UVOD V
KVANTNO RAČUNALNIŠTVO

Matija Pretnar

FMF
UNIVERZA V LJUBLJANI
Fakulteta za matematiko in fiziko

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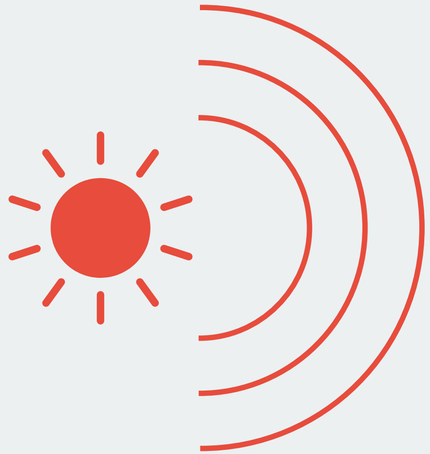
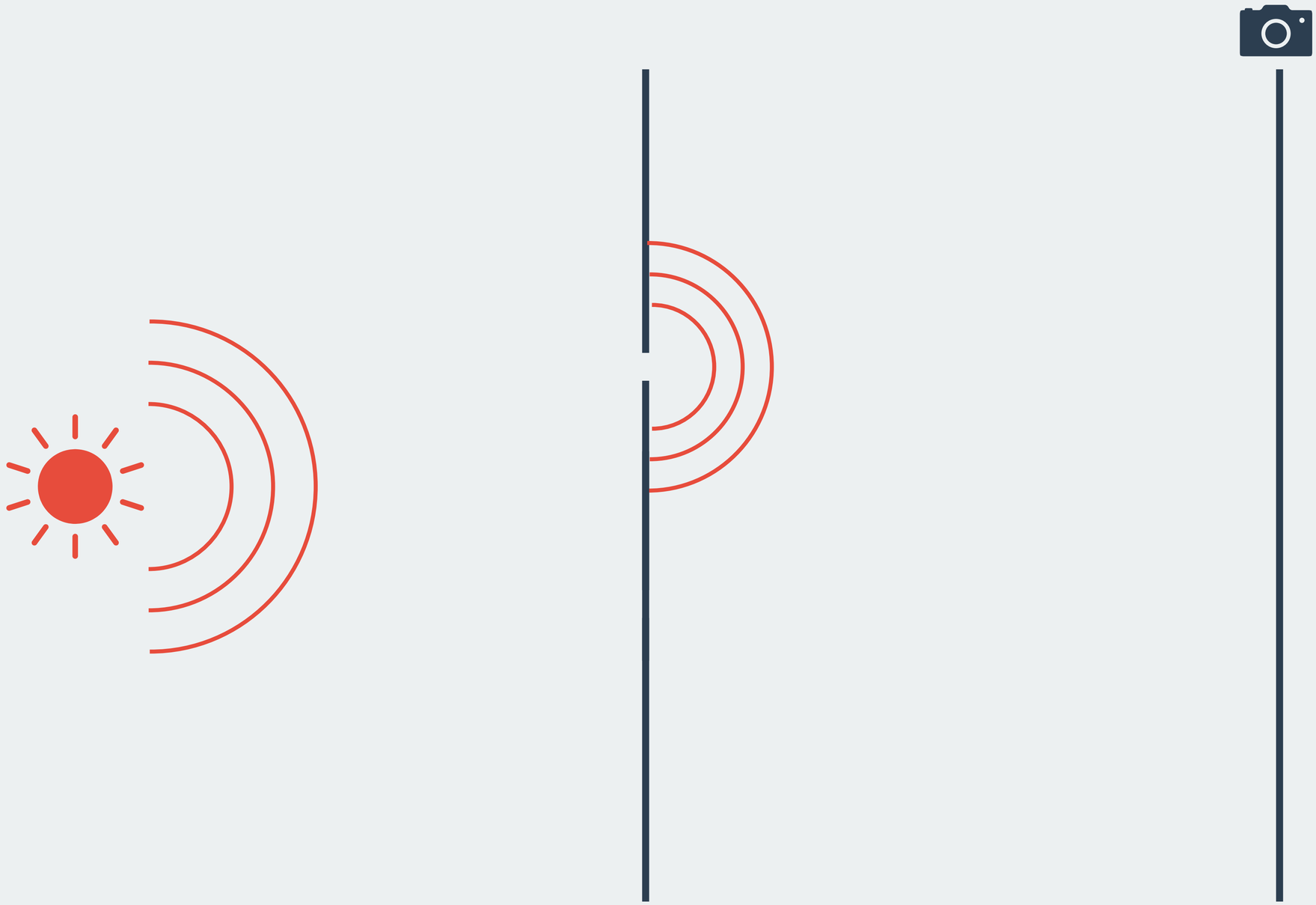
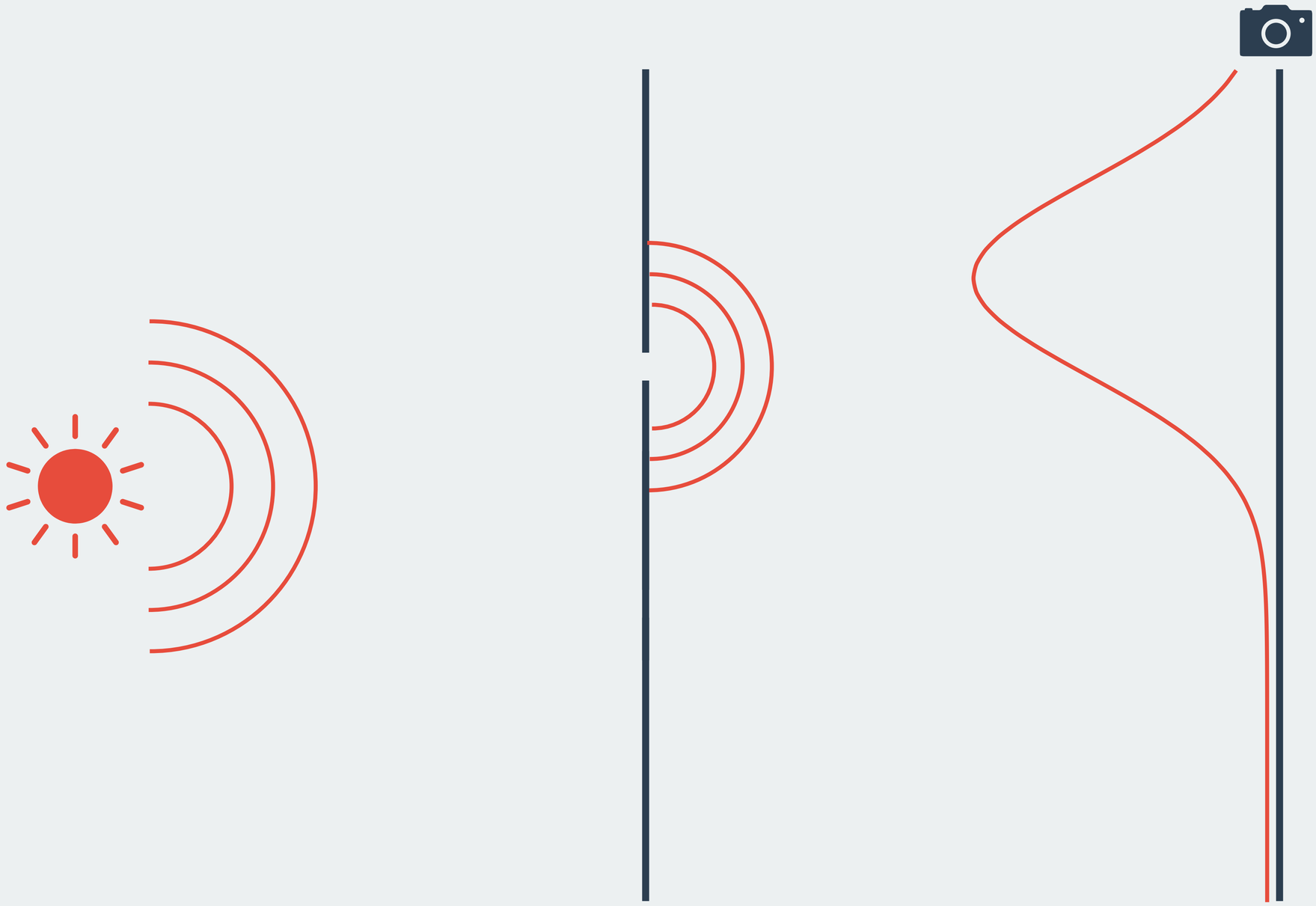
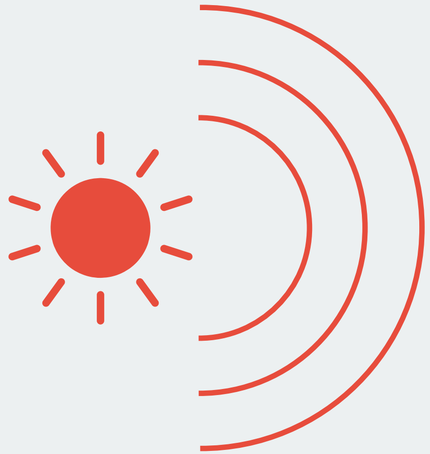
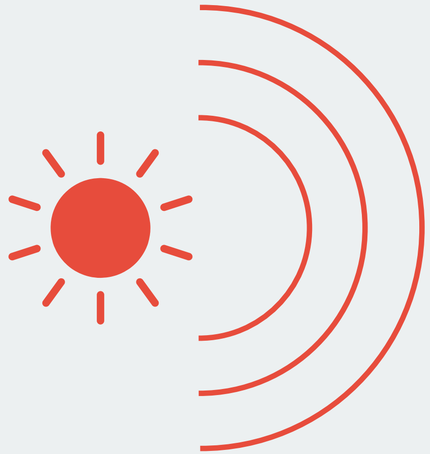


