Open problems

- Formulas with yet more general gates?
- Similar algorithms for *circuits*?
- Can we compute a certificate for the value of a formula?
- Improved formula rebalancing?

Zero-energy eigenstates evaluate NAND: Qualitative version

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Theorem.
If $\mathrm{NAND}(p) = 1$, then $\langle p | \Psi \rangle = 0$ for any $|\Psi\rangle$ with $H|\Psi\rangle = 0$.
If $\mathrm{NAND}(r) = 0$, then $|\langle r | \Psi \rangle| > 0$ for some $|\Psi\rangle$ with $H|\Psi\rangle = 0$.

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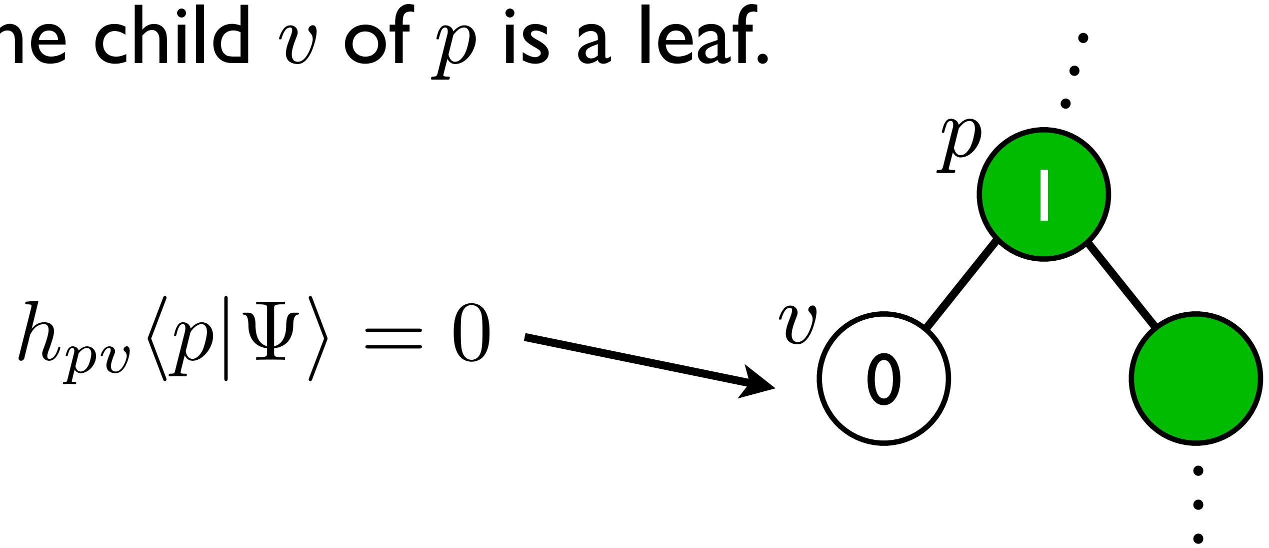

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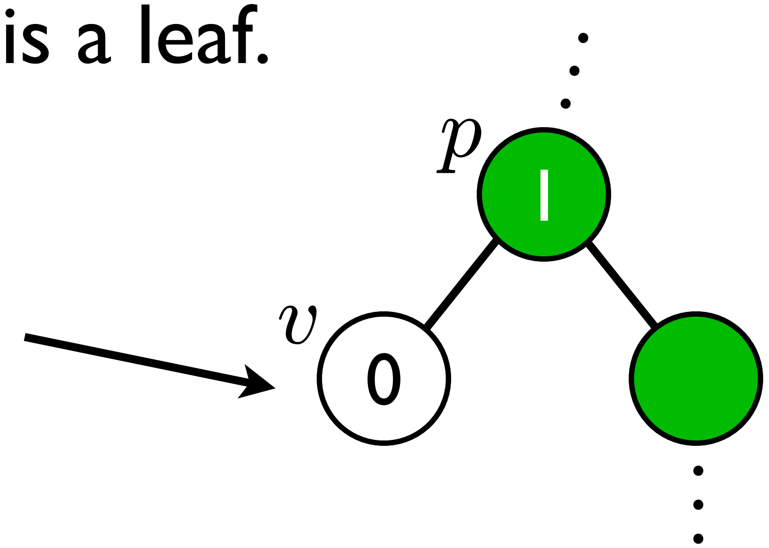