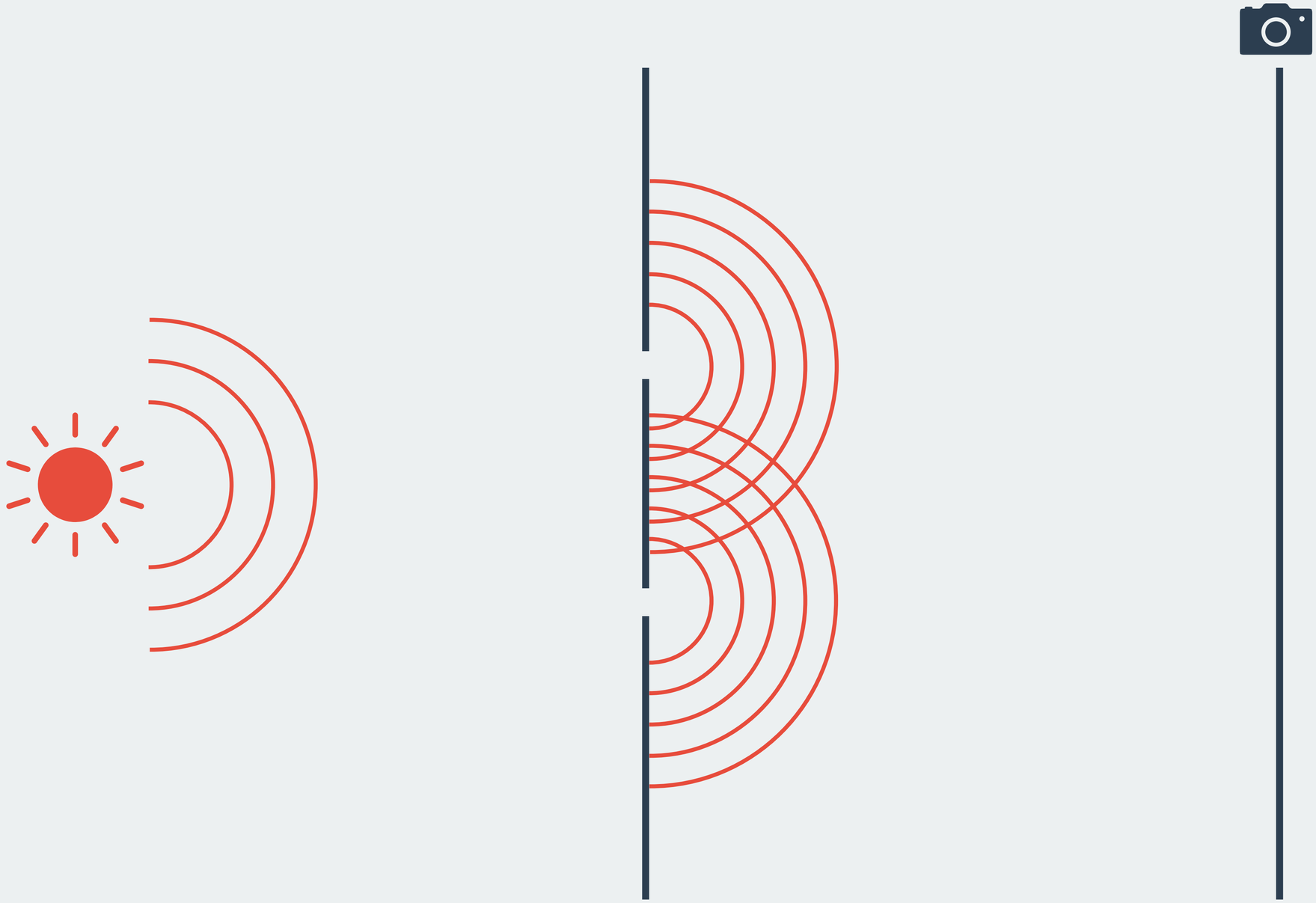


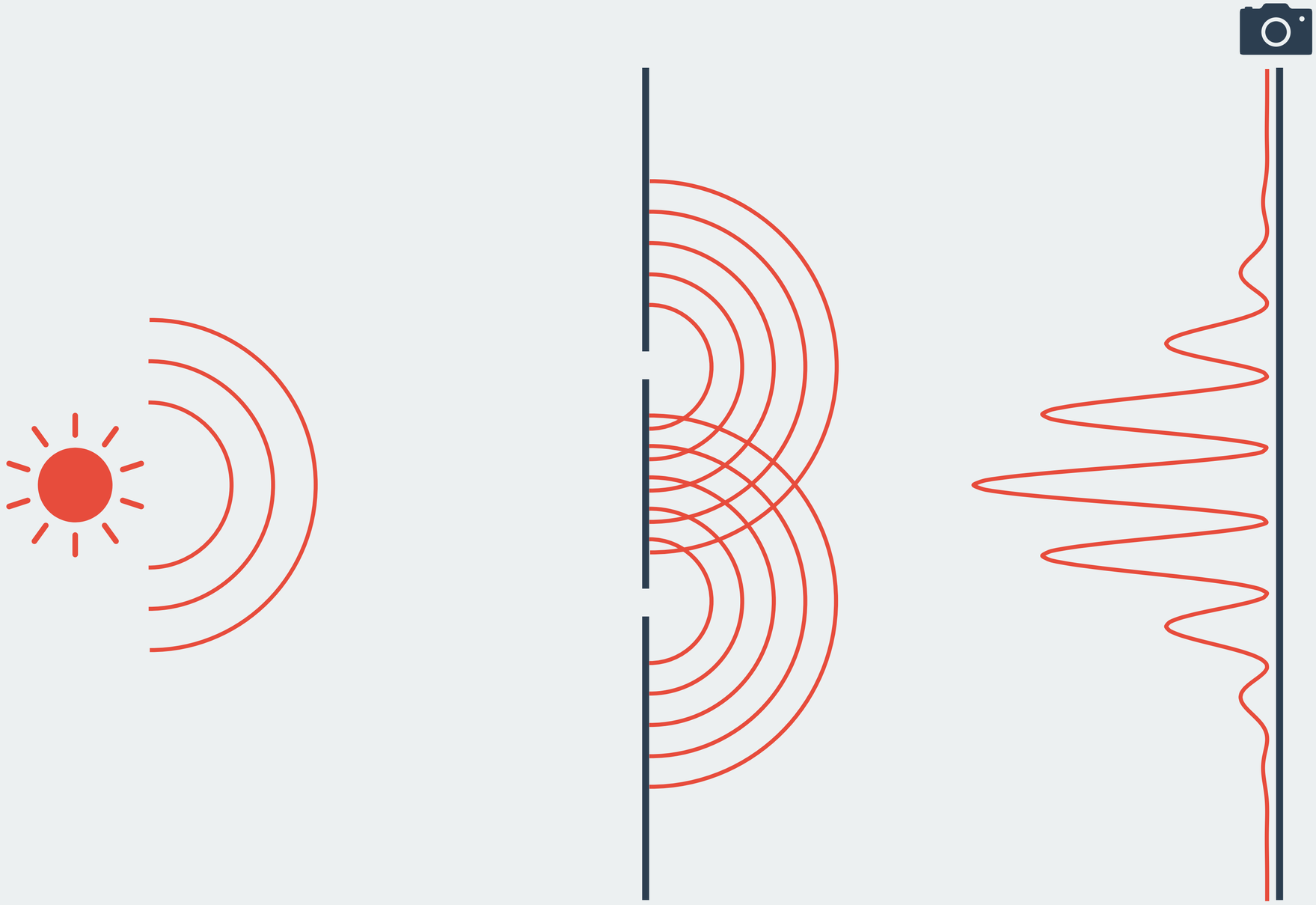


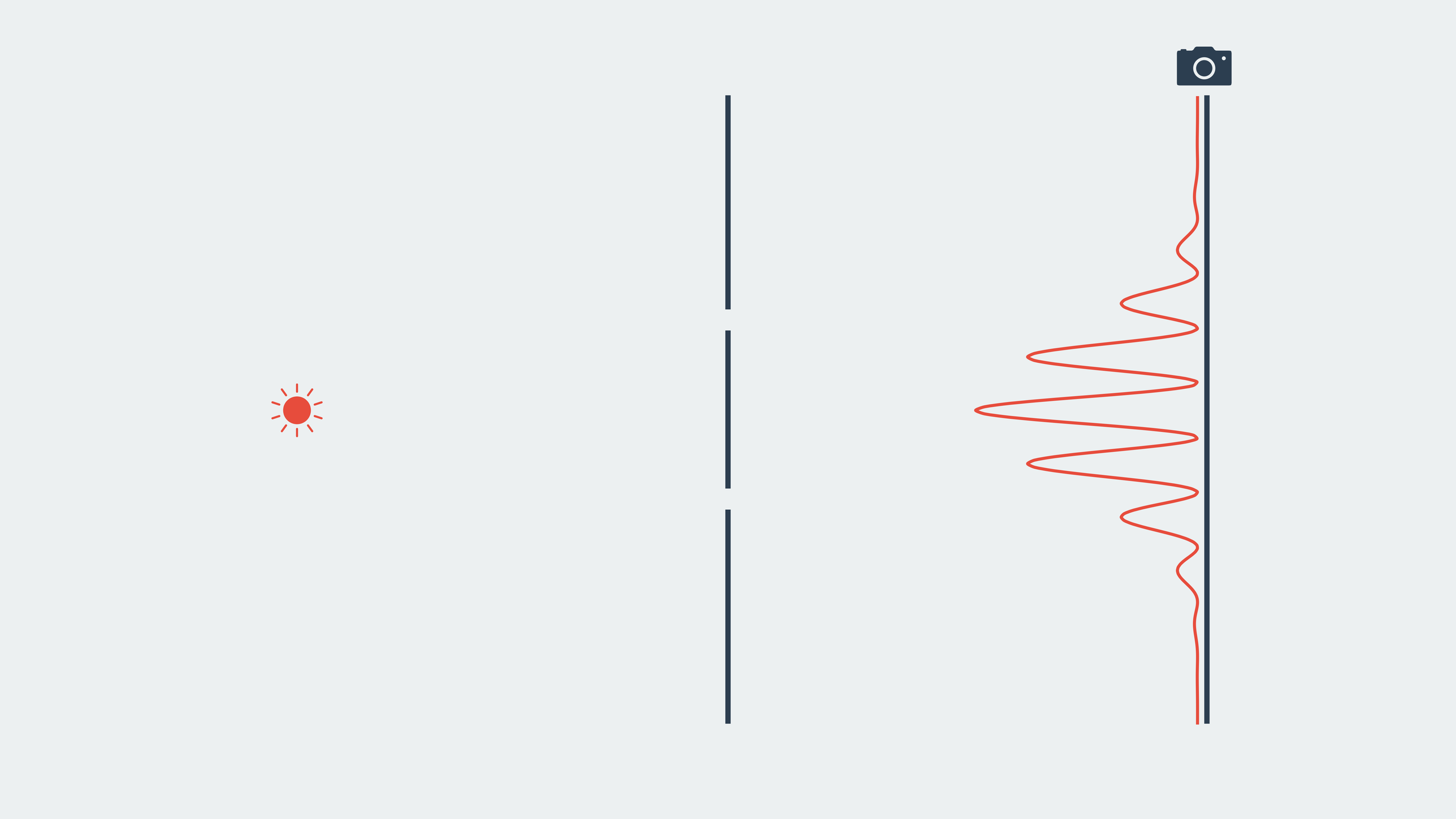


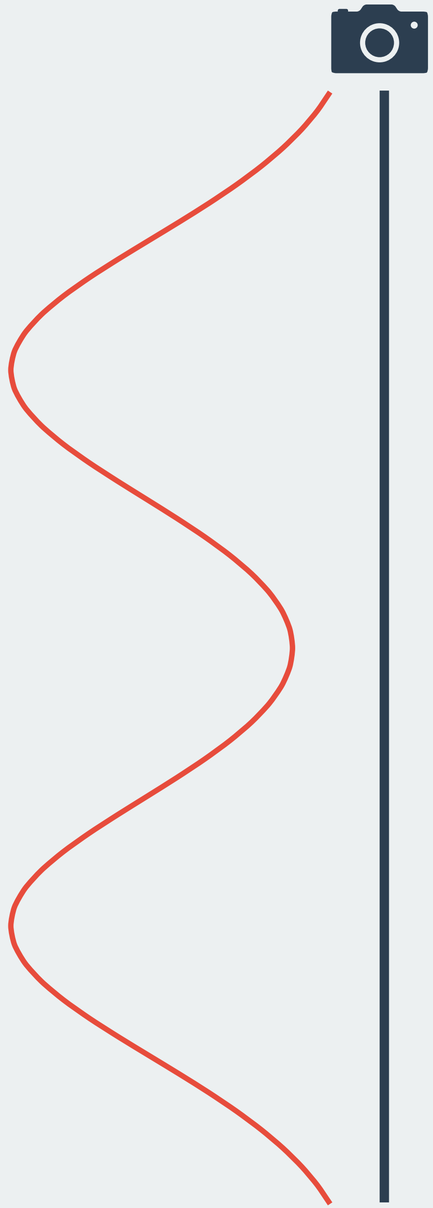

Jay E. Newman











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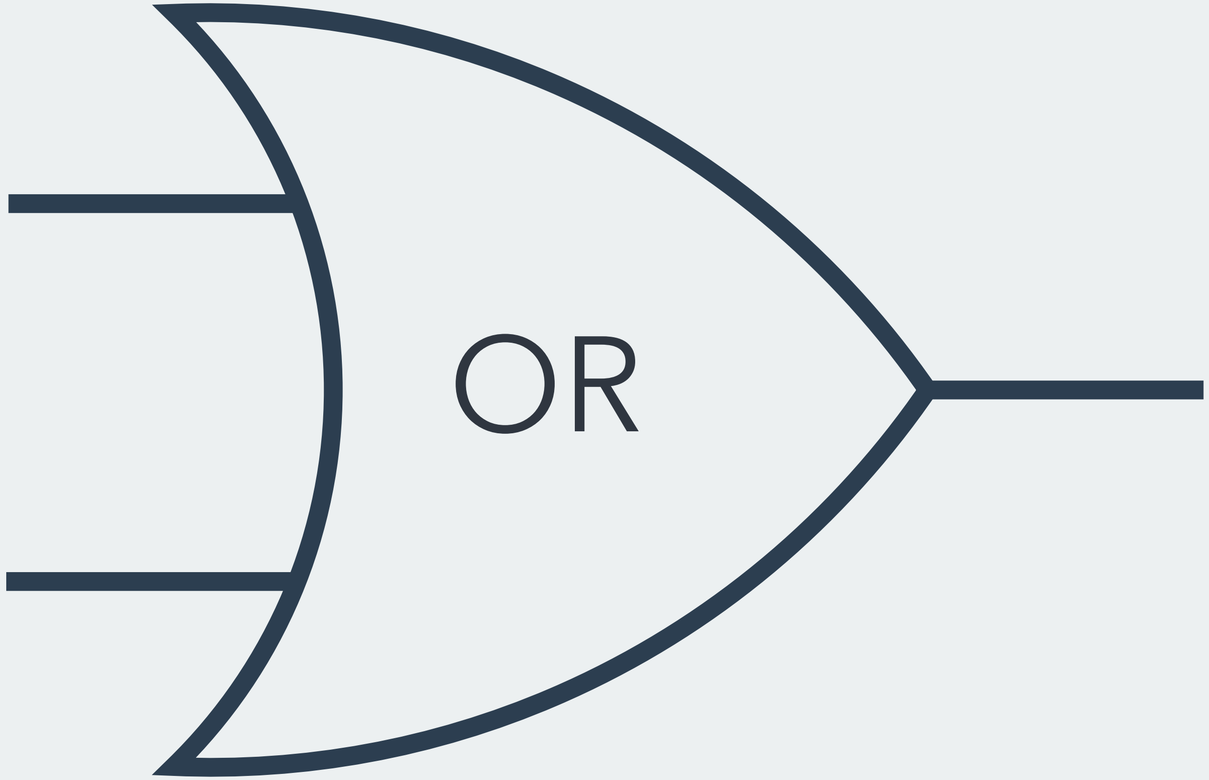
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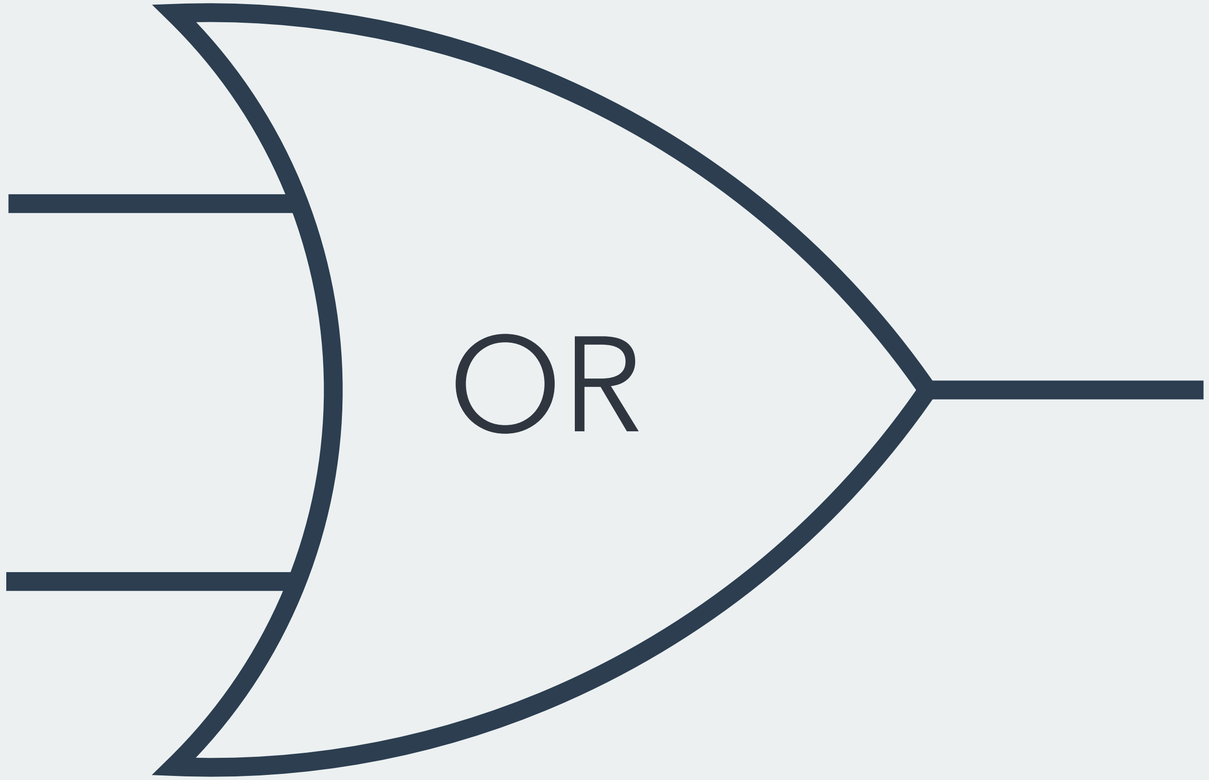
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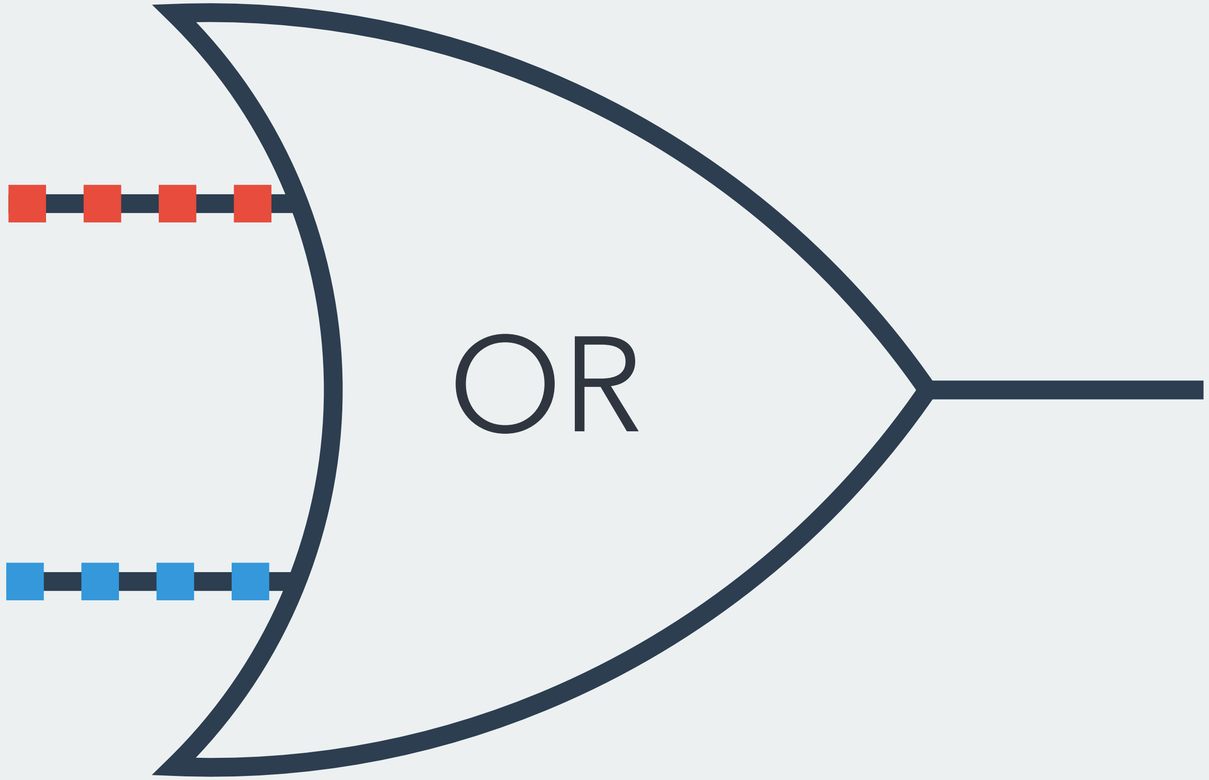
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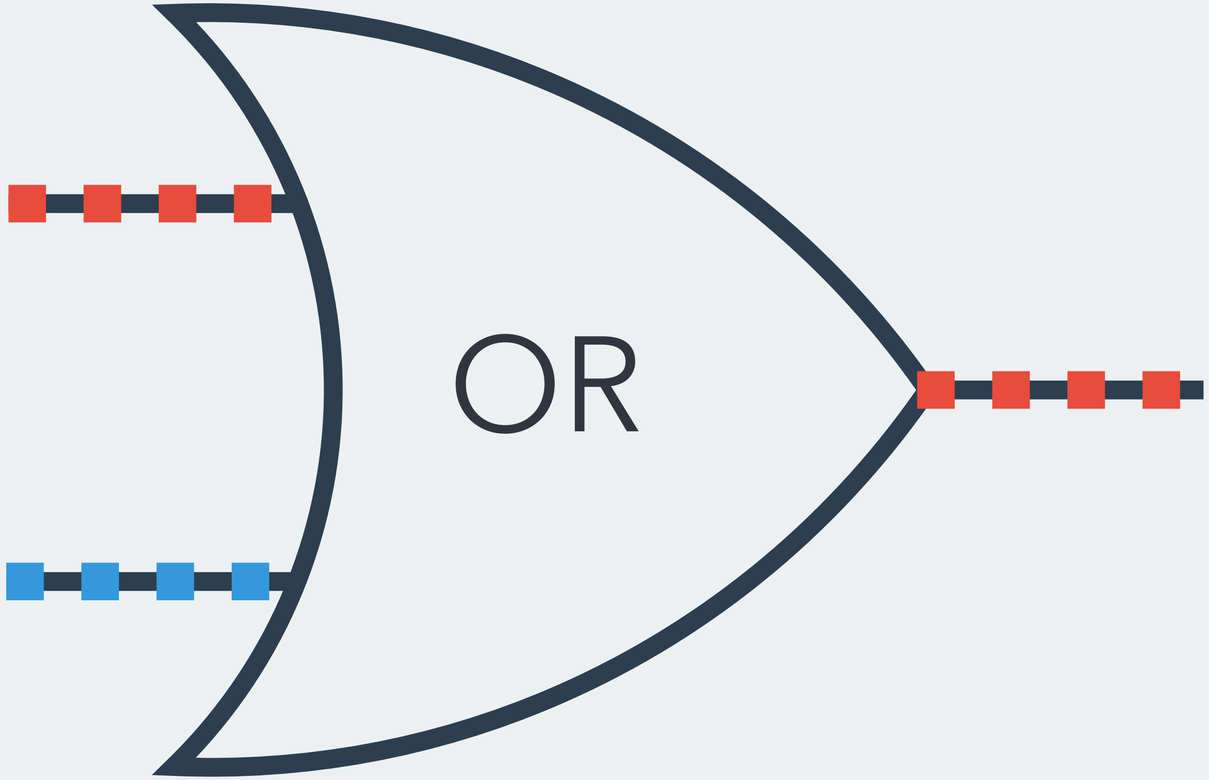
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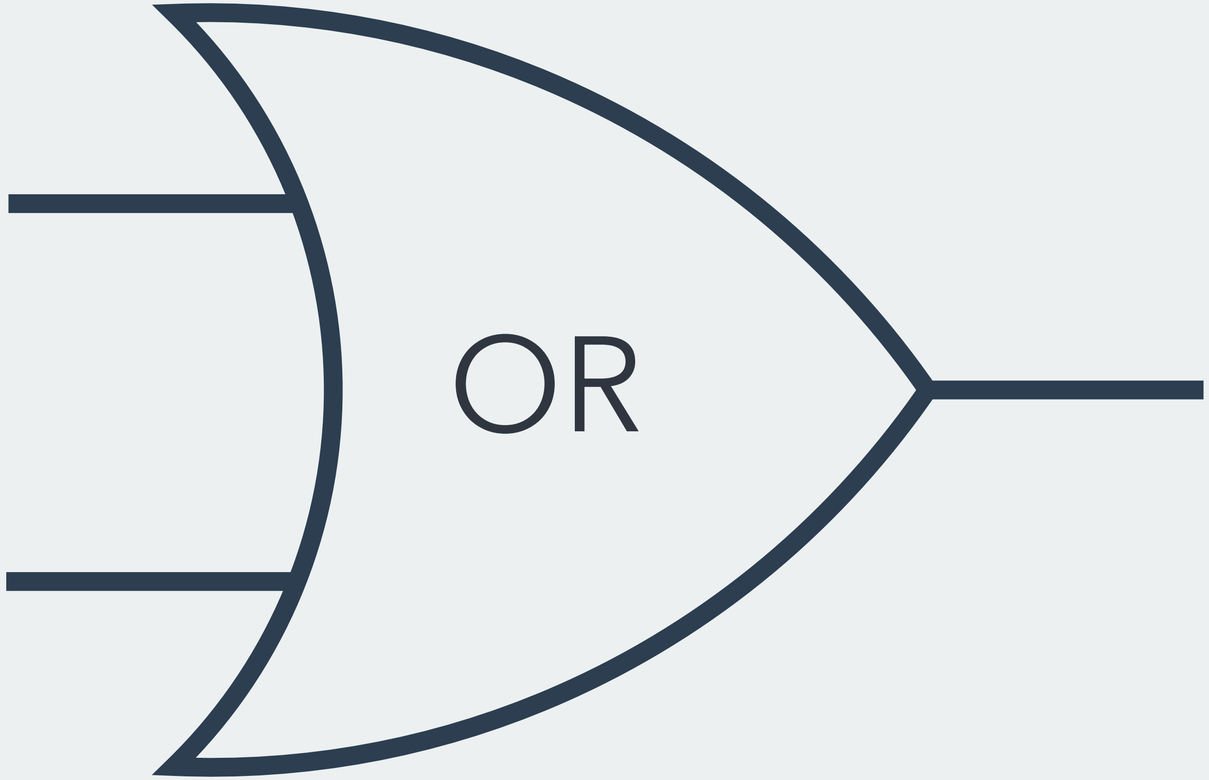
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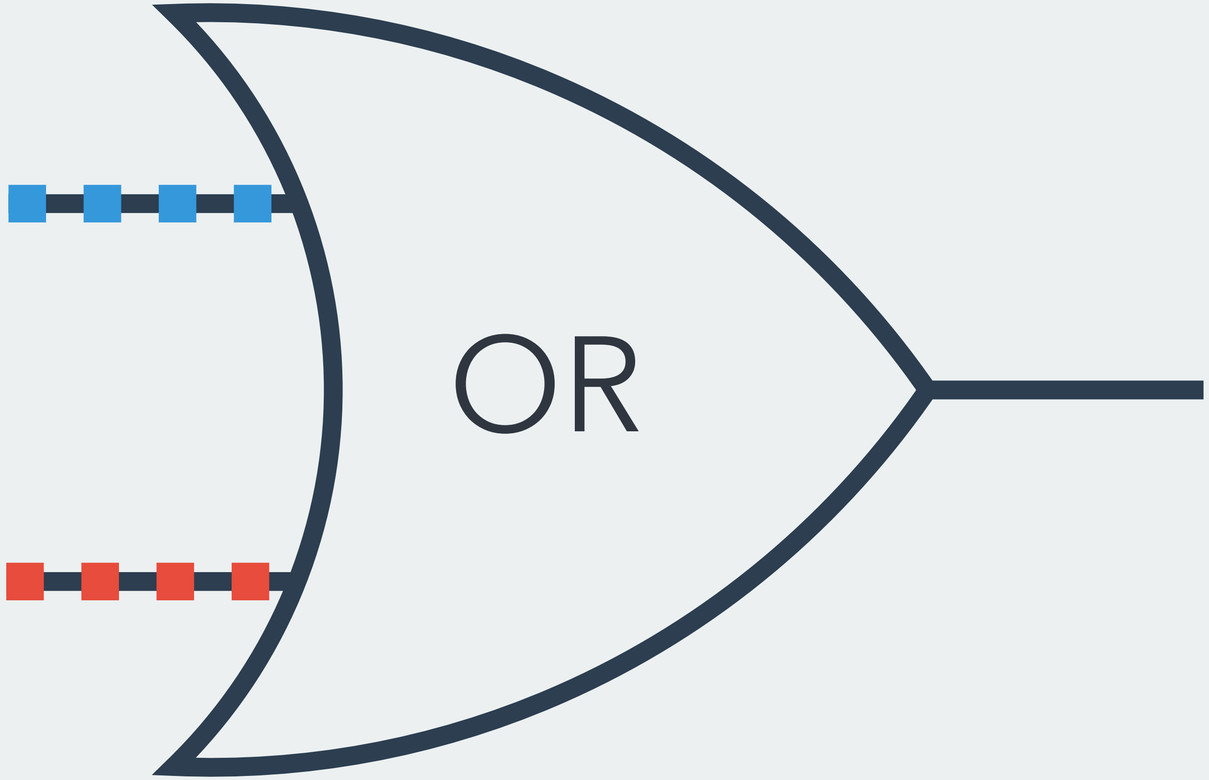
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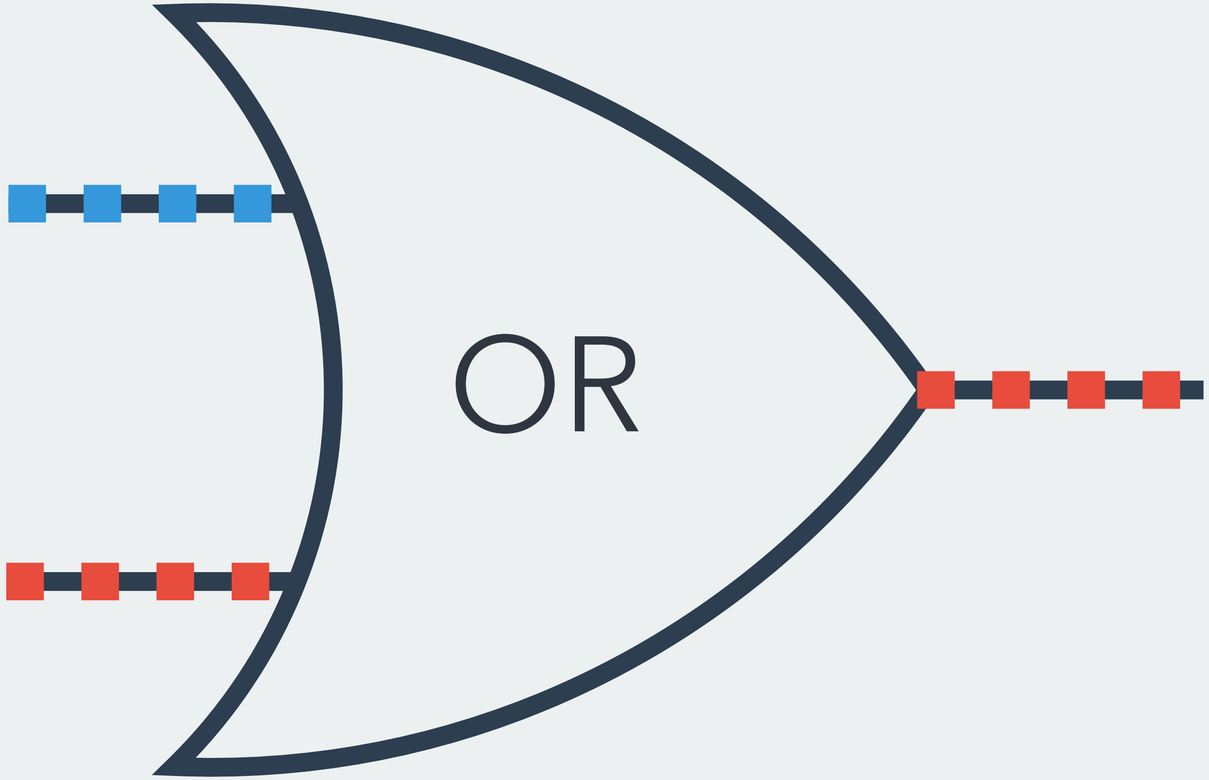
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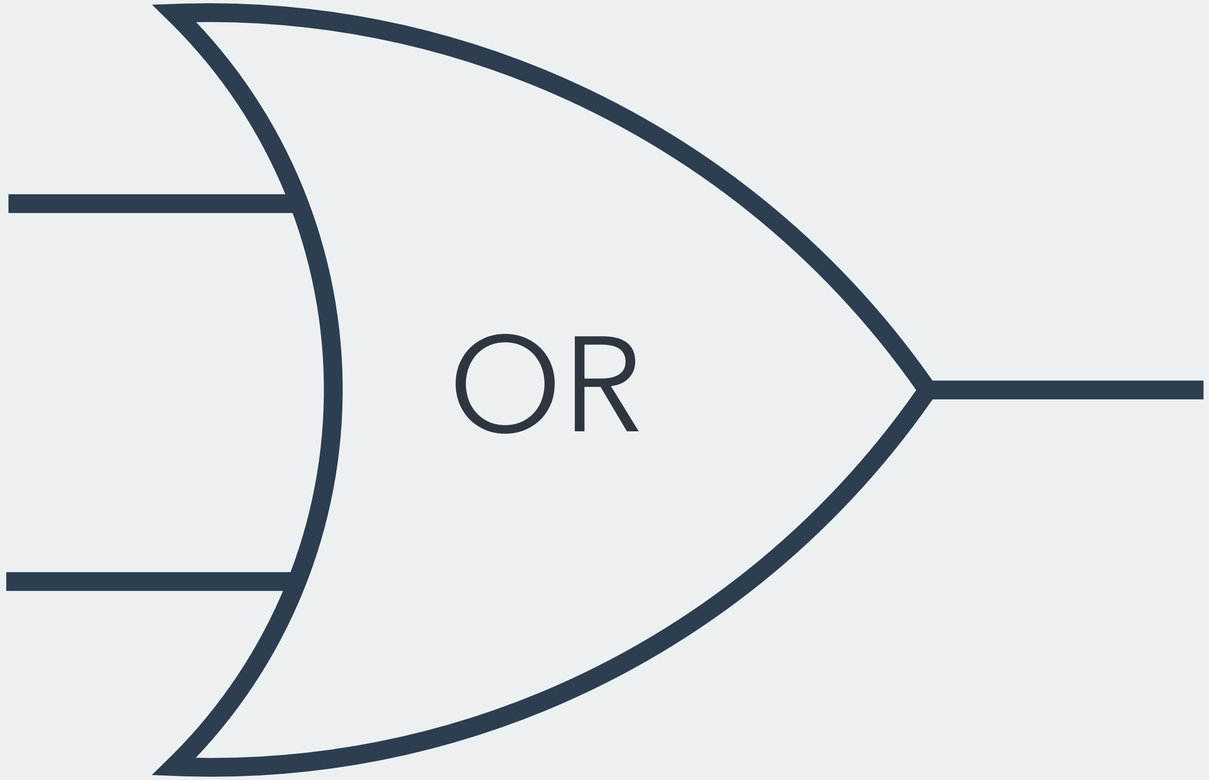
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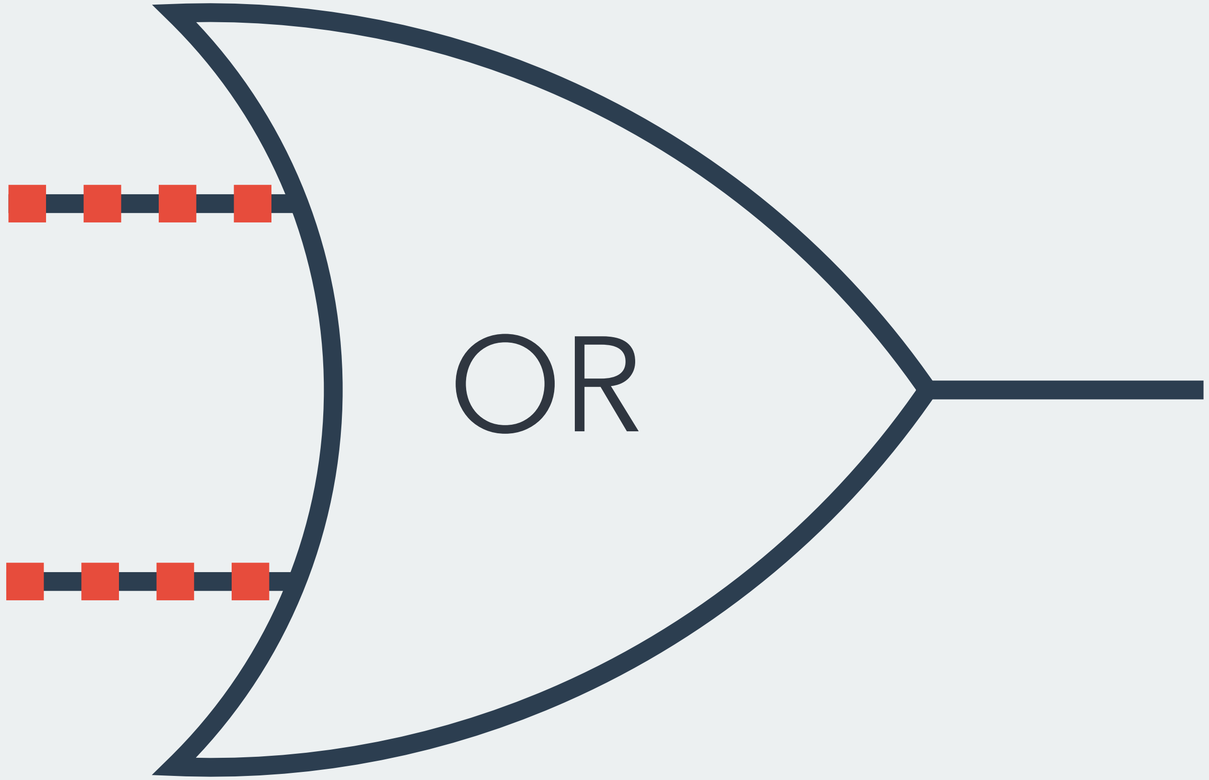
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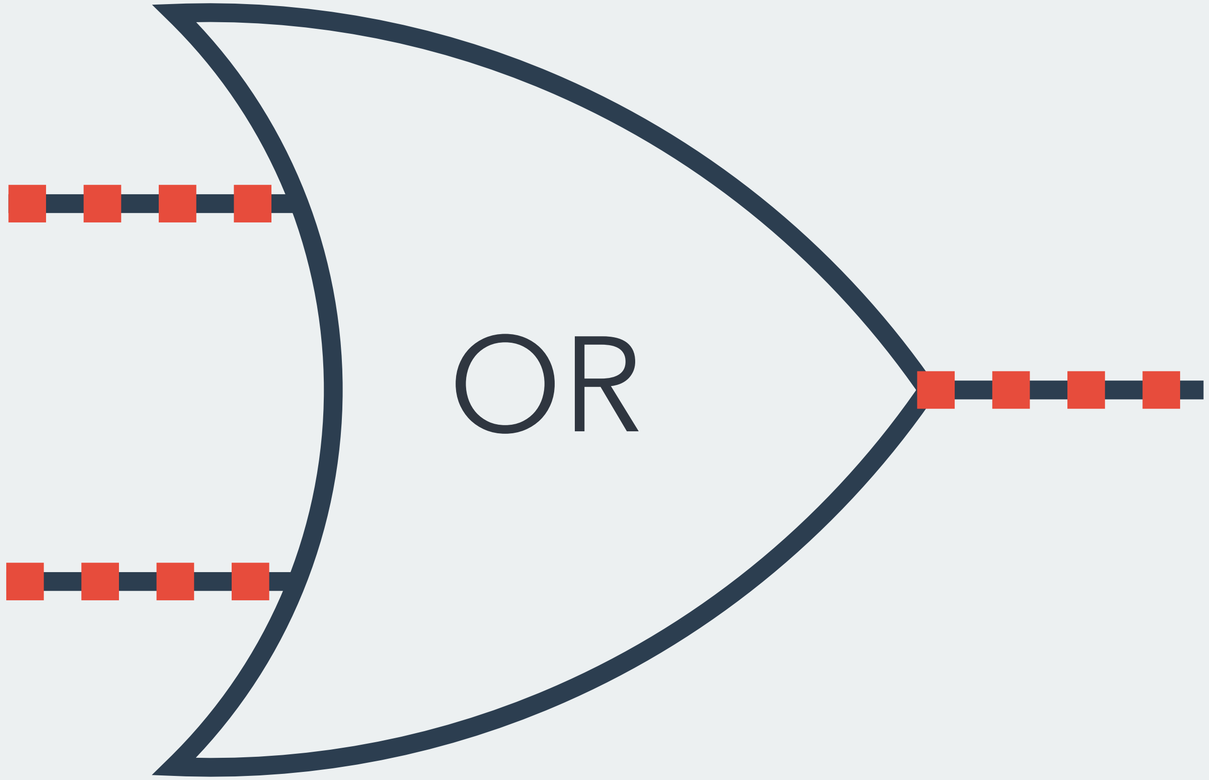
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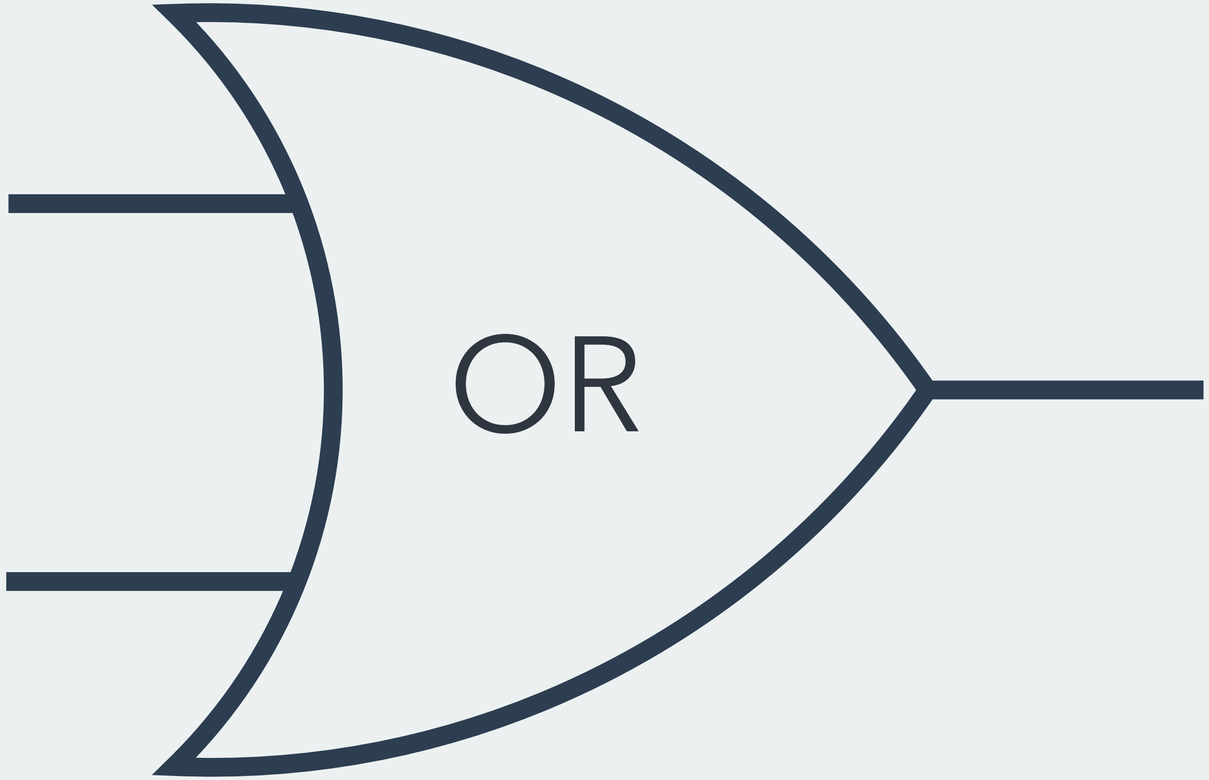
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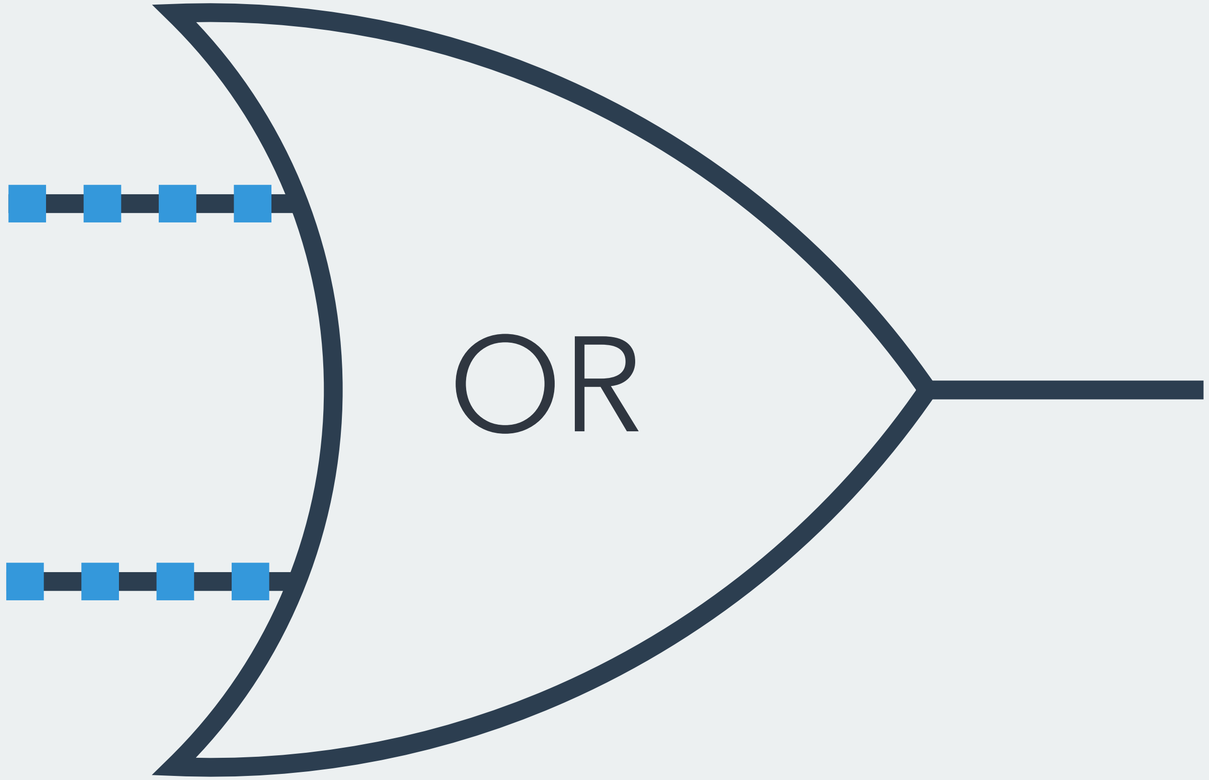
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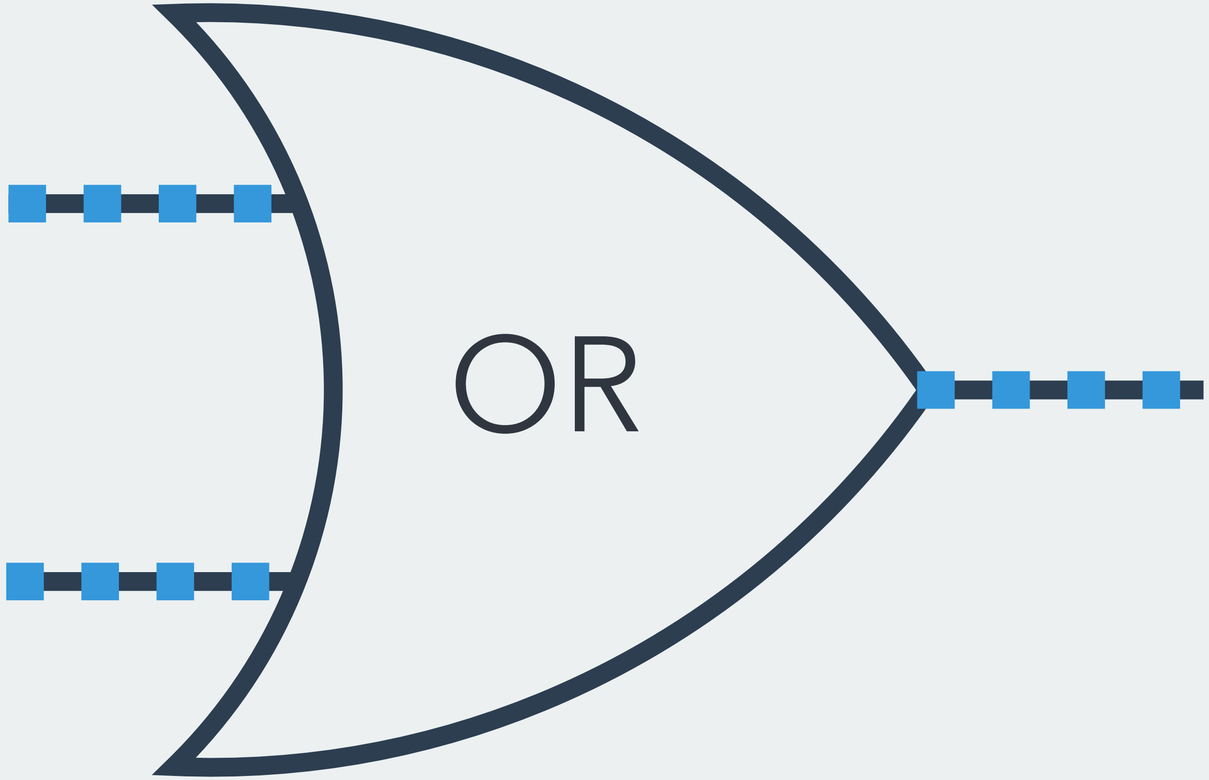
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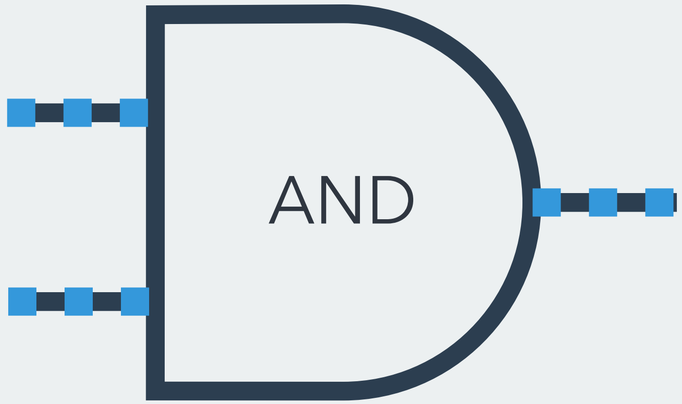
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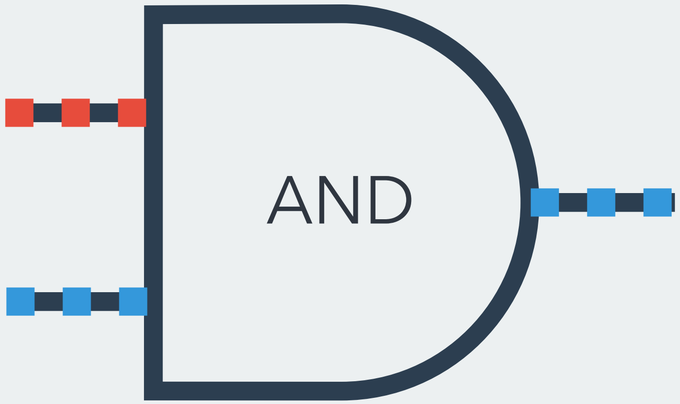
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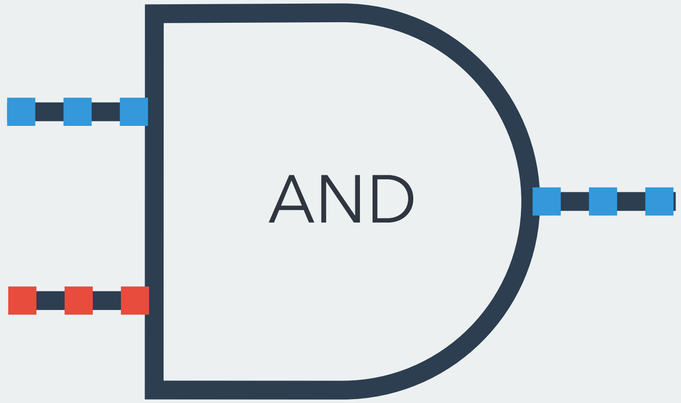
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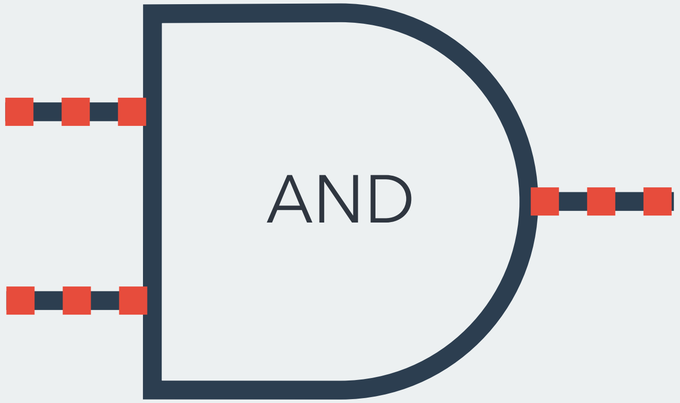
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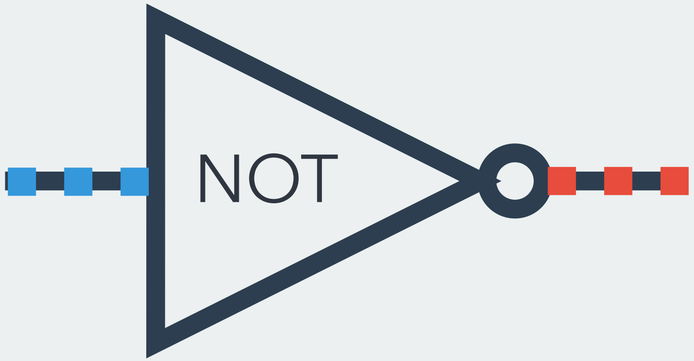
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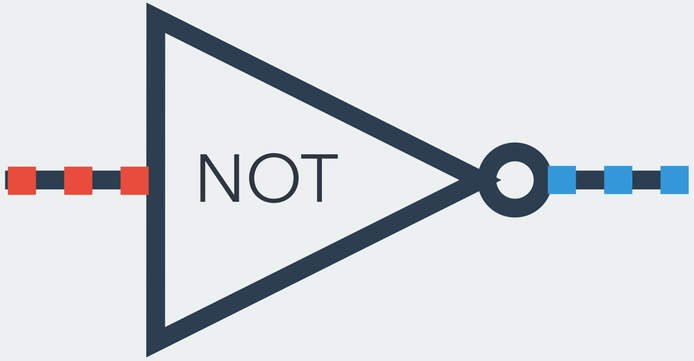
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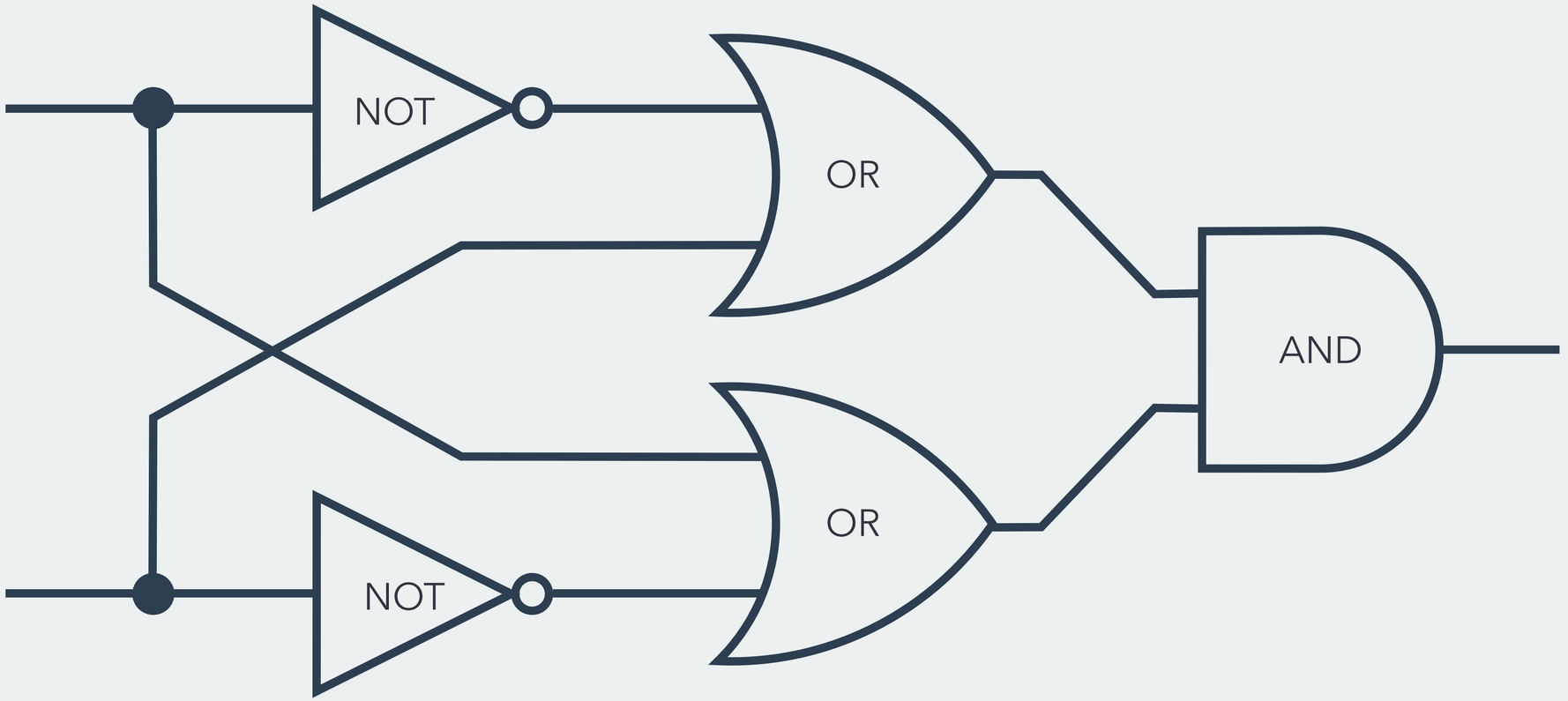
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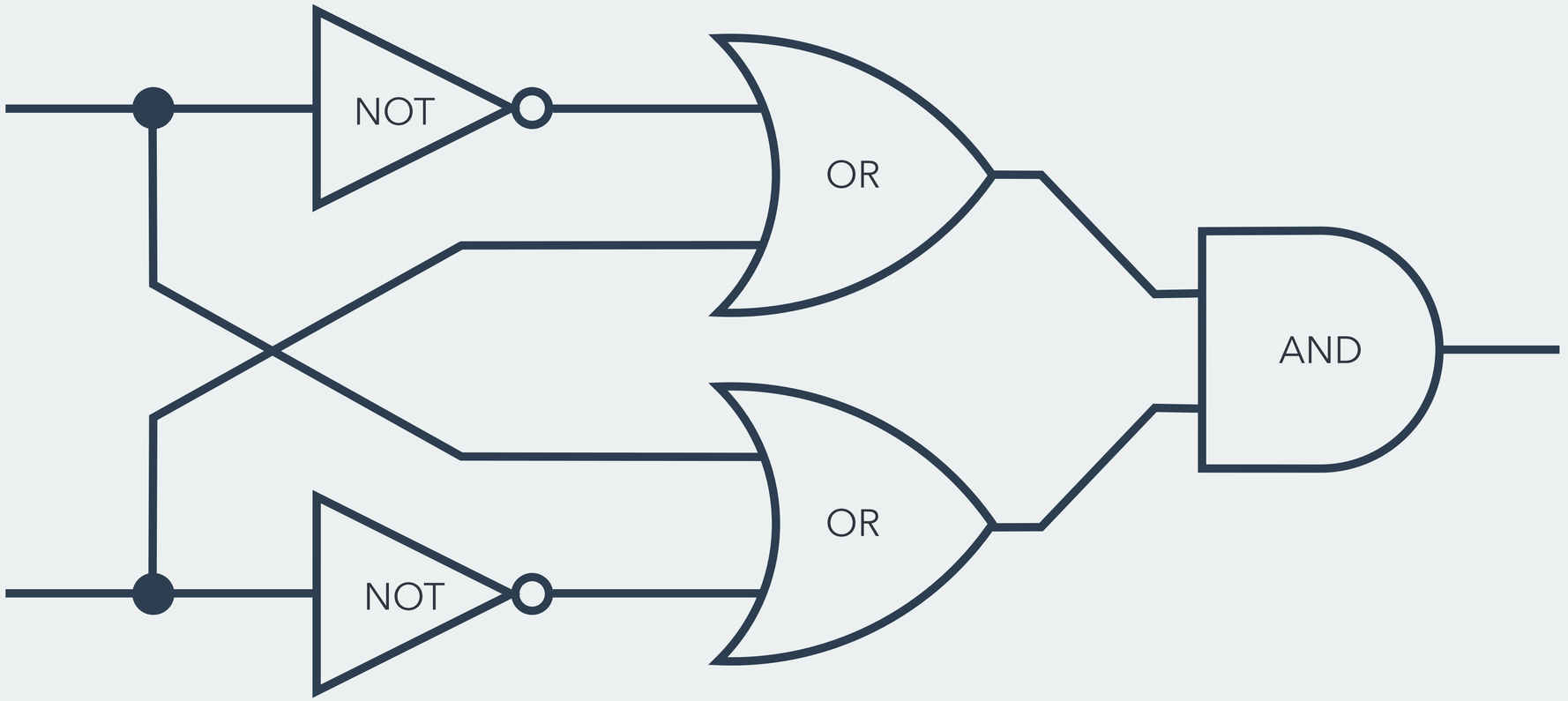
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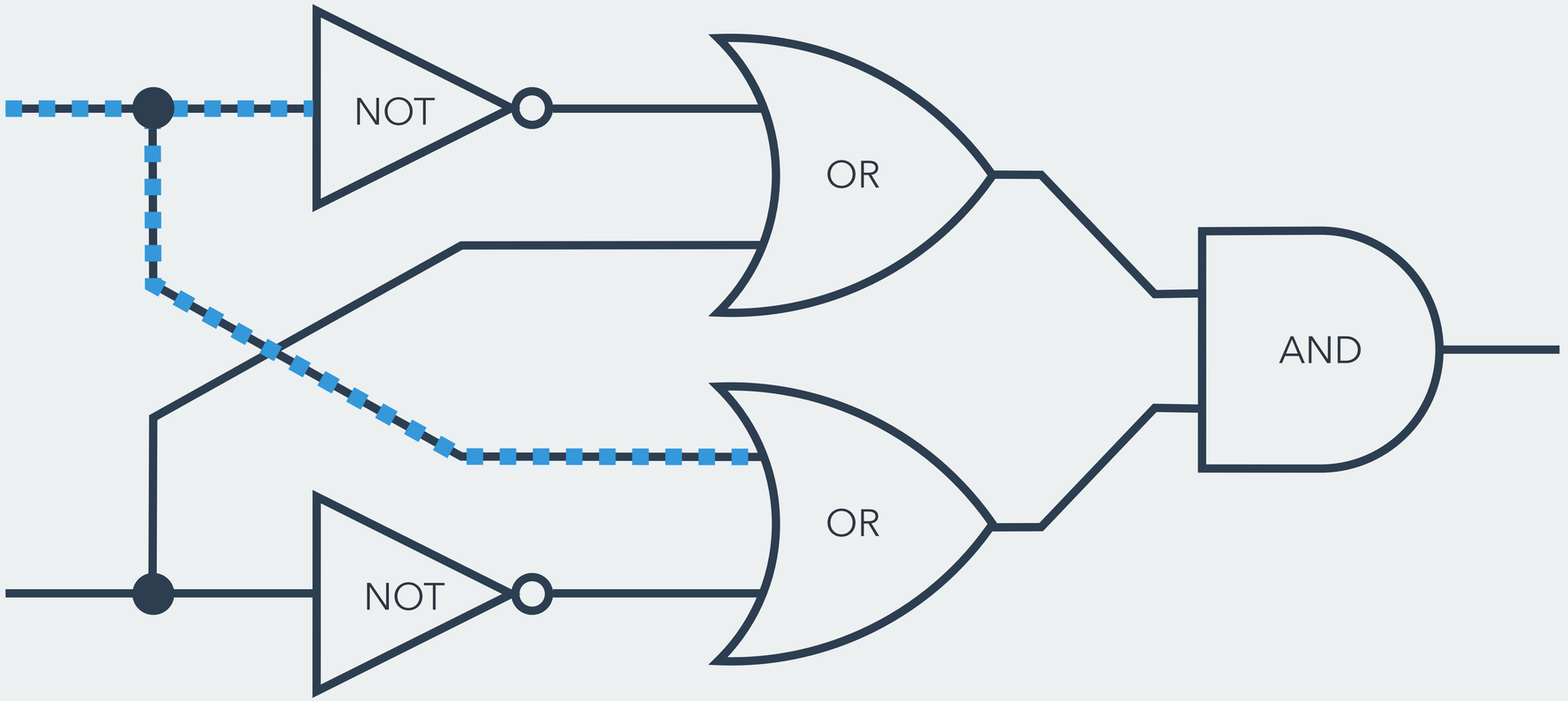
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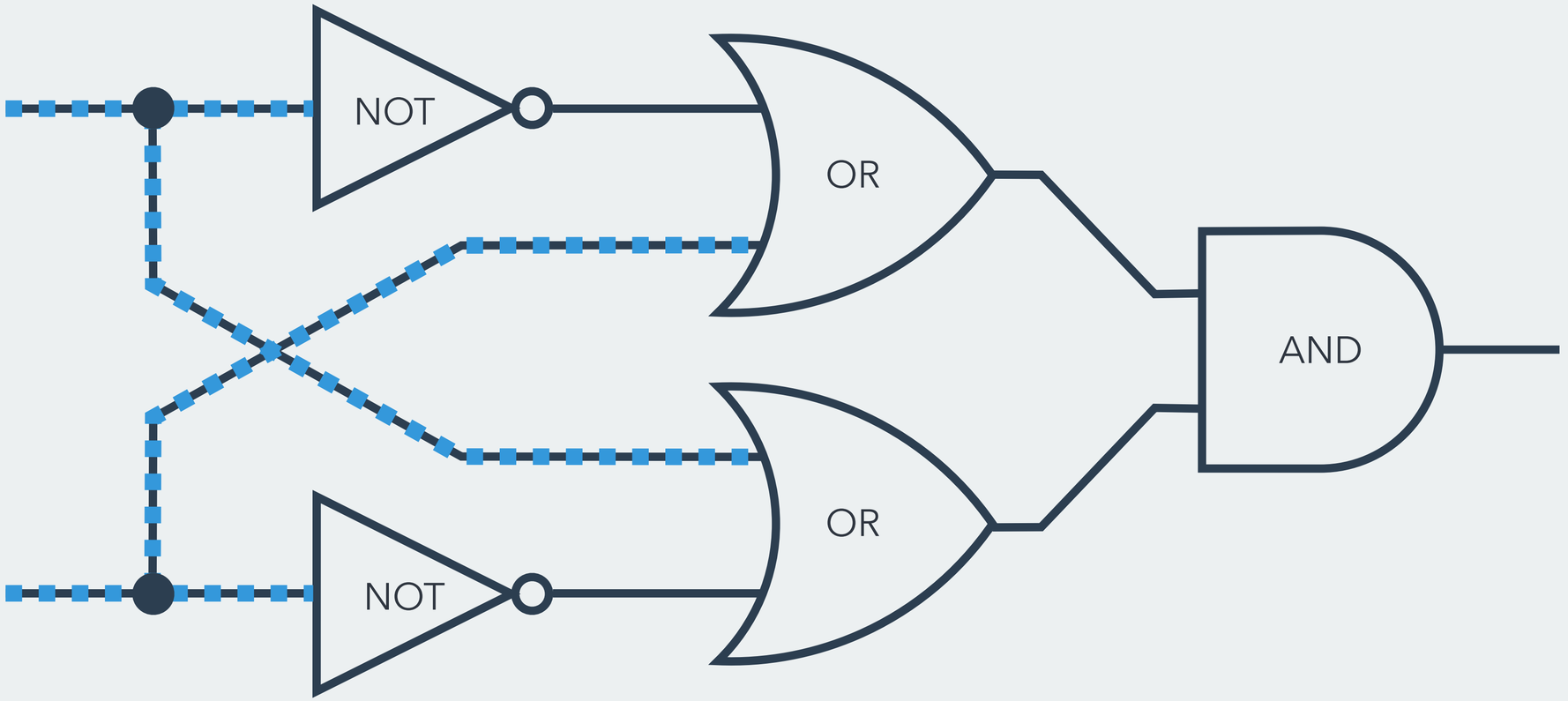
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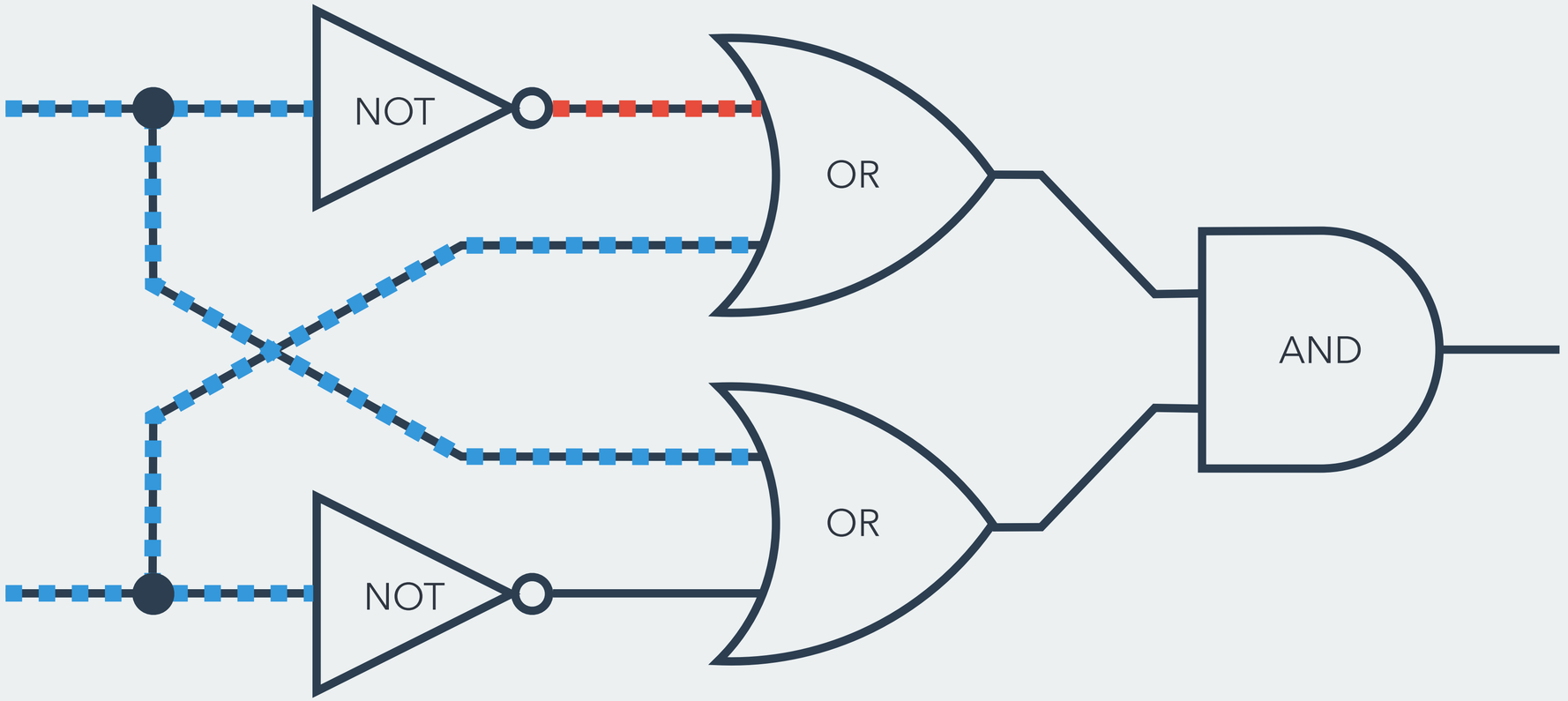
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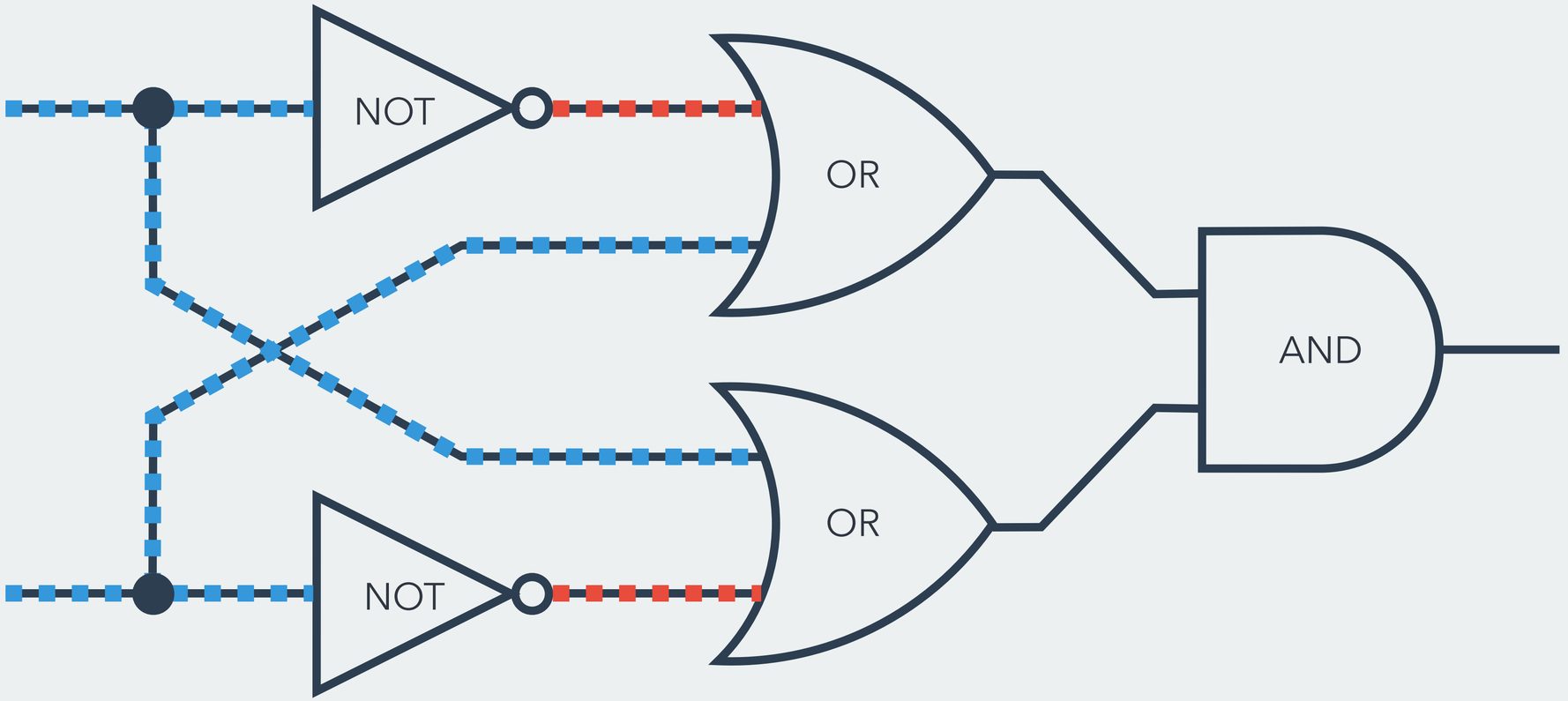