Induction: Some child v of p has $\mathrm{NAND}(v) = 0$;
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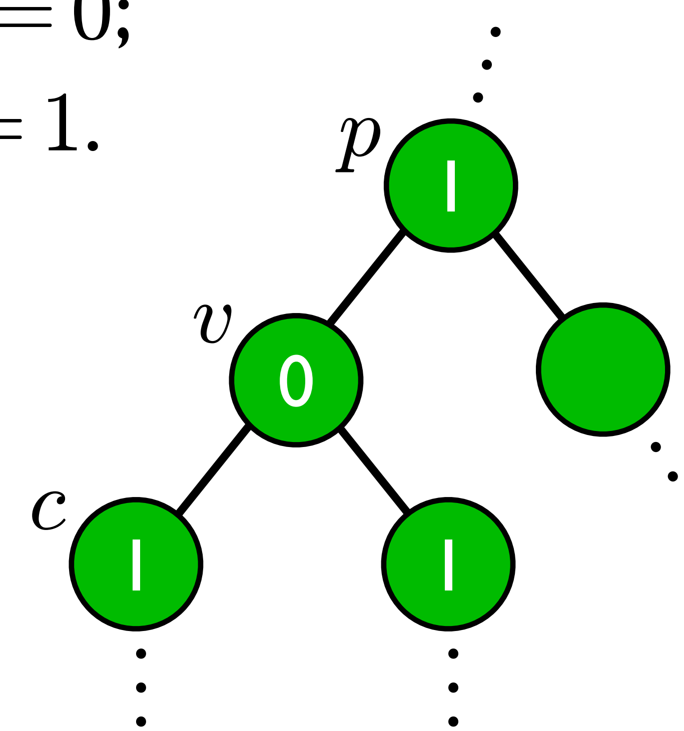

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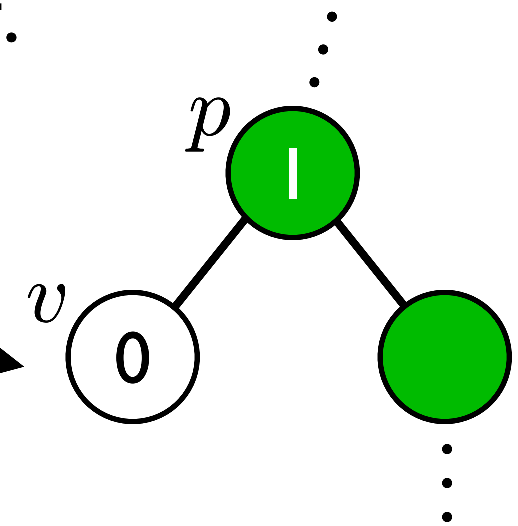

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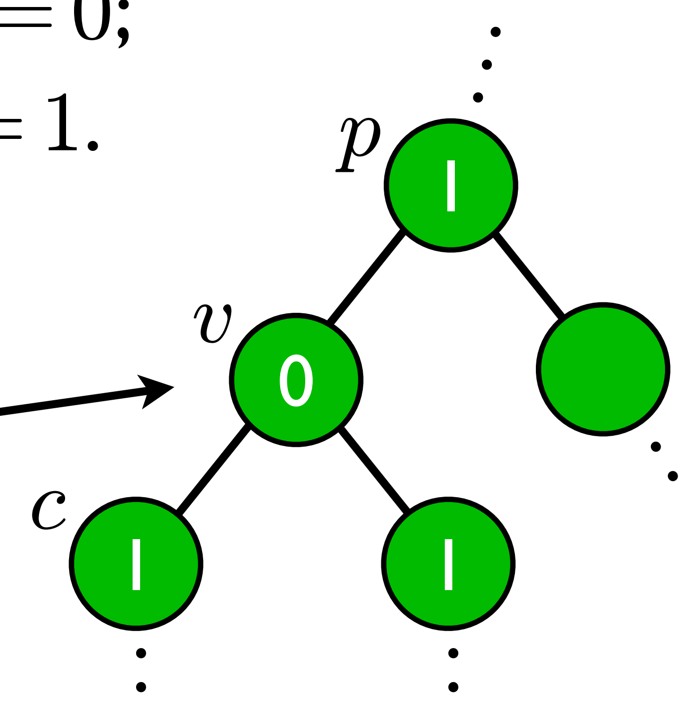

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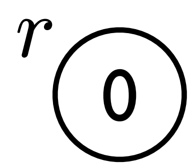

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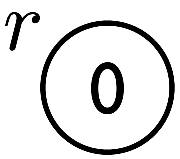

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Induction: All children v of r have $\mathrm{NAND}(v) = 1$;
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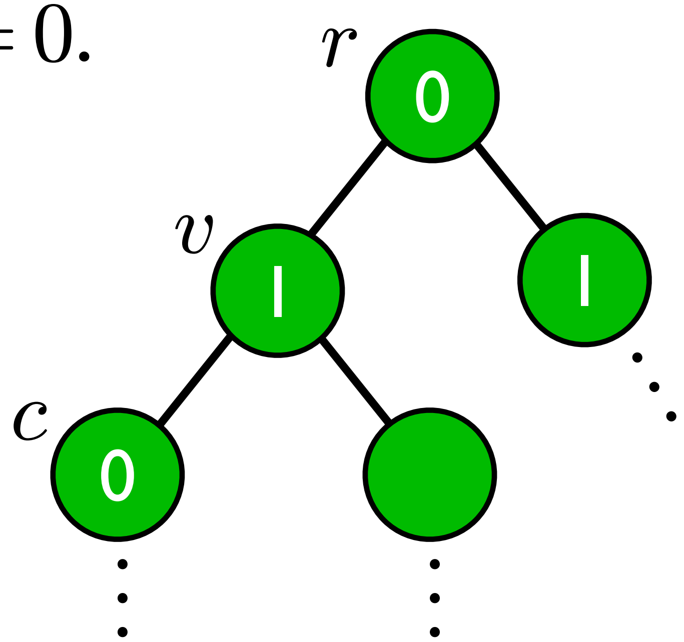