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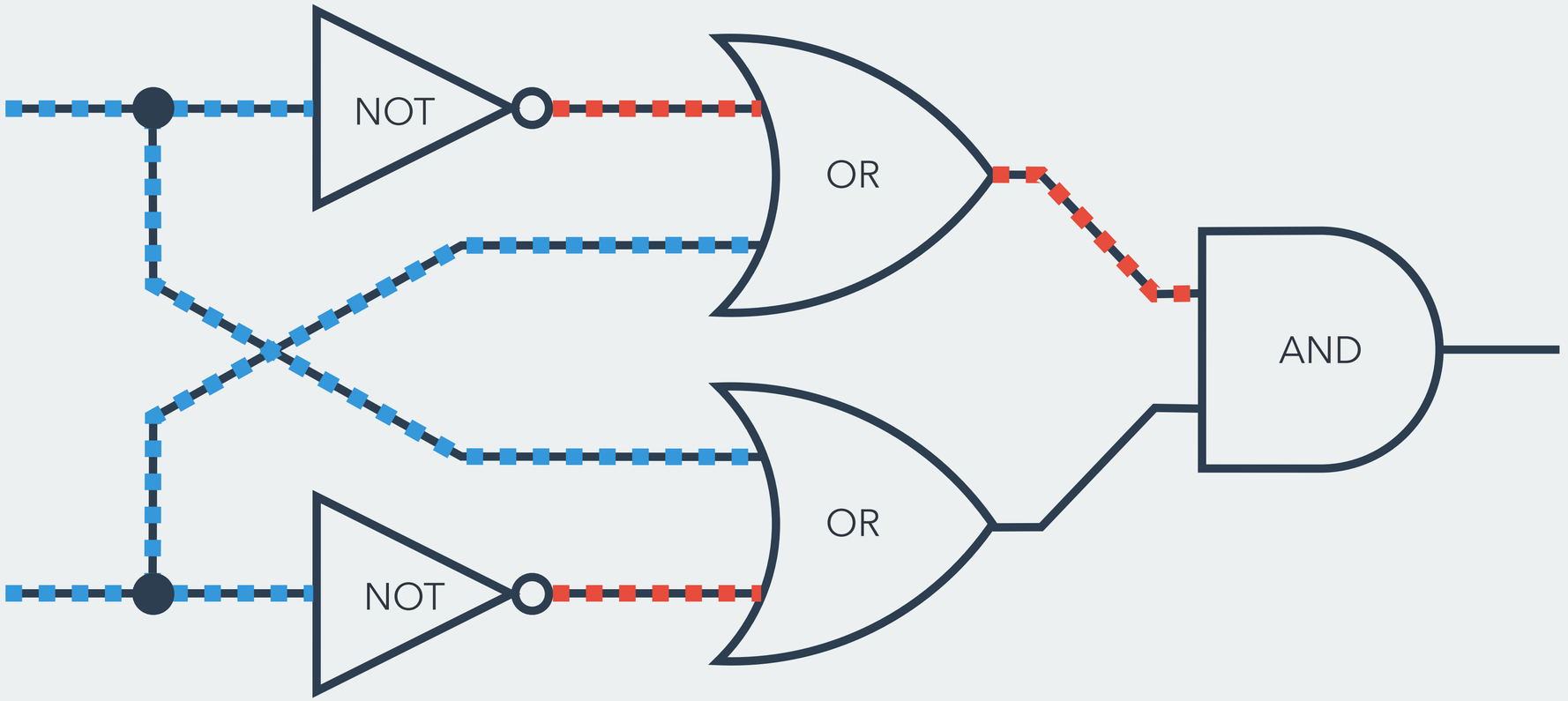
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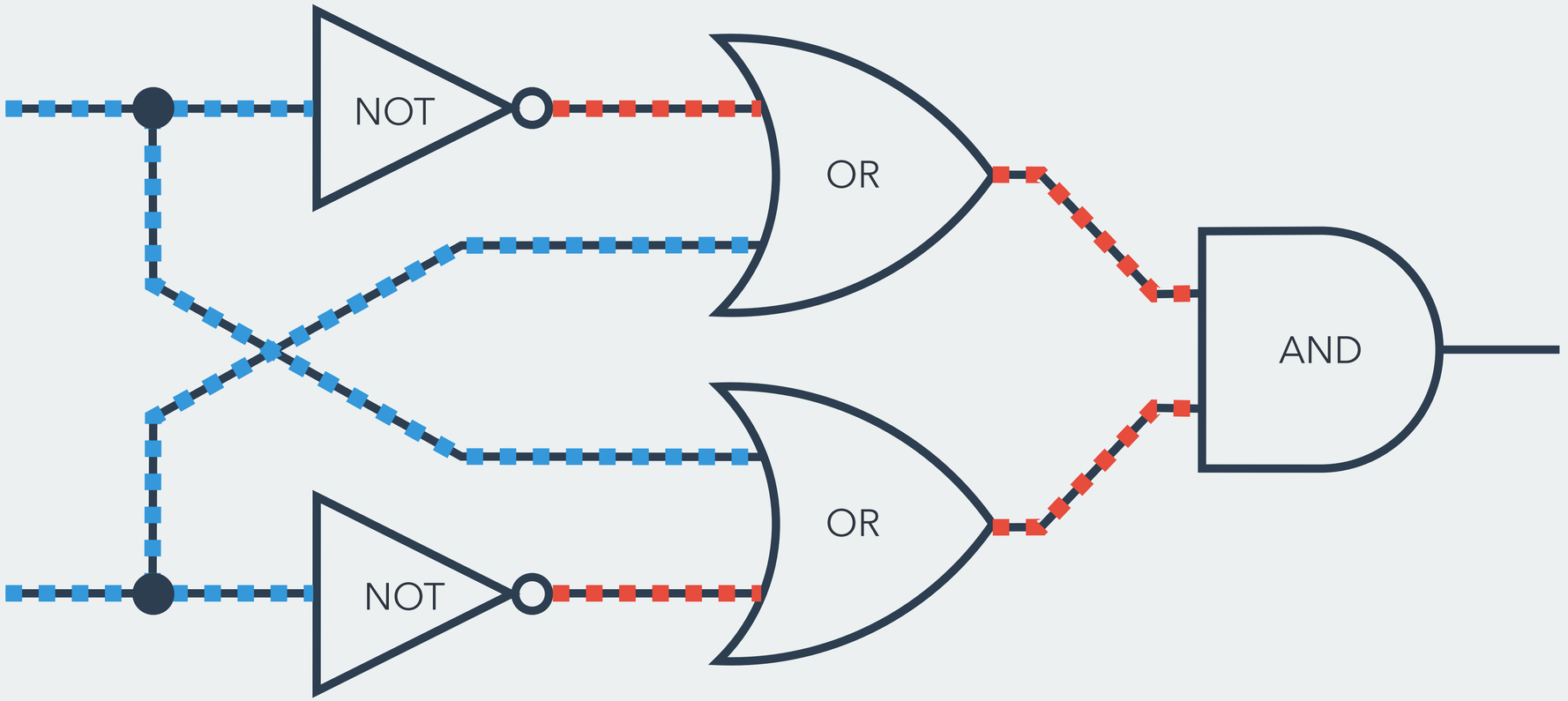
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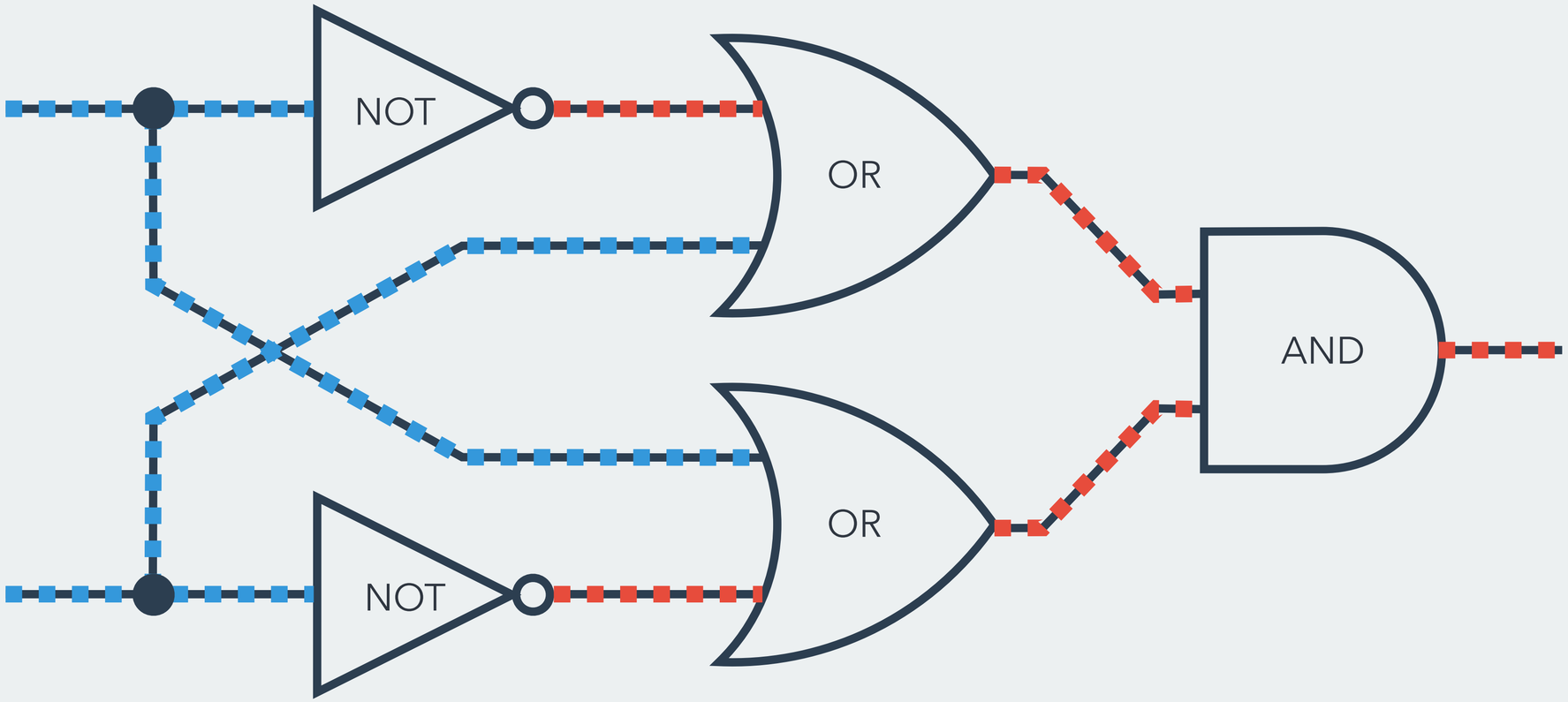
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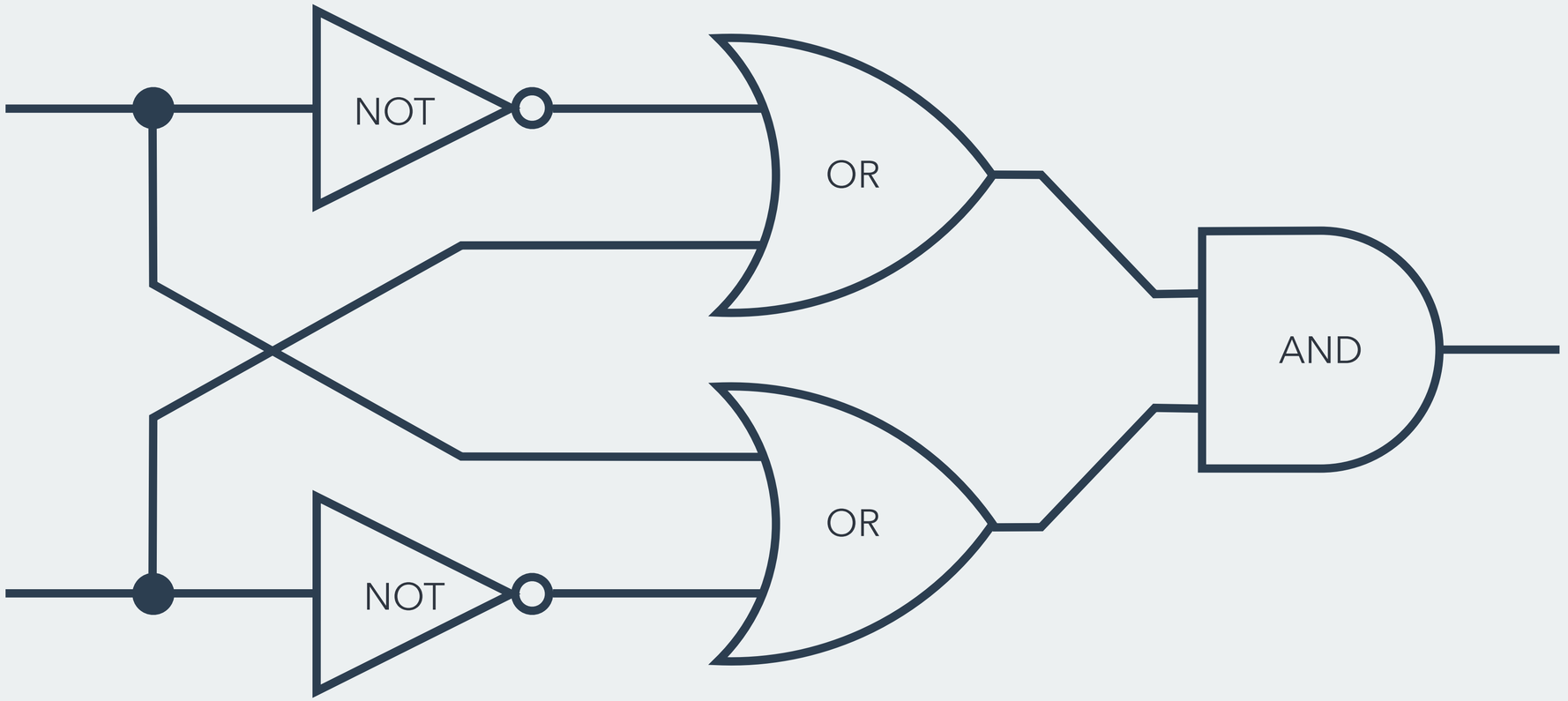
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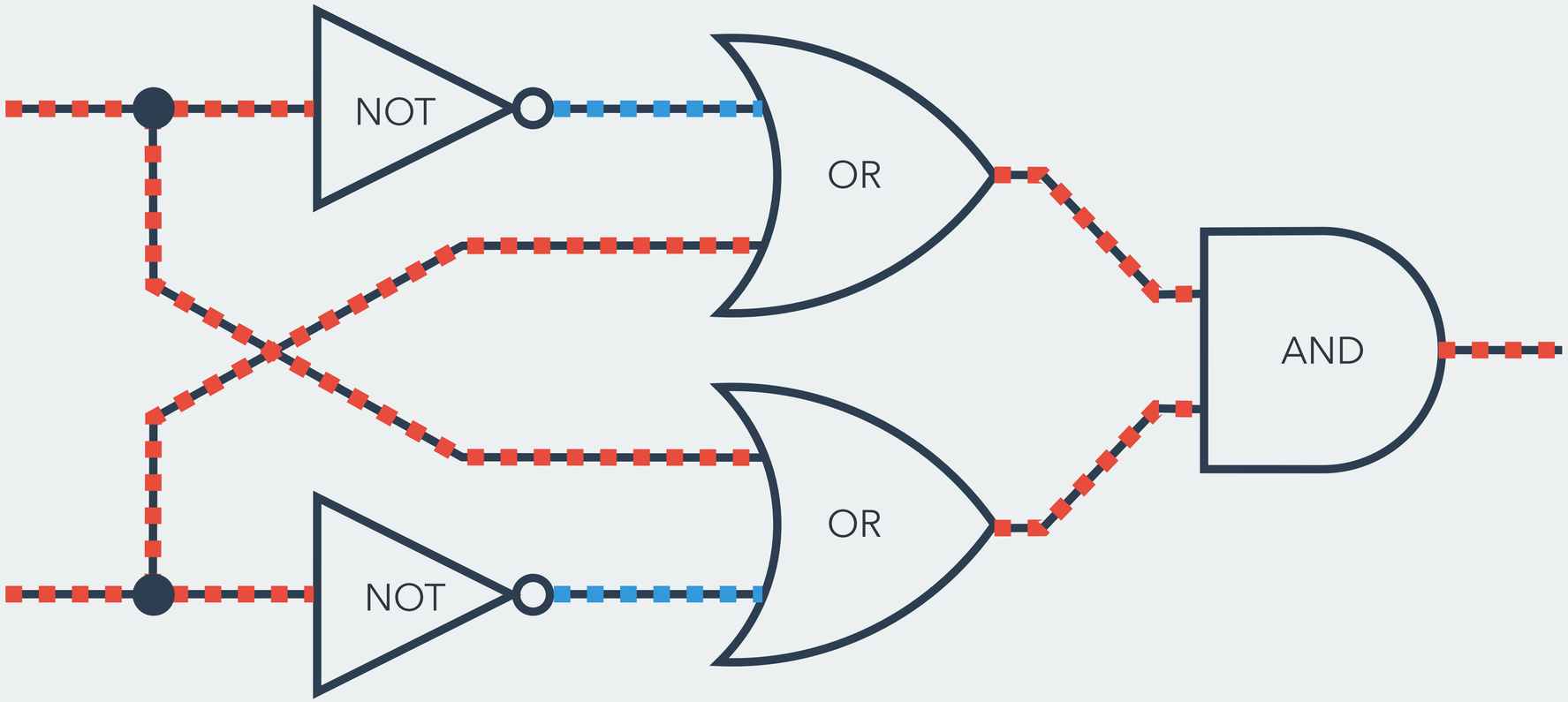
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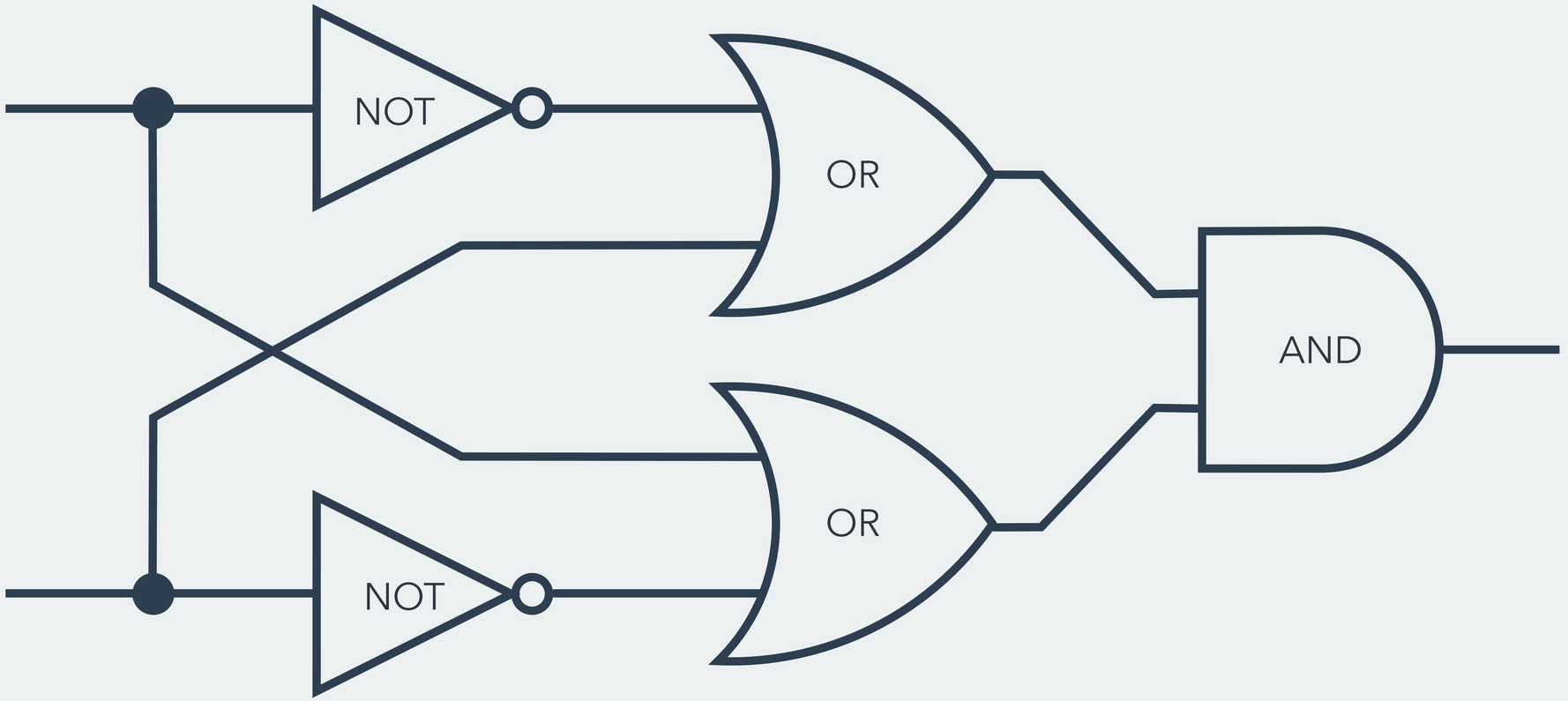
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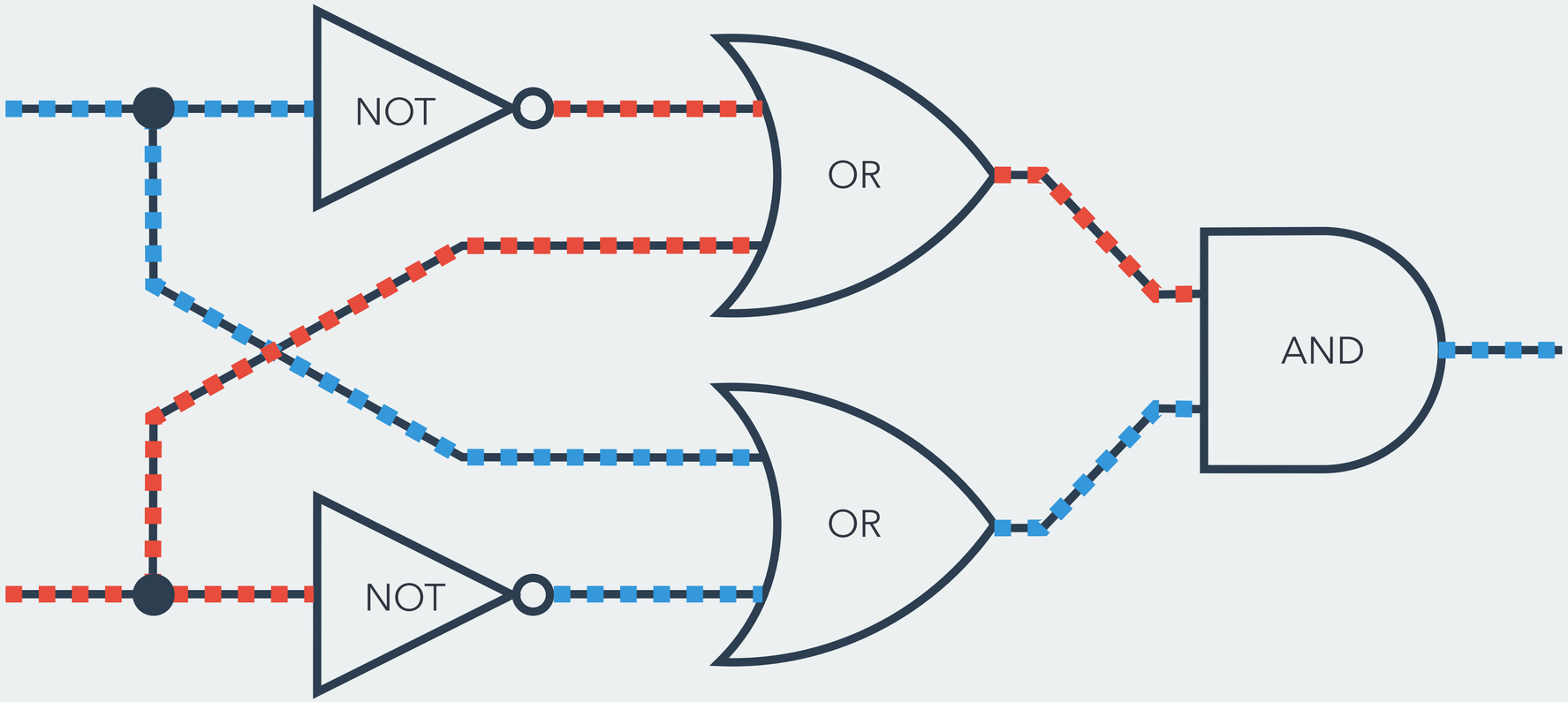
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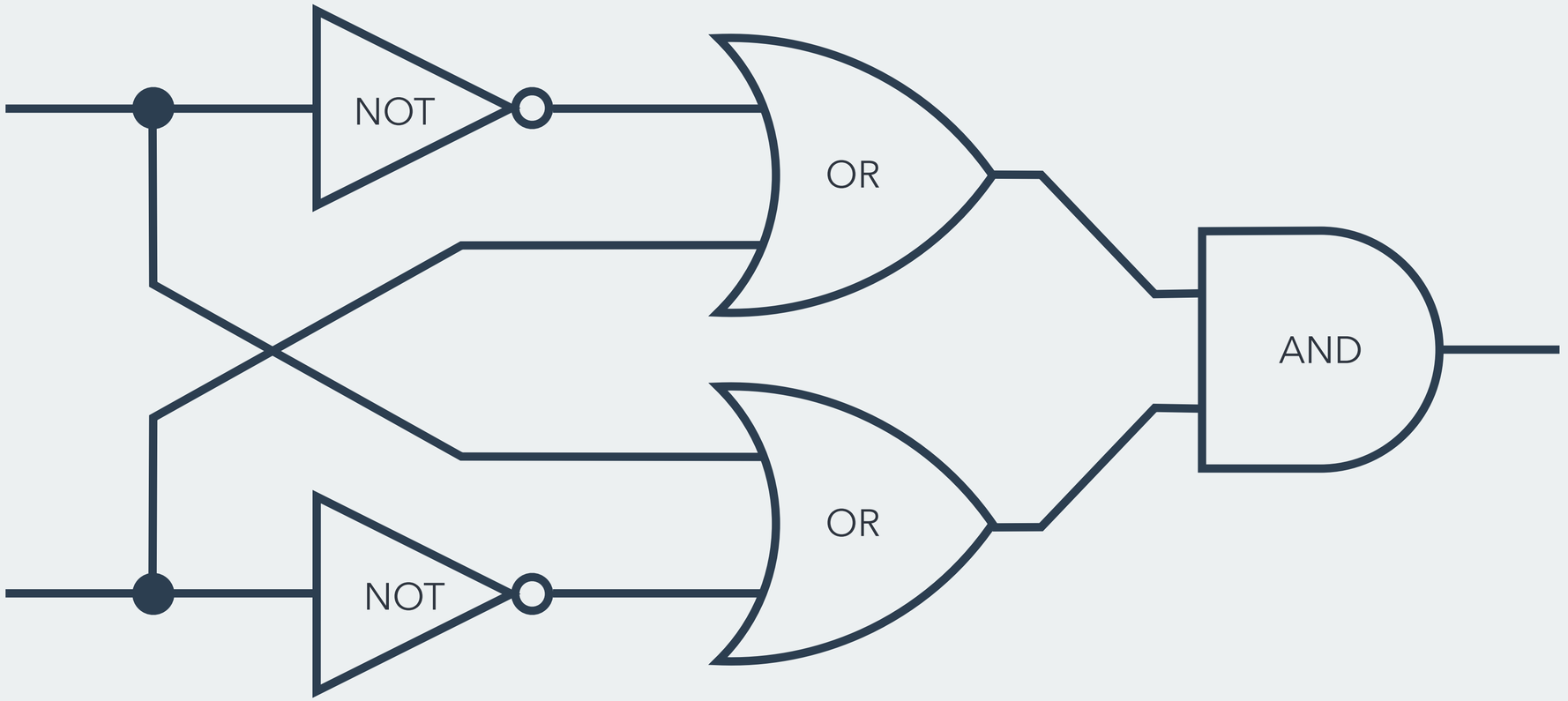
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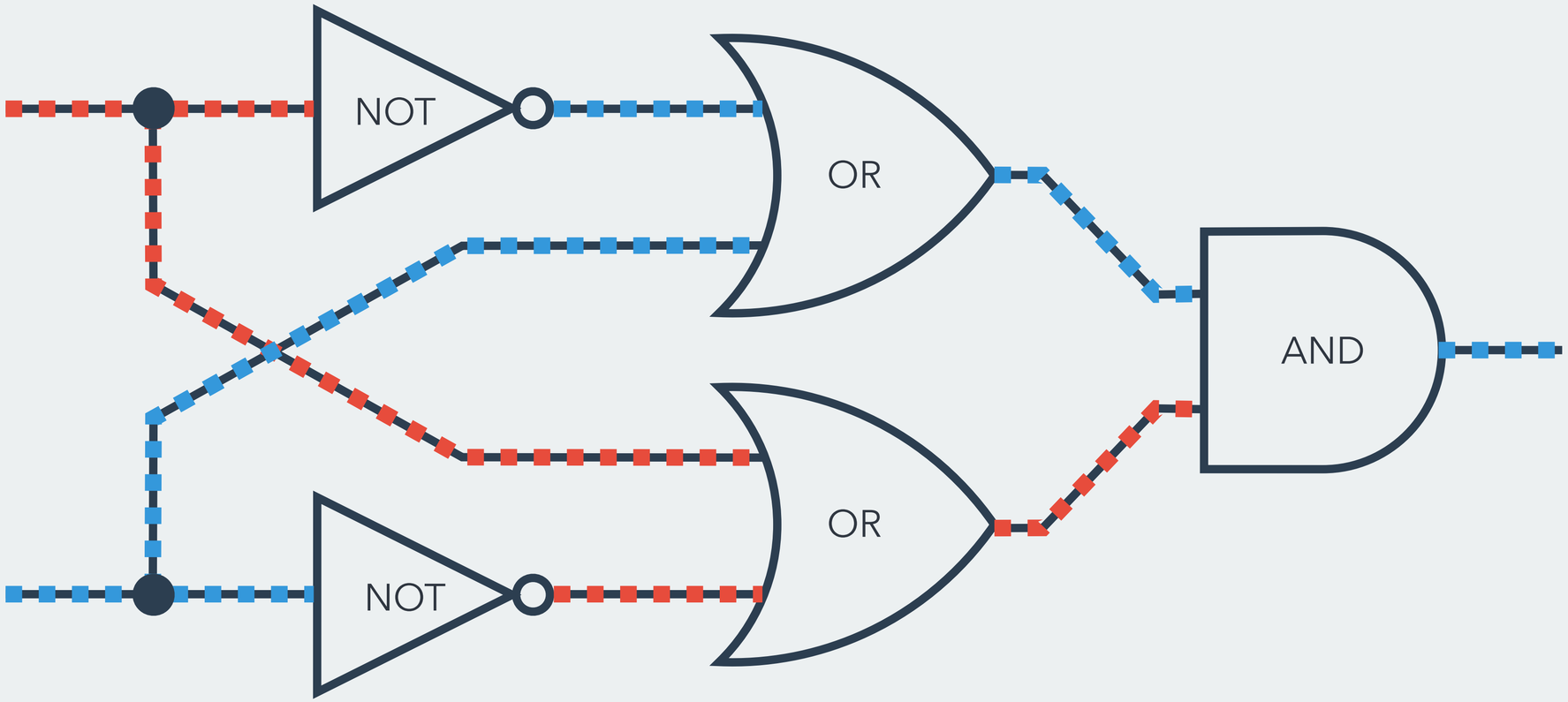
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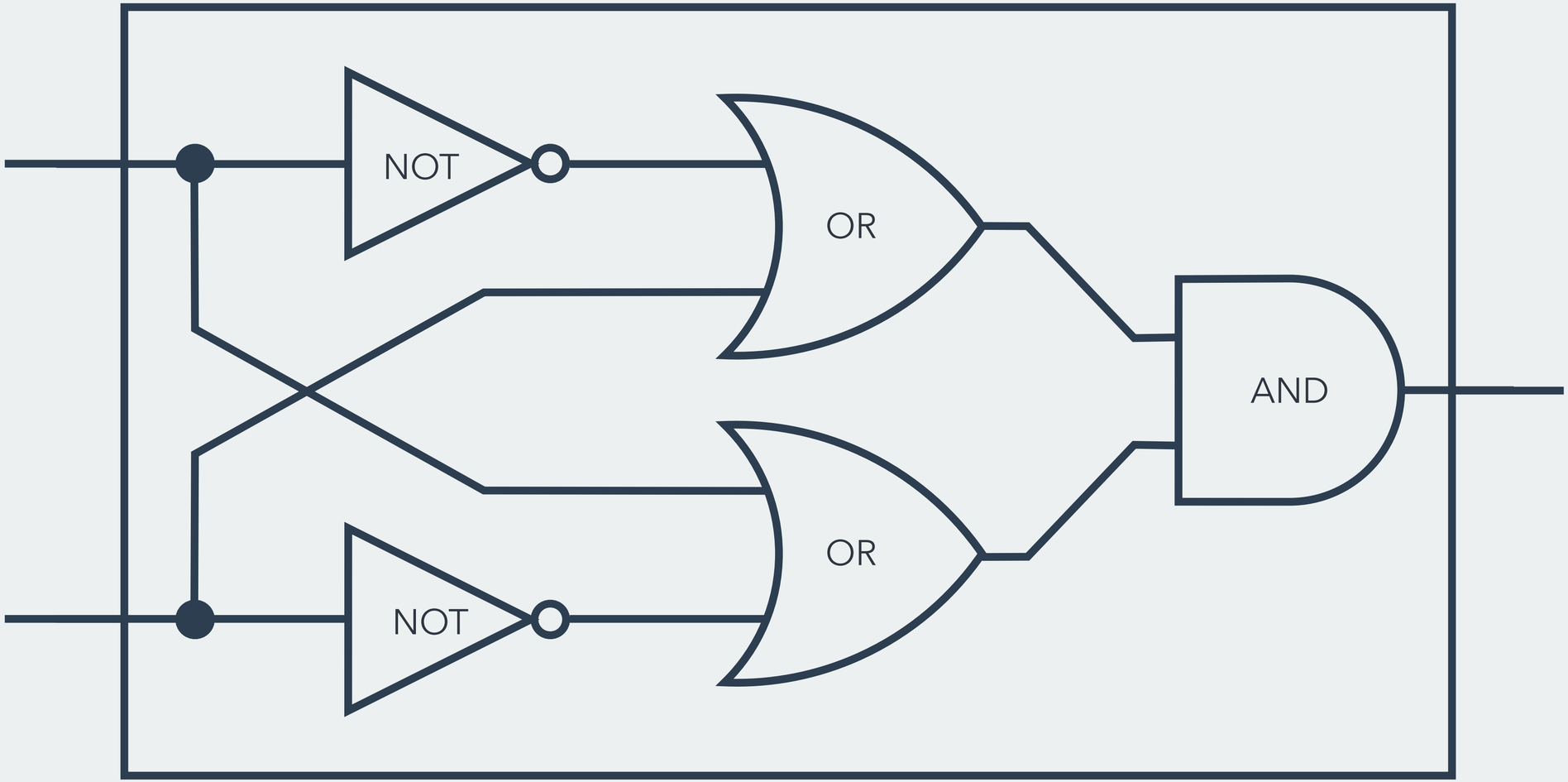
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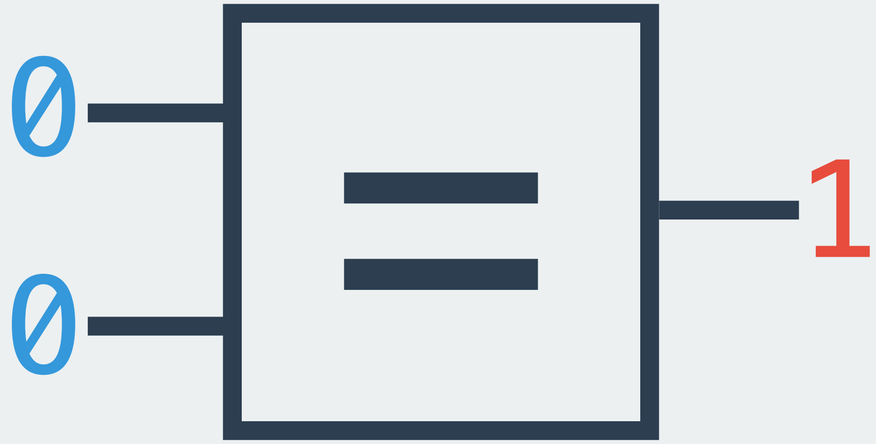
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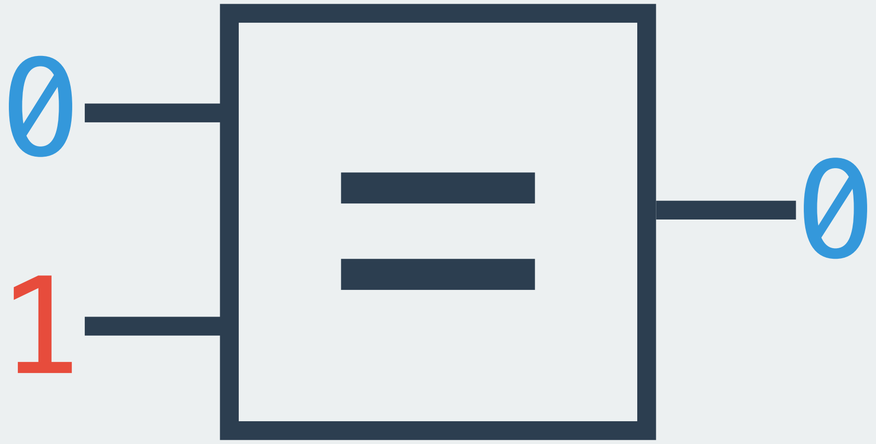
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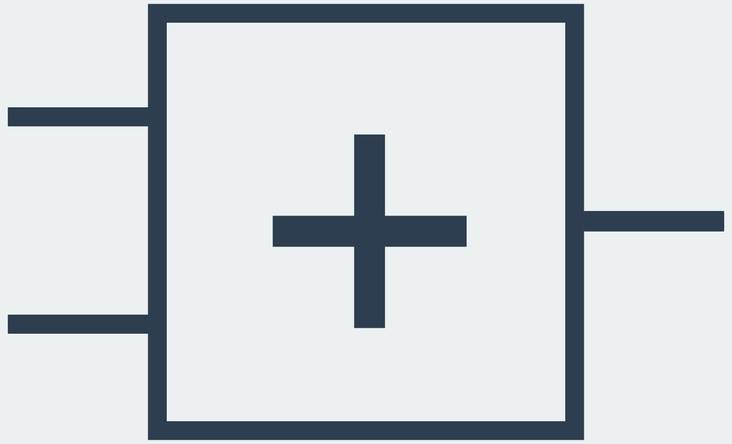

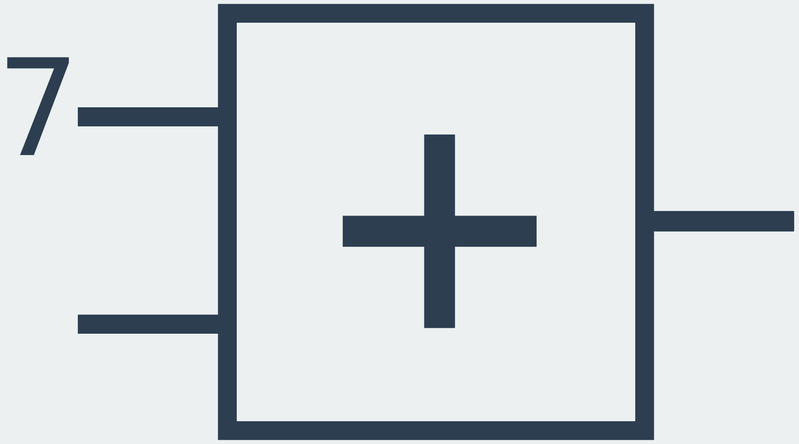
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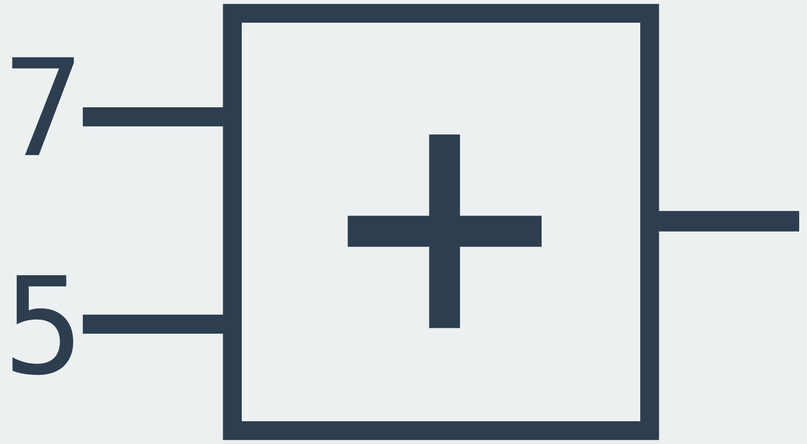
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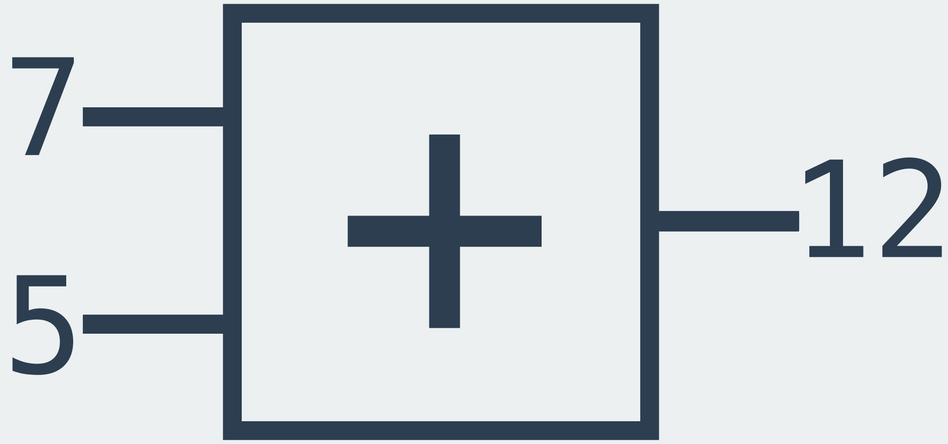
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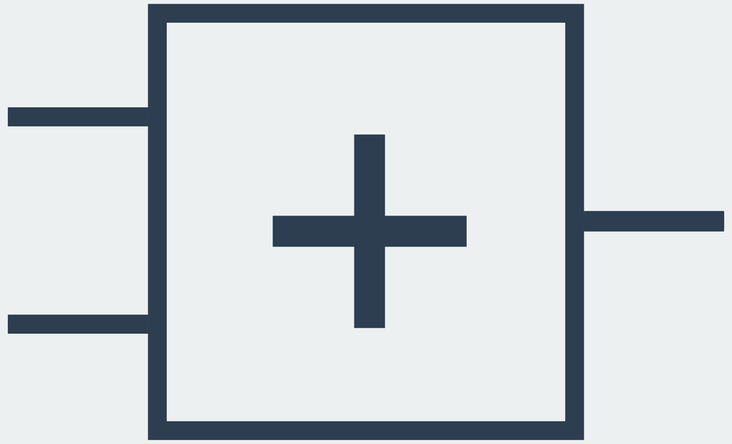