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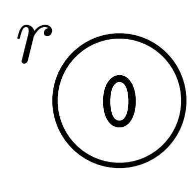

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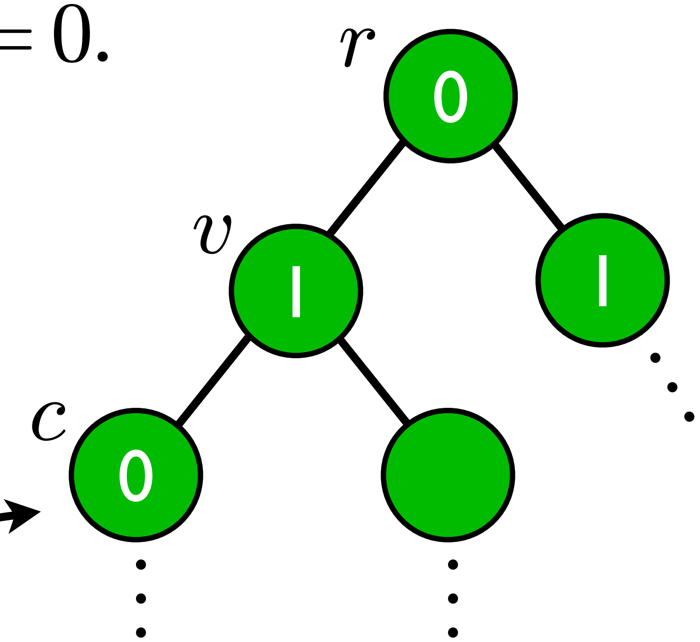

put a state here with $|\langle c|\Psi\rangle| > 0$

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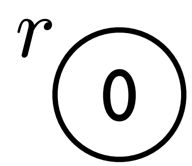
If $\mathrm{NAND}(r) = 0$, then $|\langle r|\Psi\rangle| > 0$ for some $|\Psi\rangle$ with $H|\Psi\rangle = 0$.

Base case: A single leaf.

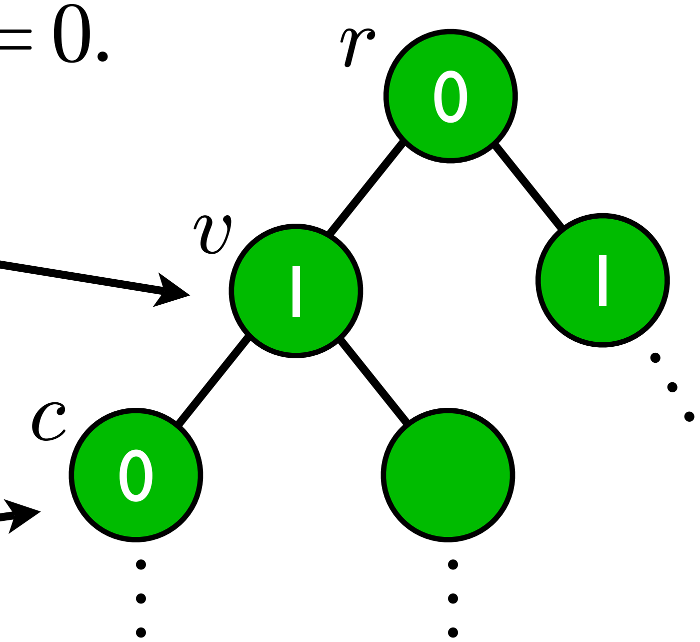


$$|\Psi\rangle = |r\rangle$$

Induction: All children v of r have $\mathrm{NAND}(v) = 1$;
some child c of v has $\mathrm{NAND}(c) = 0$.

$$h_{rv}\langle r|\Psi\rangle = -h_{vc}\langle c|\Psi\rangle \neq 0$$

put a state here with $|\langle c|\Psi\rangle| > 0$



Zero-energy eigenstates evaluate NAND: Quantitative version

Theorem (qualitative).

If $\mathrm{NAND}(p) = 1$, then $\langle p|\Psi\rangle = 0$ for any $|\Psi\rangle$ with $H|\Psi\rangle = 0$.

If $\mathrm{NAND}(r) = 0$, then $|\langle r|\Psi\rangle| > 0$ for some $|\Psi\rangle$ with $H|\Psi\rangle = 0$.

Theorem (quantitative). For approximately balanced formulas:

If $\mathrm{NAND}(r) = 1$, then eigenstates $|E\rangle$ with $|E| < O(\frac{1}{\sqrt{n}})$ have $\langle r|E\rangle = 0$.

If $\mathrm{NAND}(r) = 0$, then $|\langle r|\Psi\rangle| > \Omega(1)$ for some $|\Psi\rangle$ with $H|\Psi\rangle = 0$.