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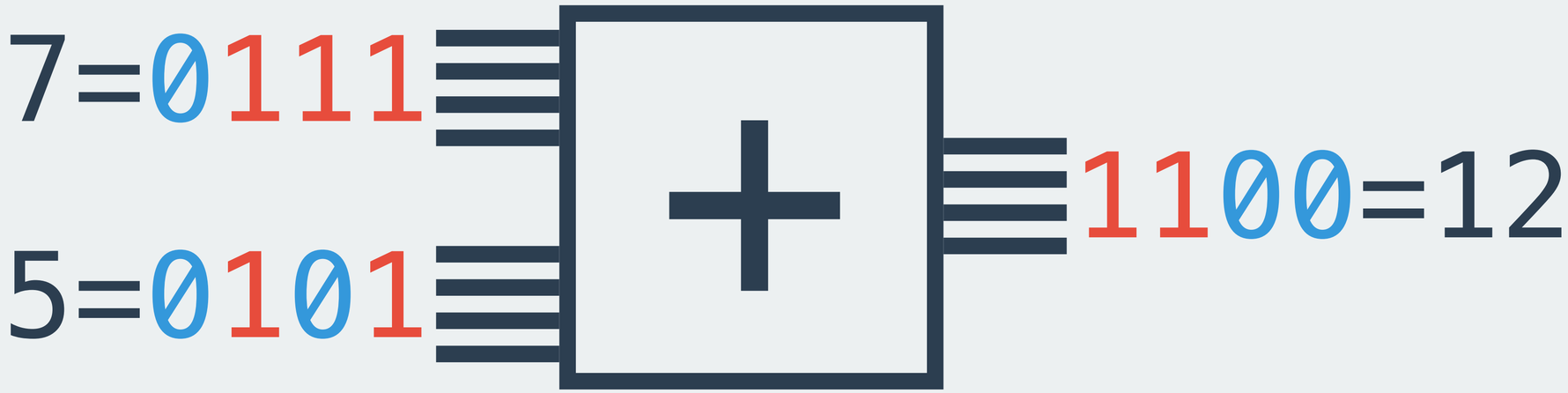
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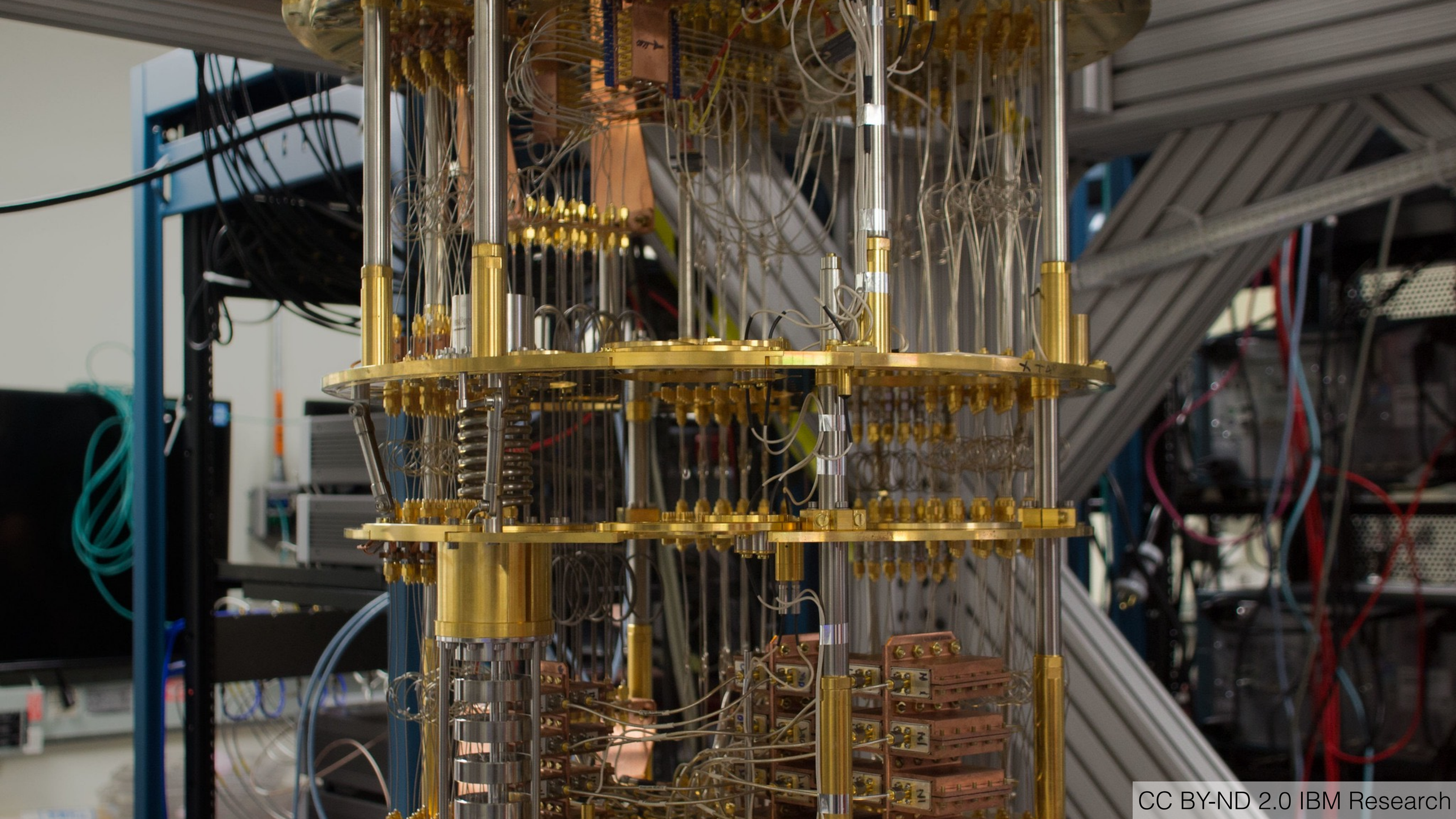

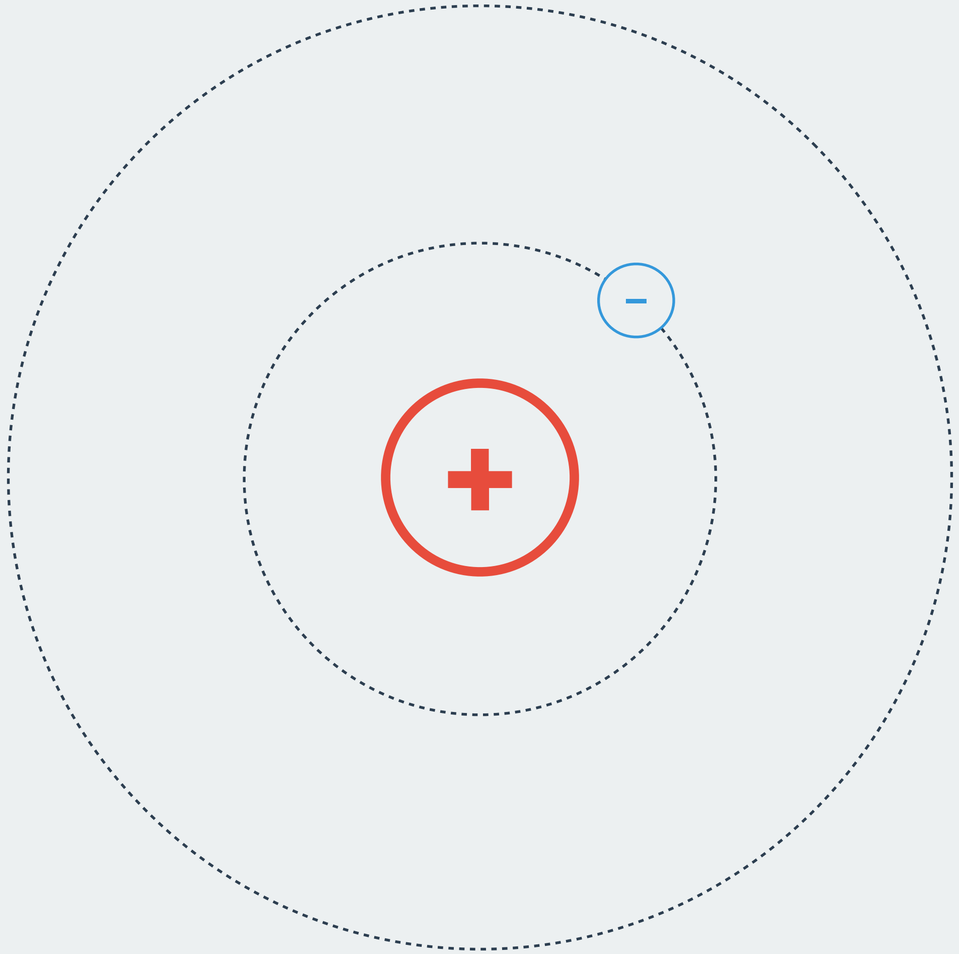

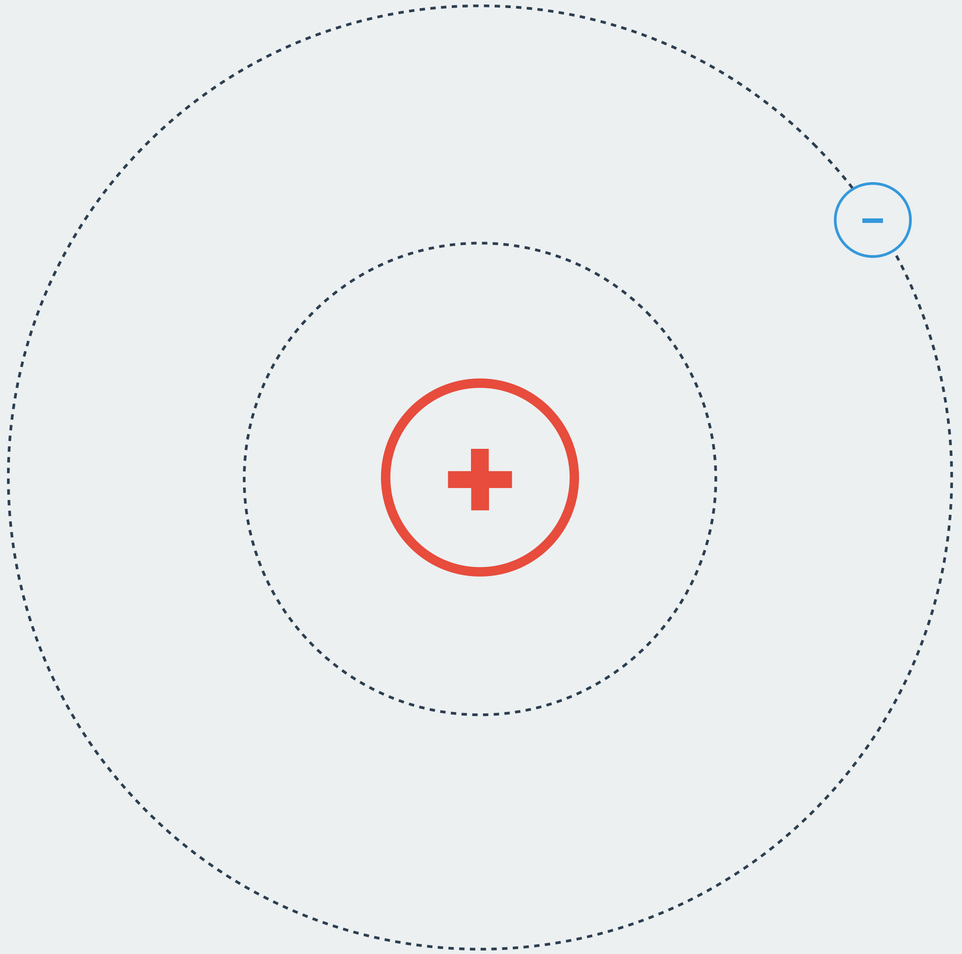

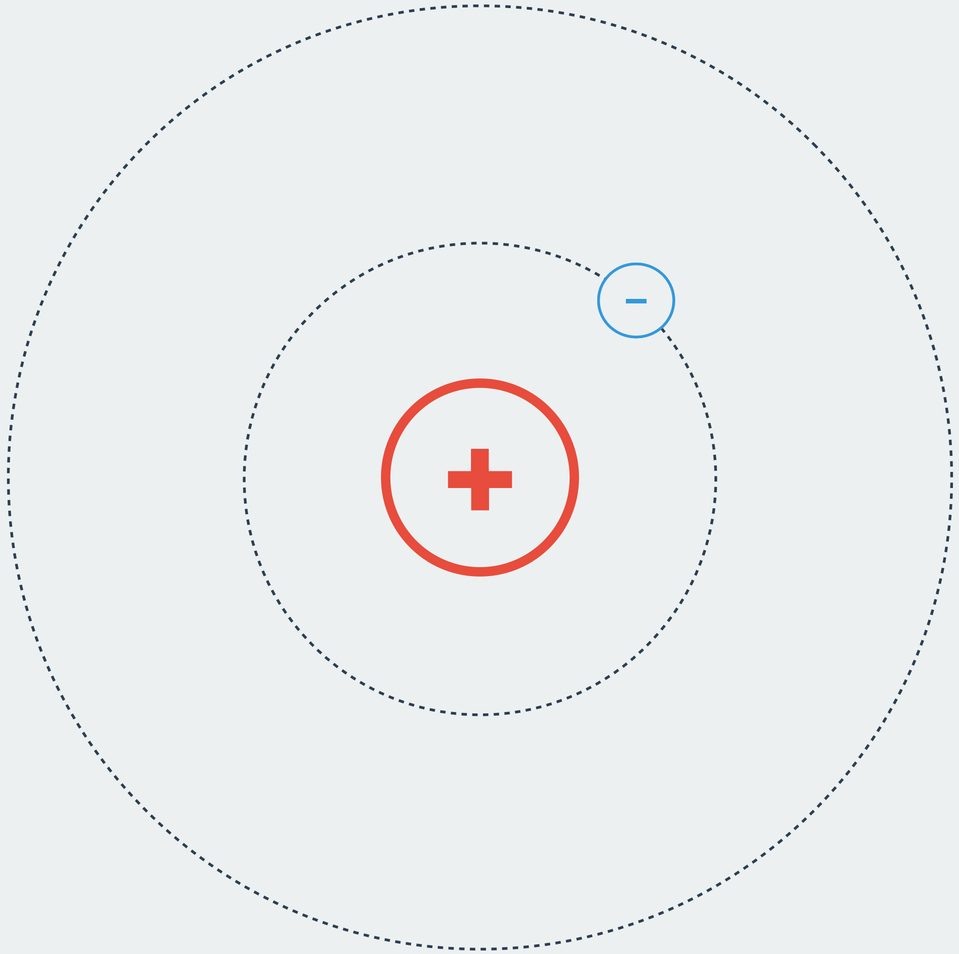

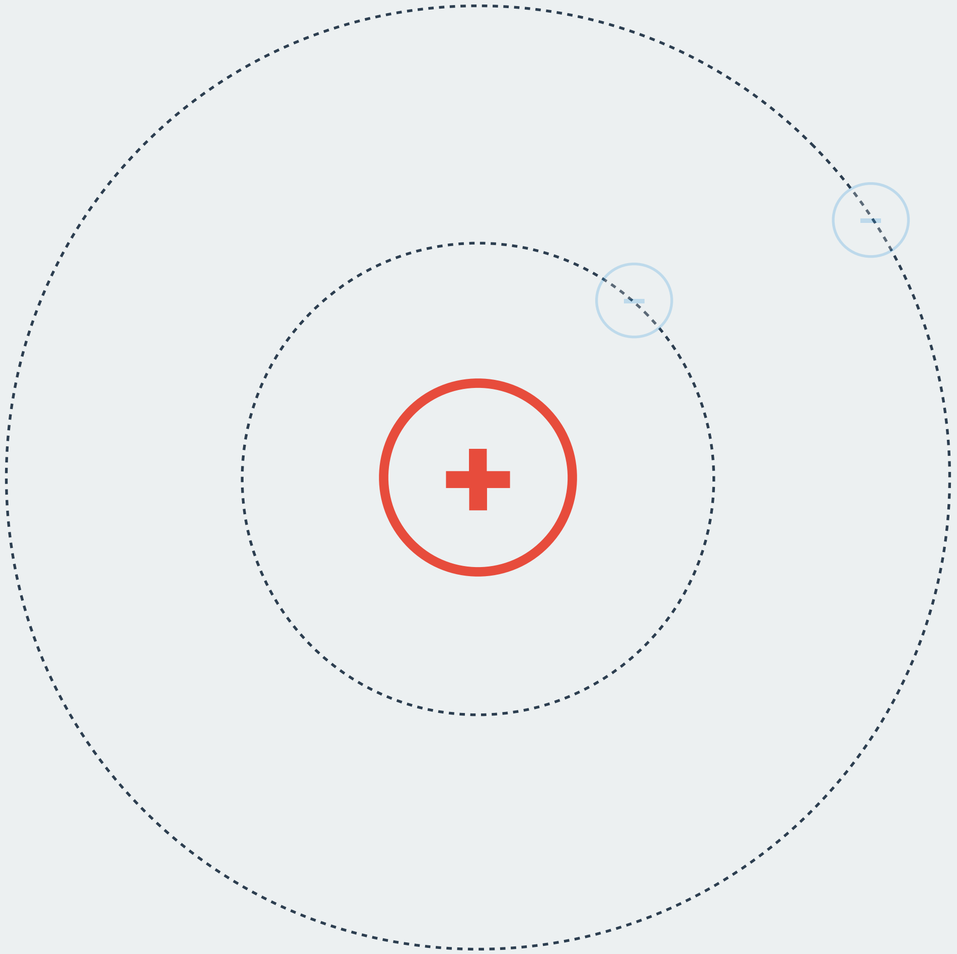

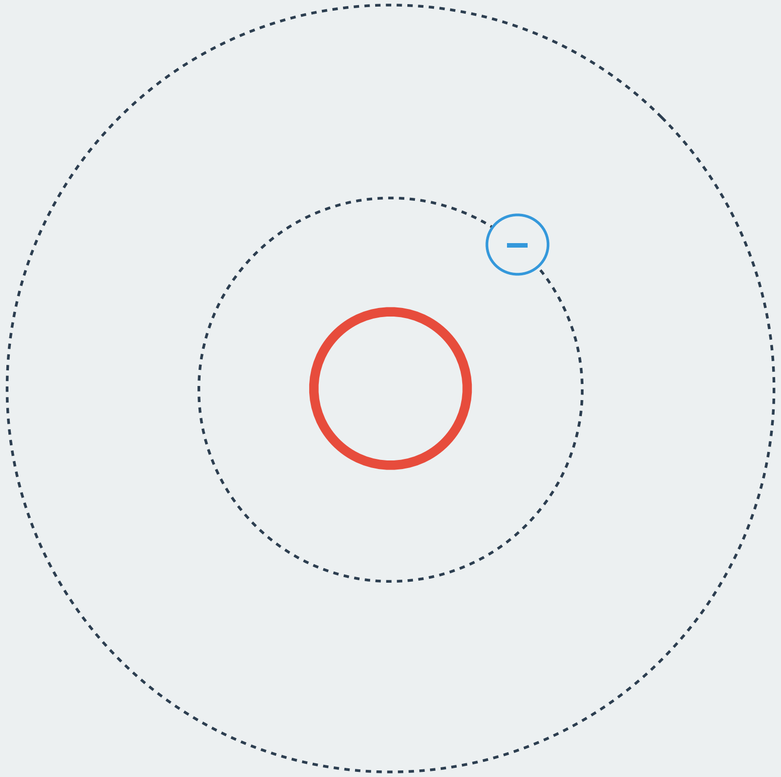

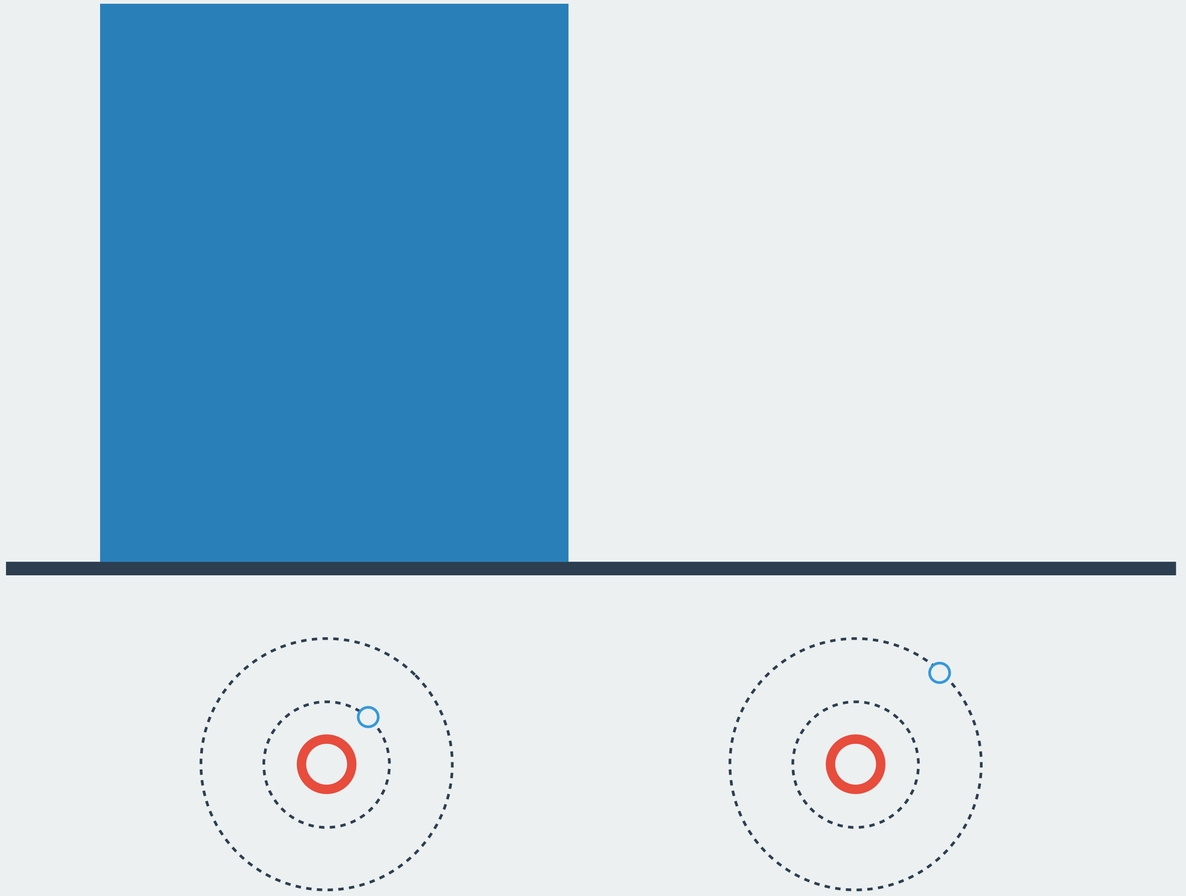

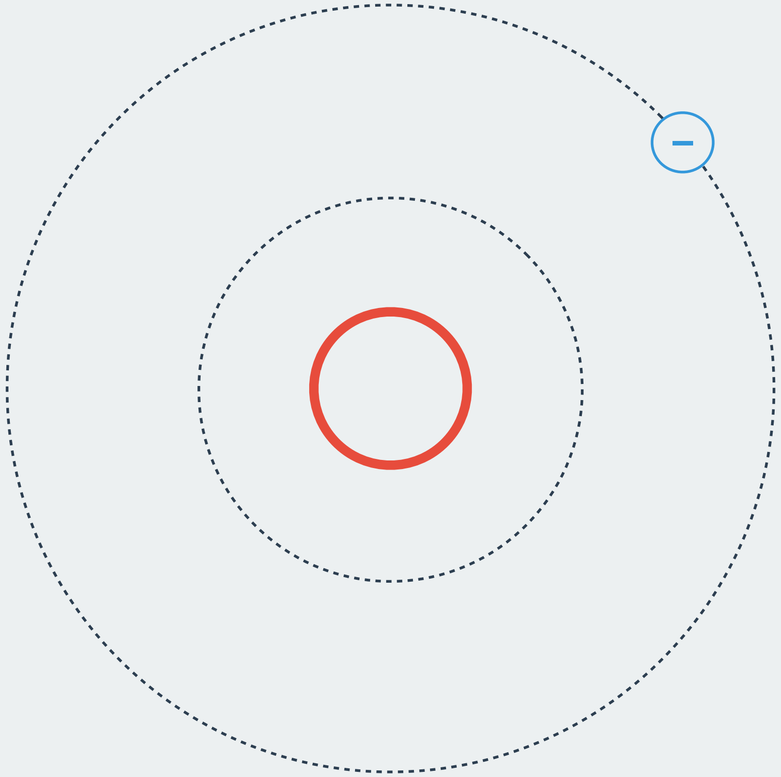

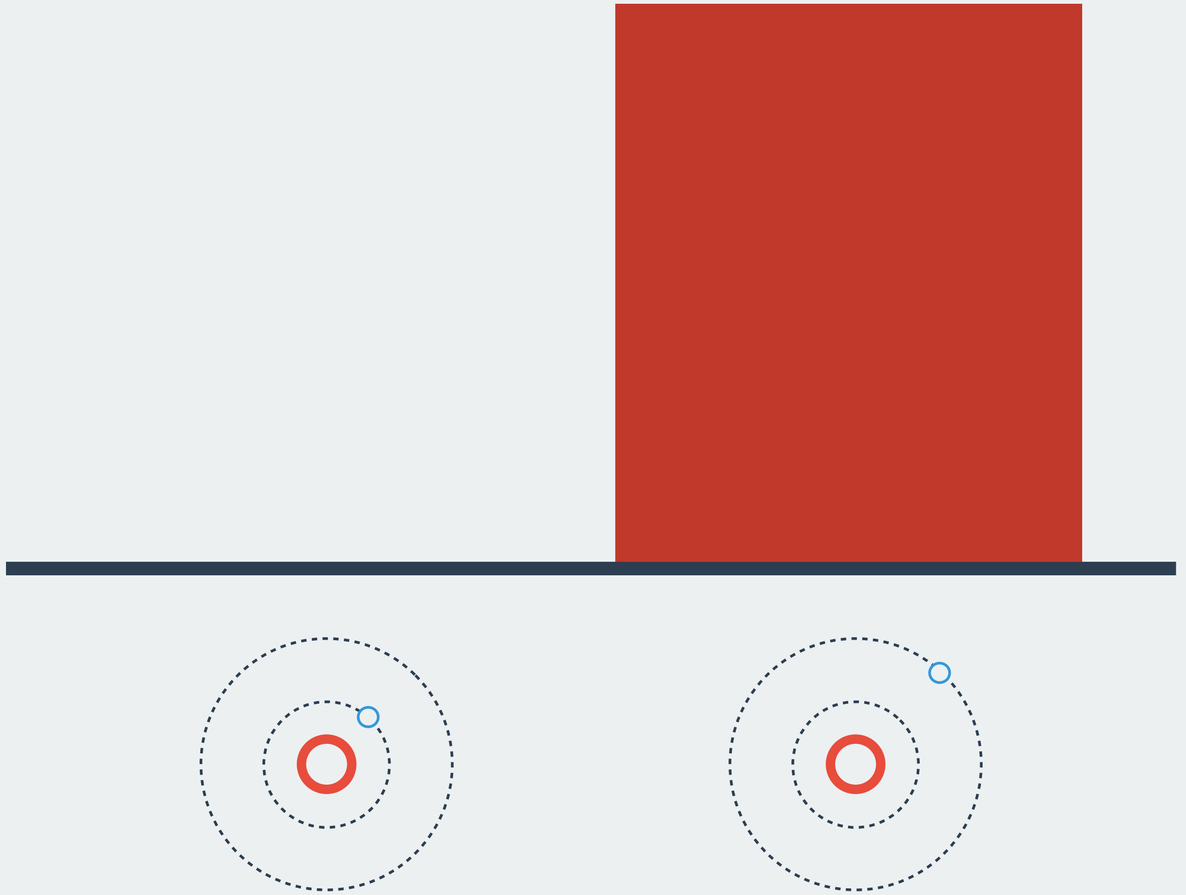

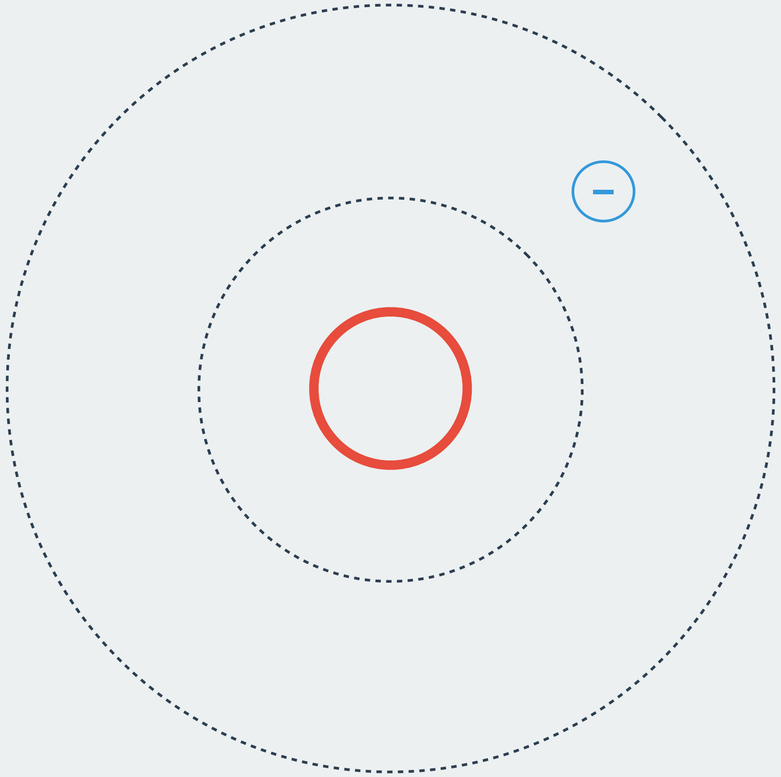

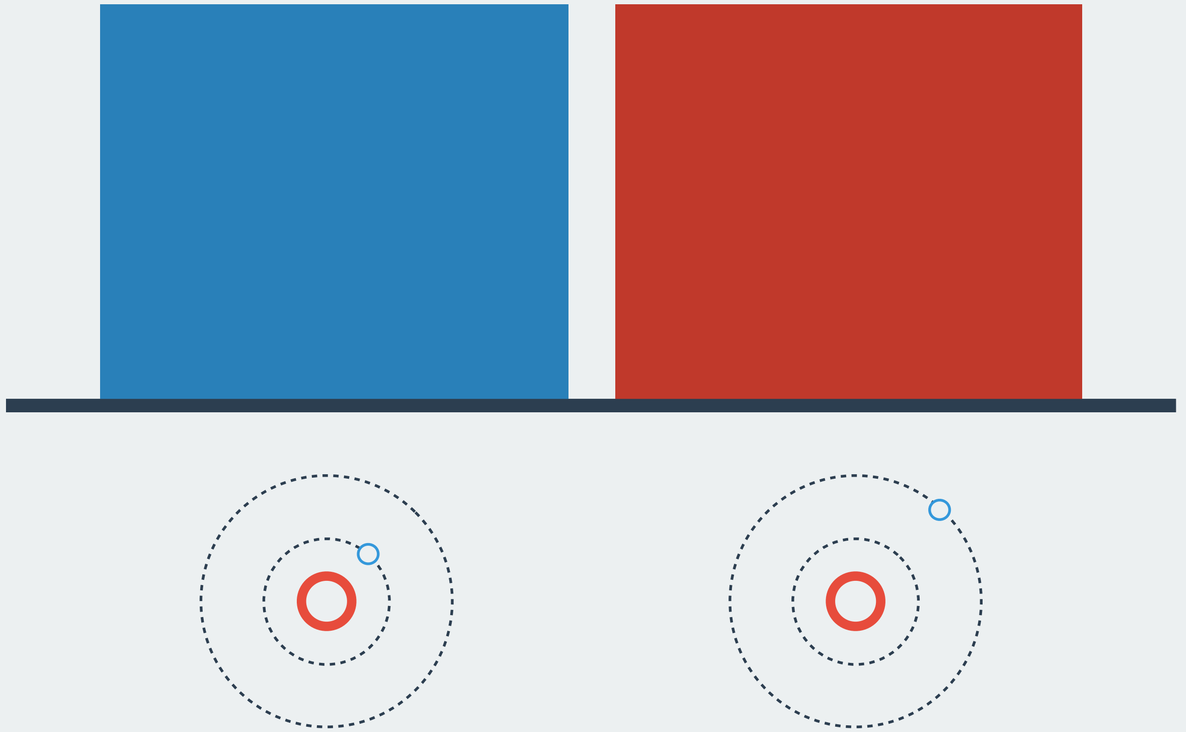

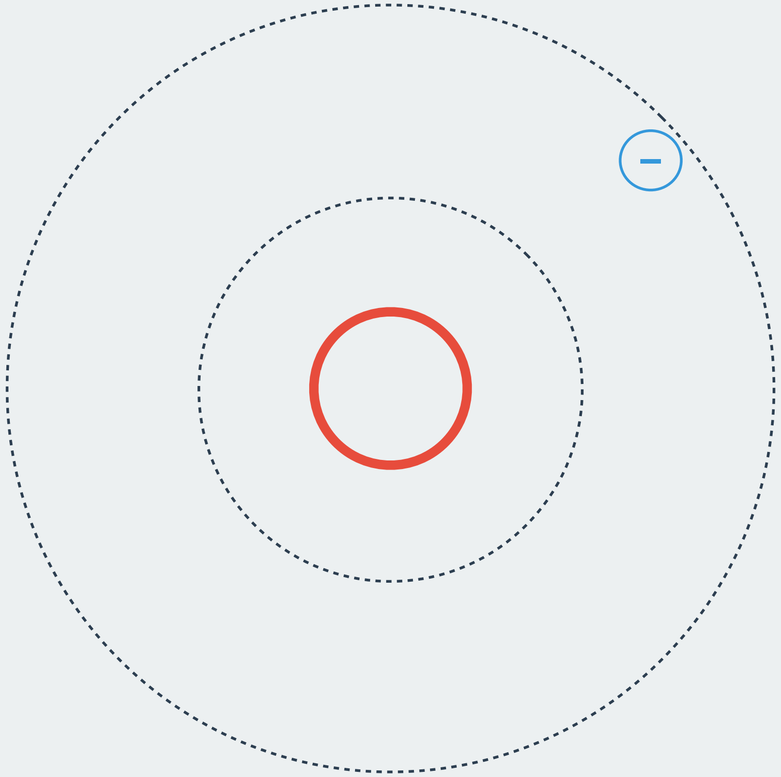

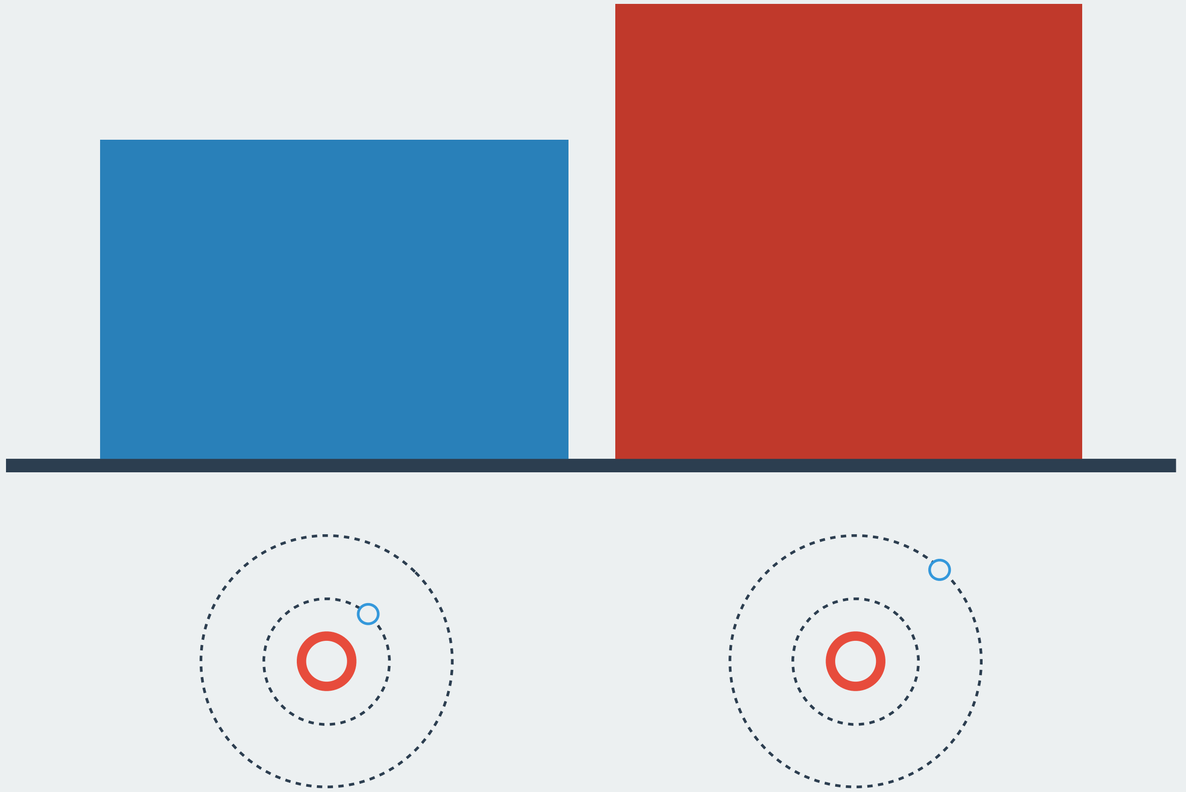

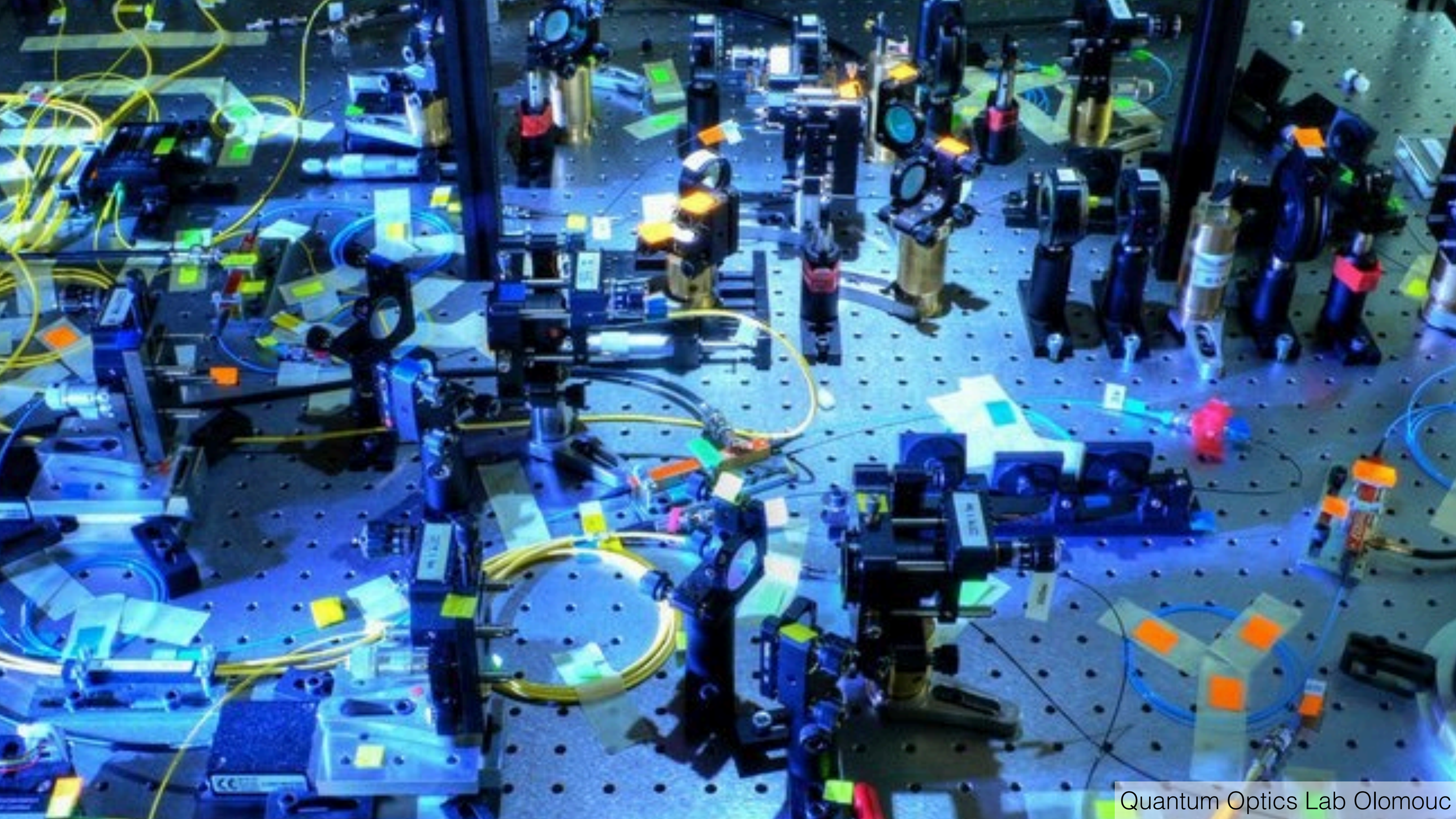
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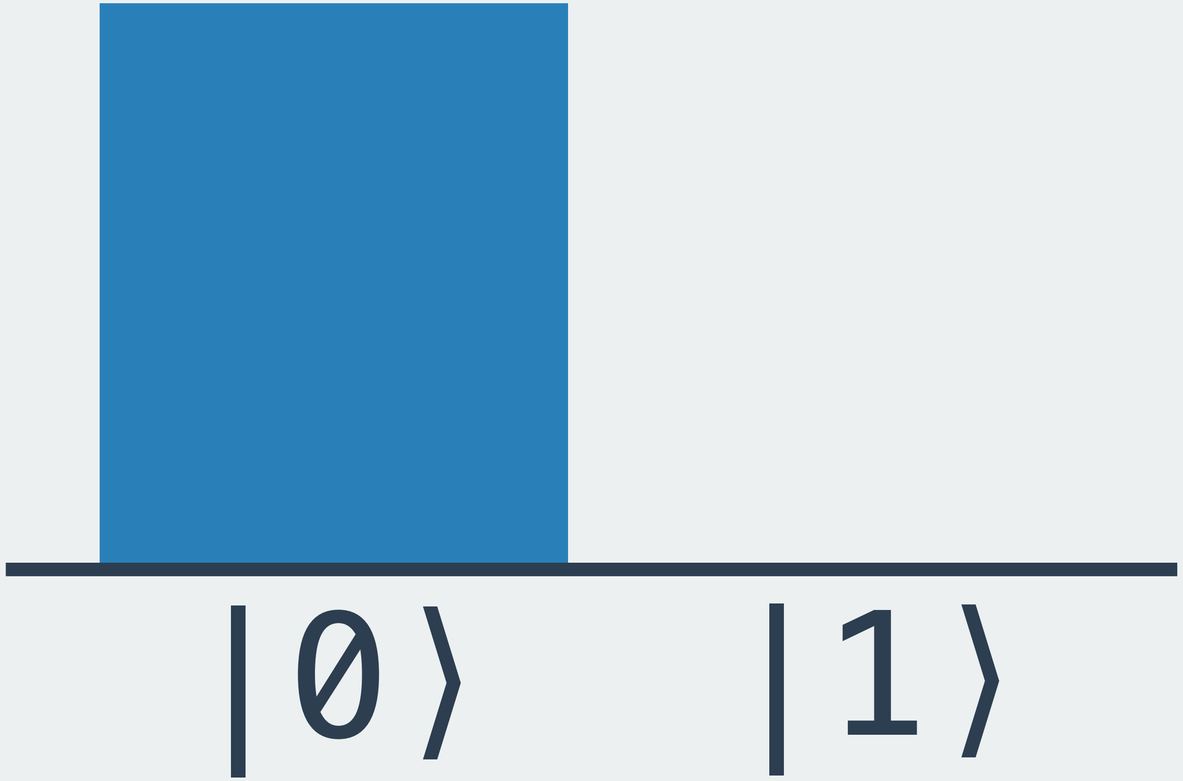
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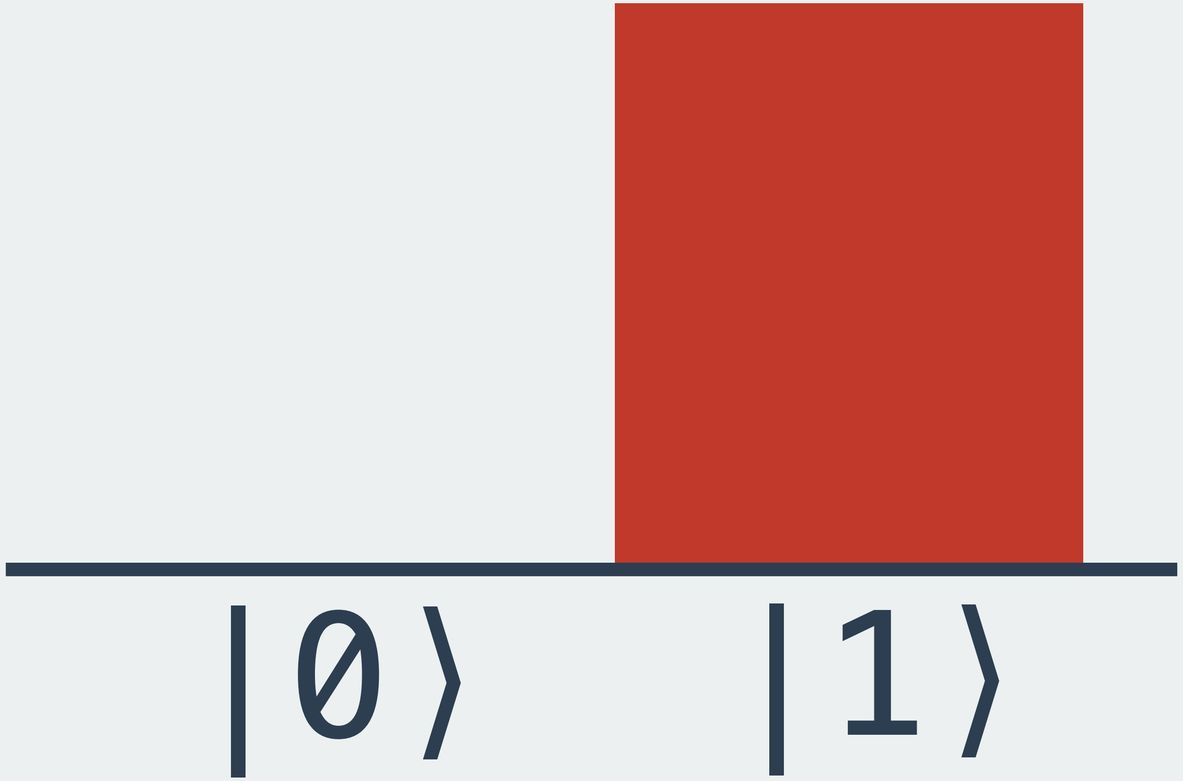
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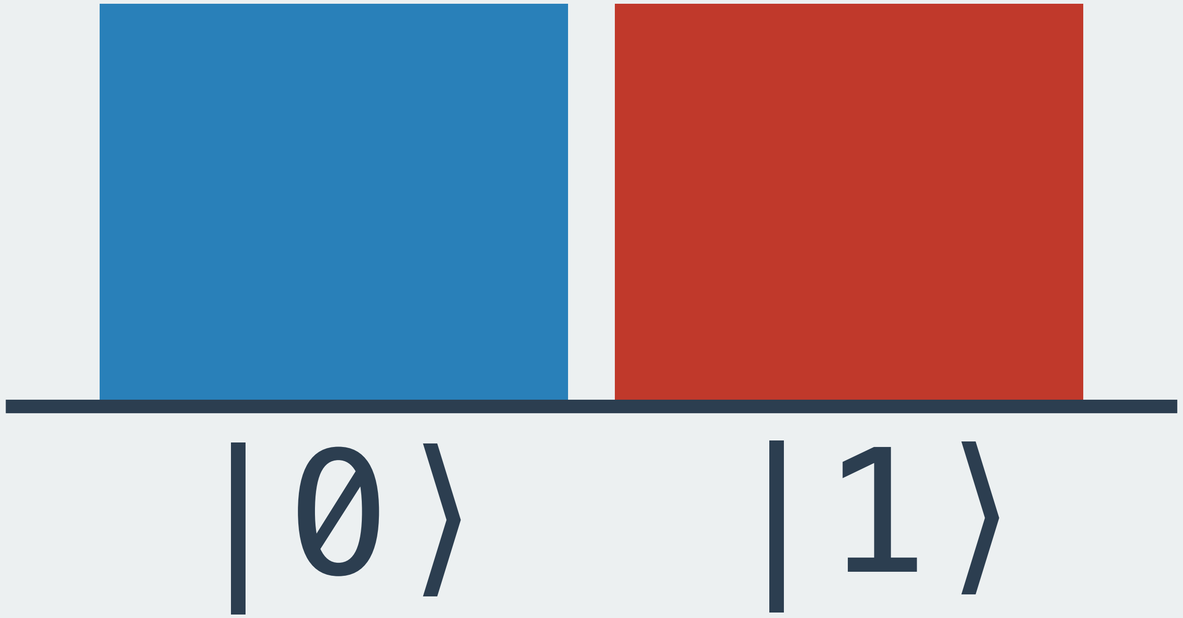
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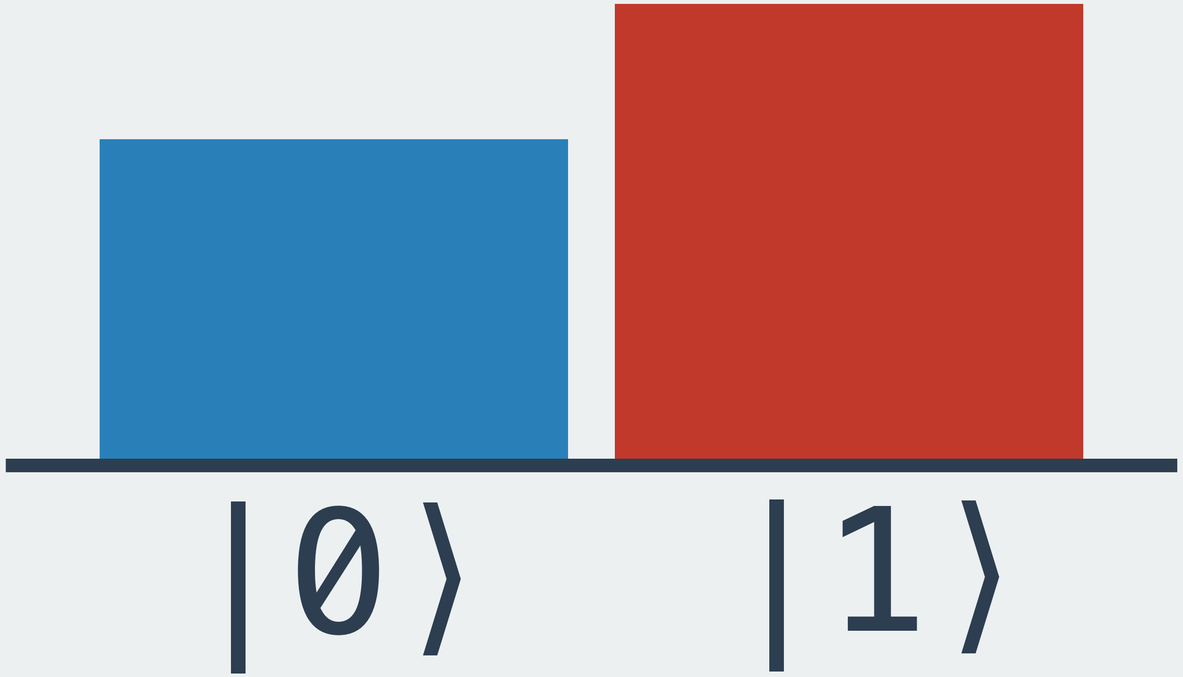
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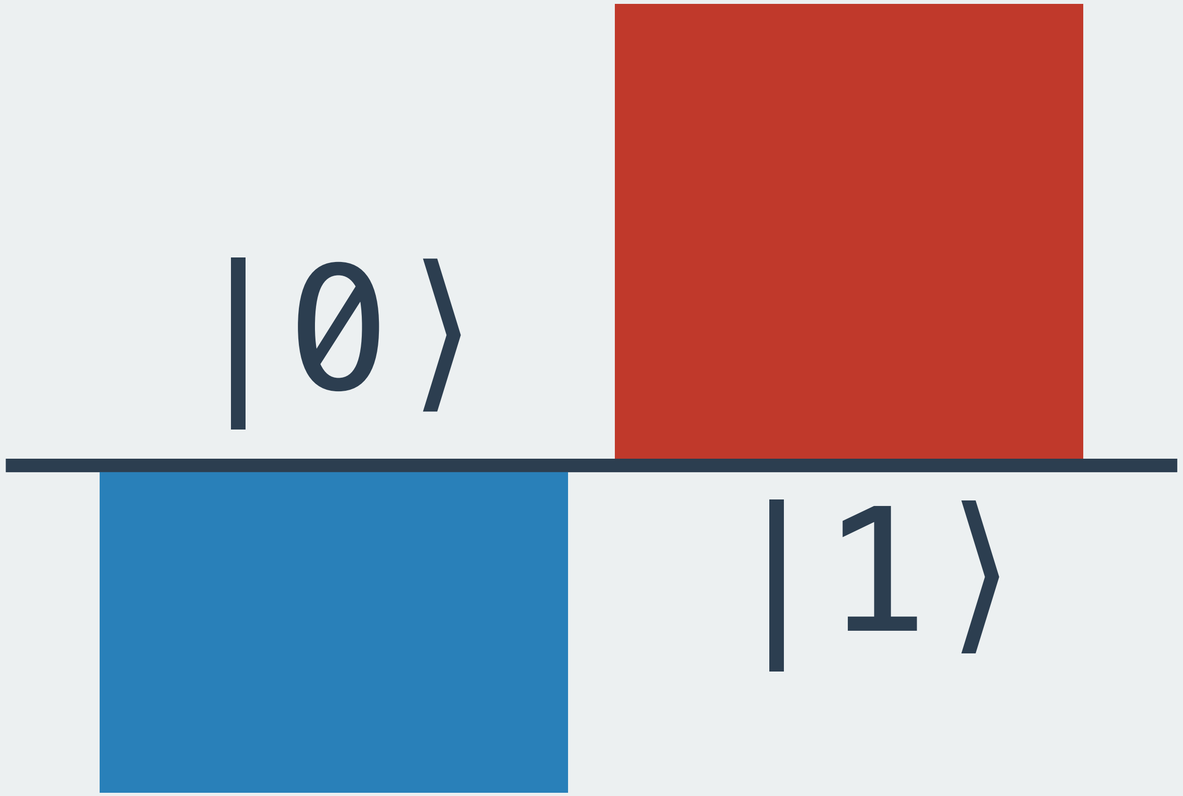
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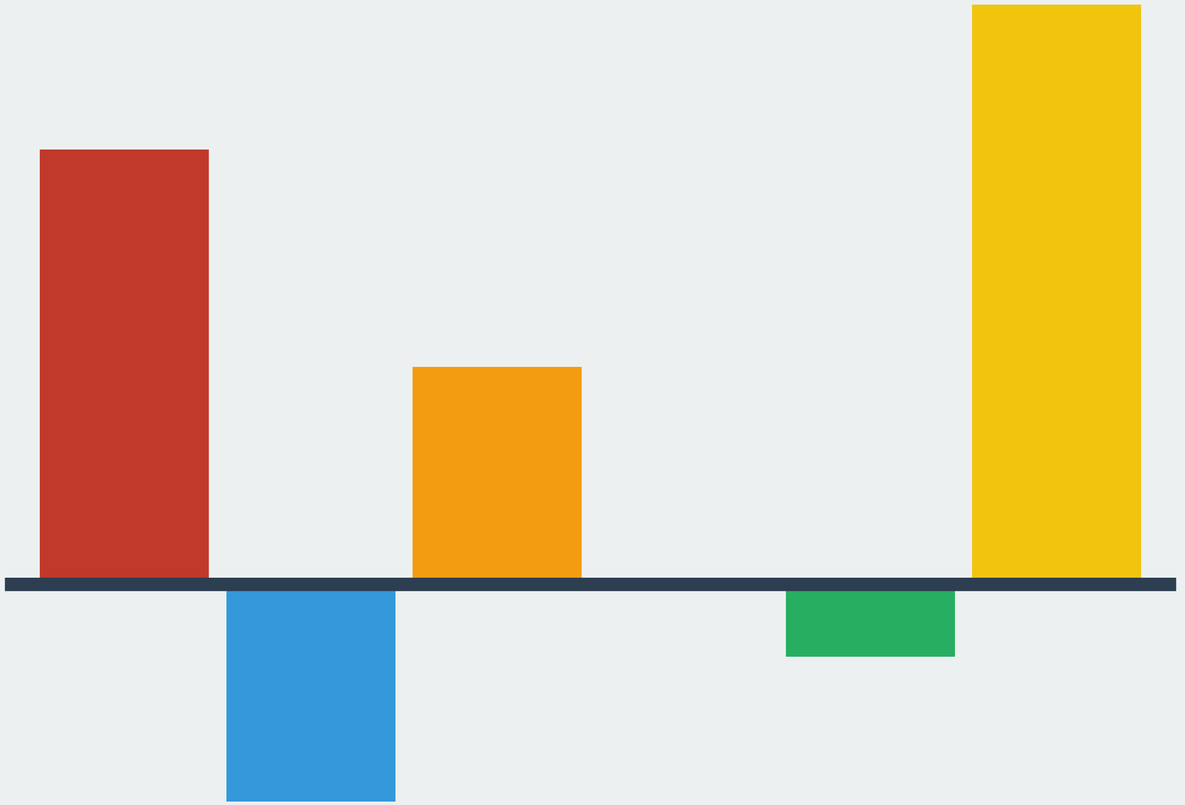

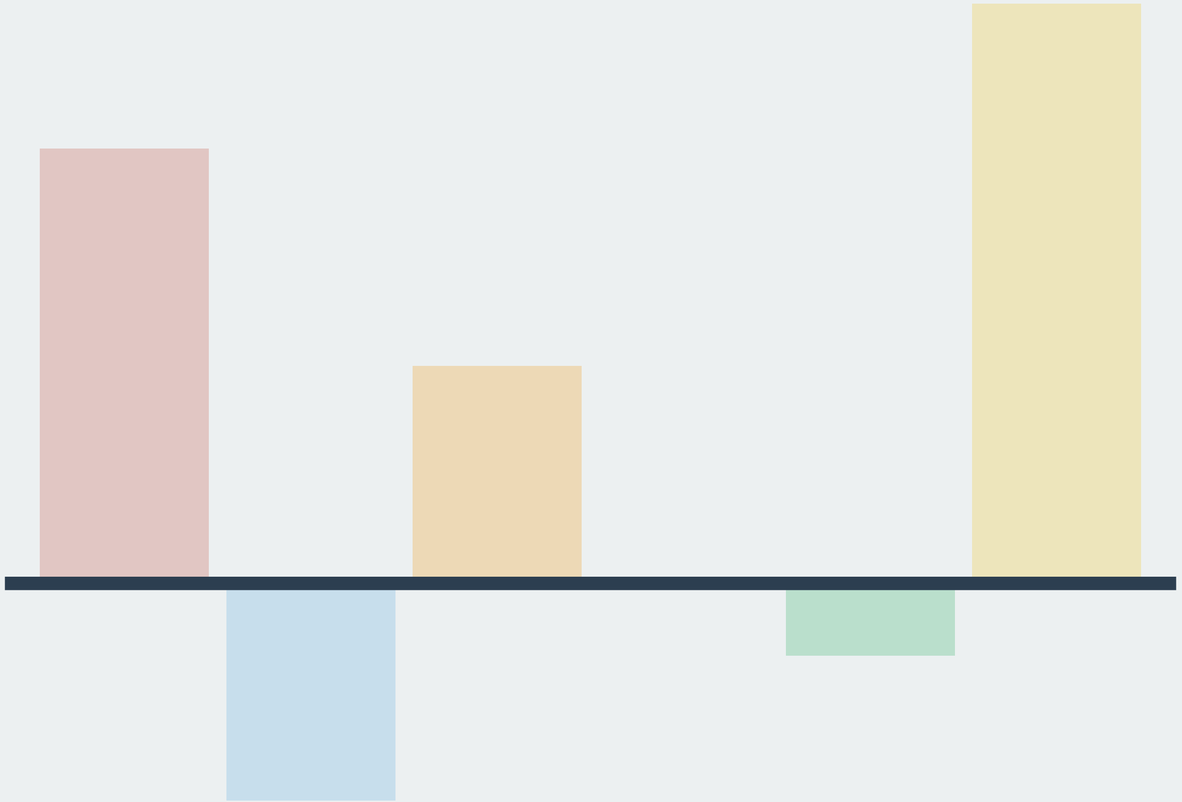

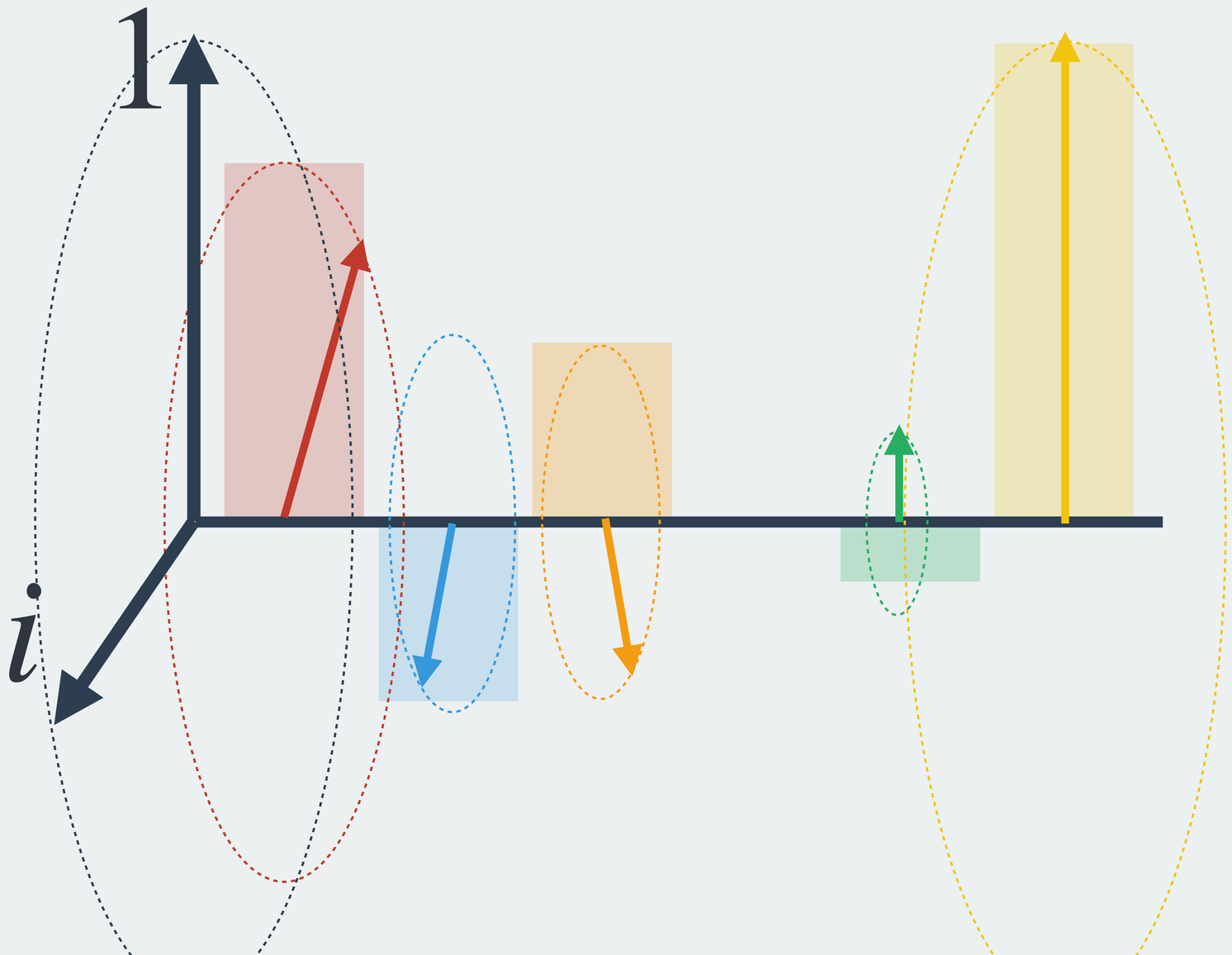
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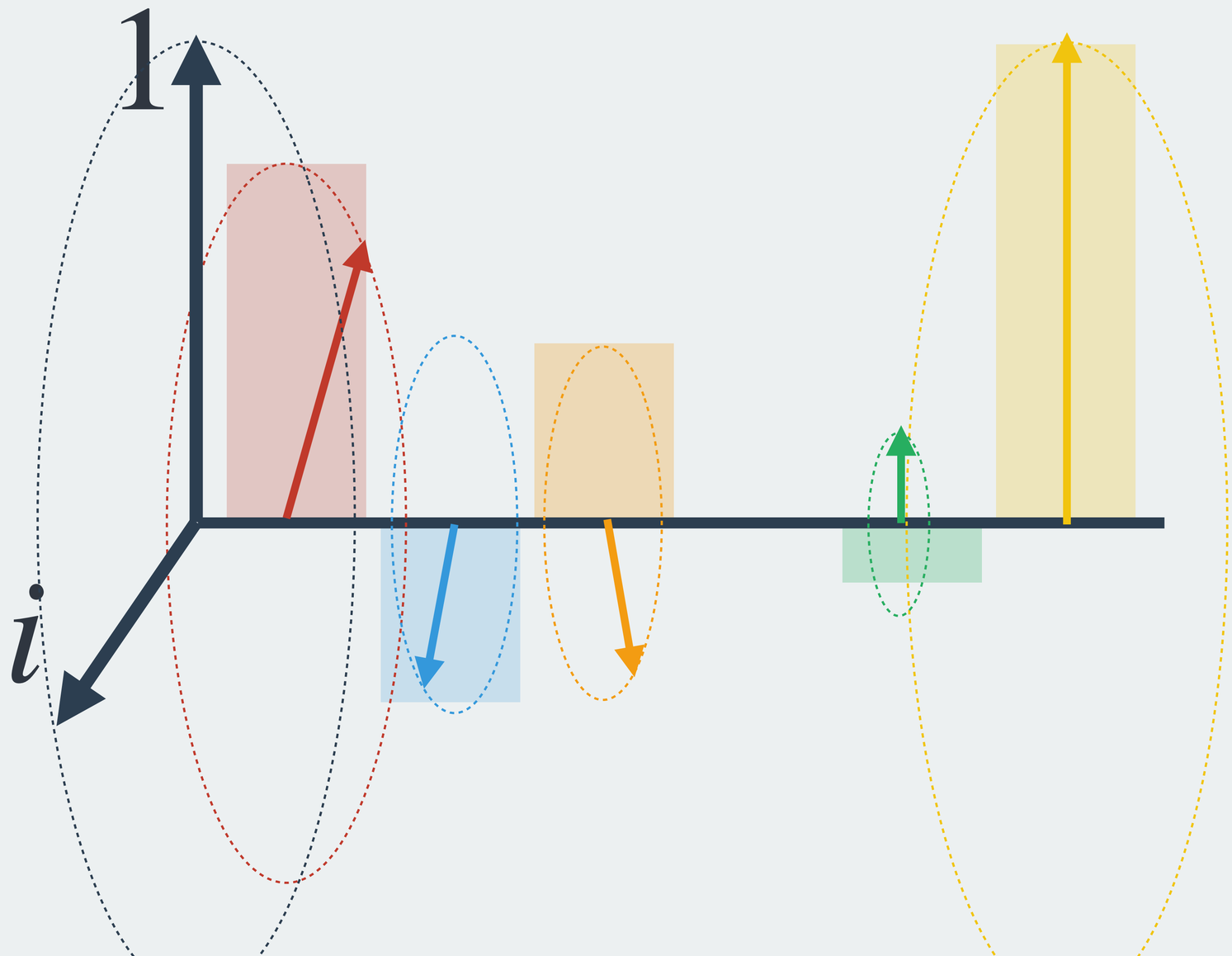

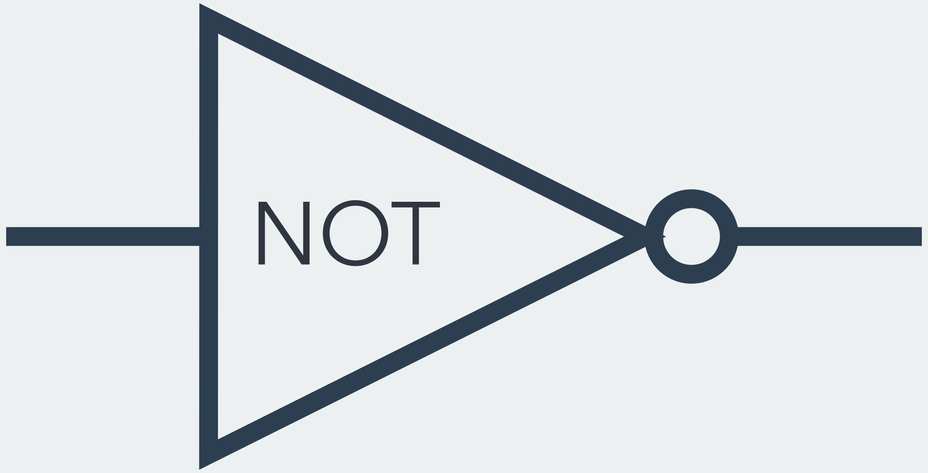
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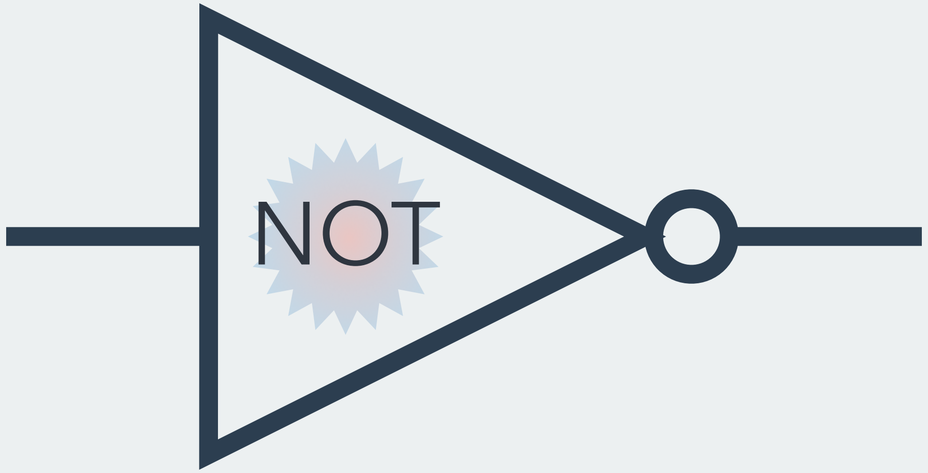
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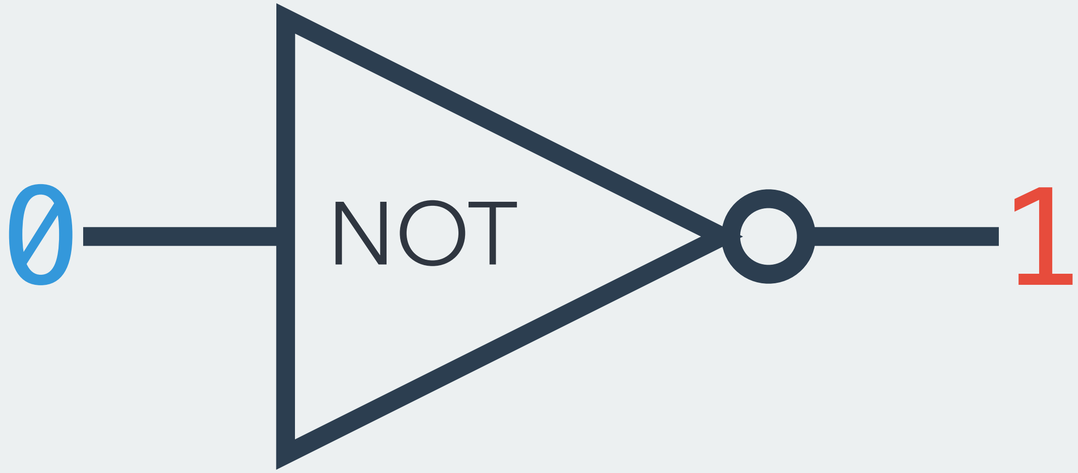
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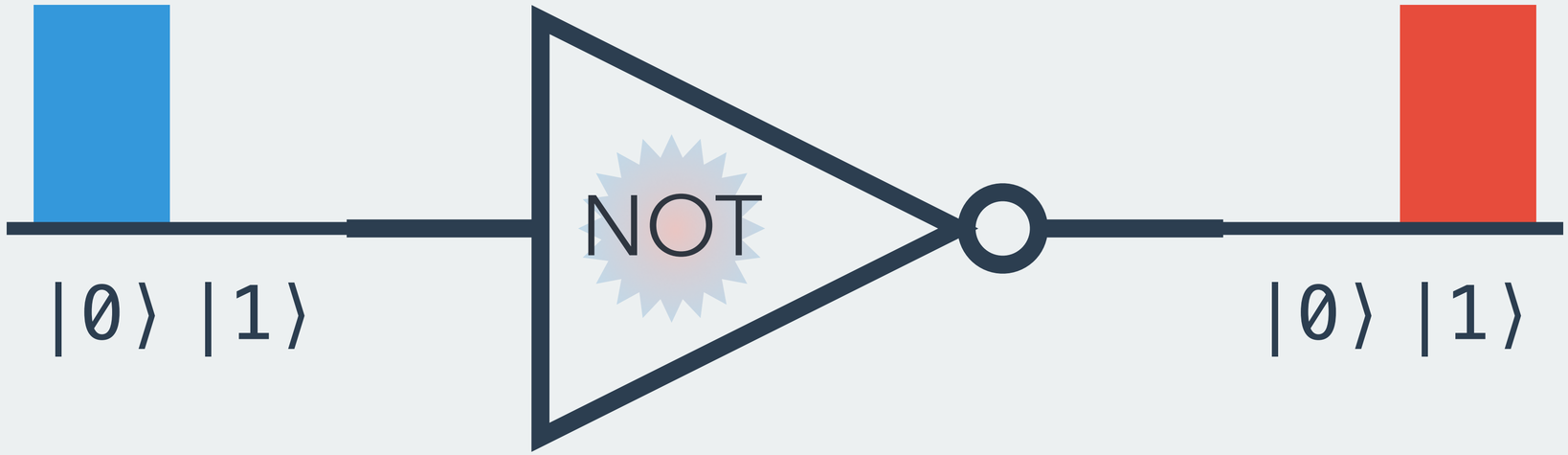
simulacija vrat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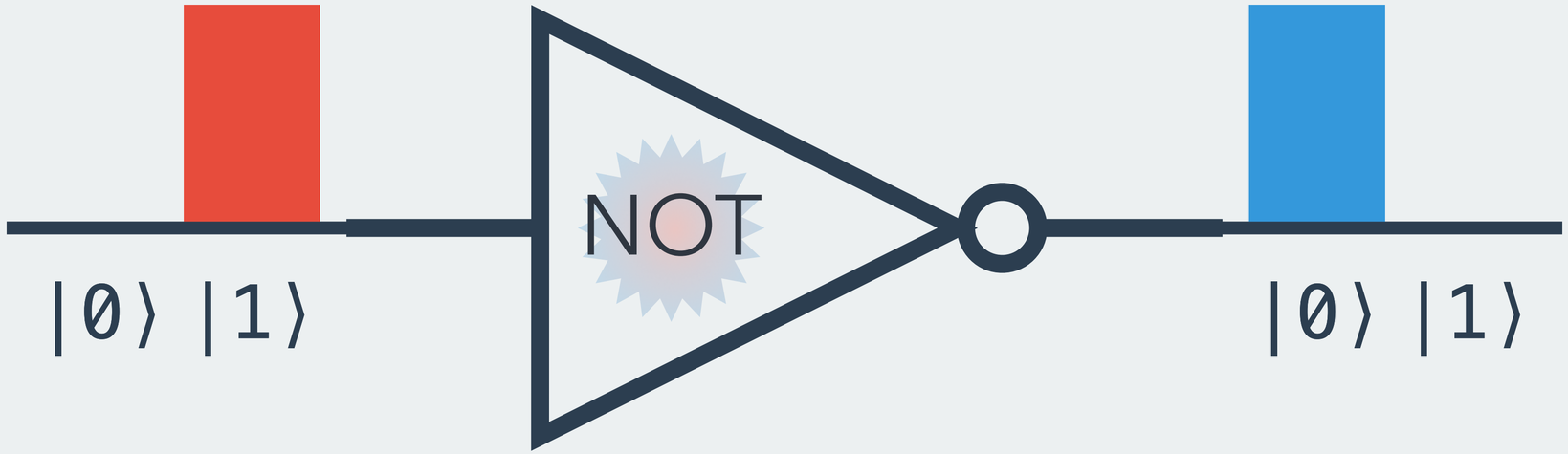
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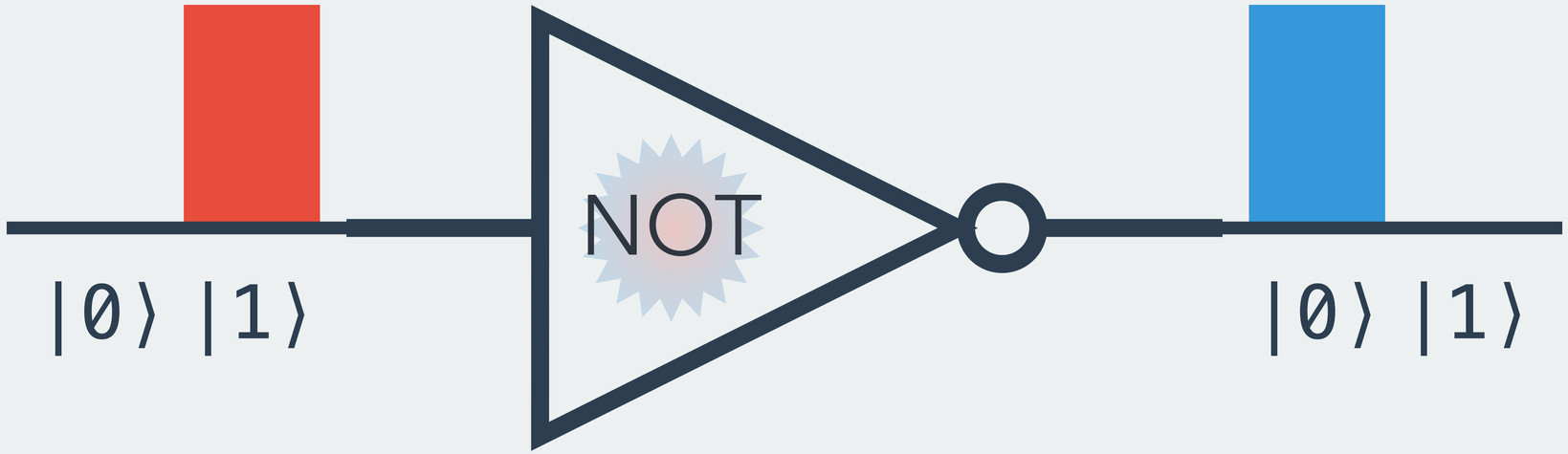
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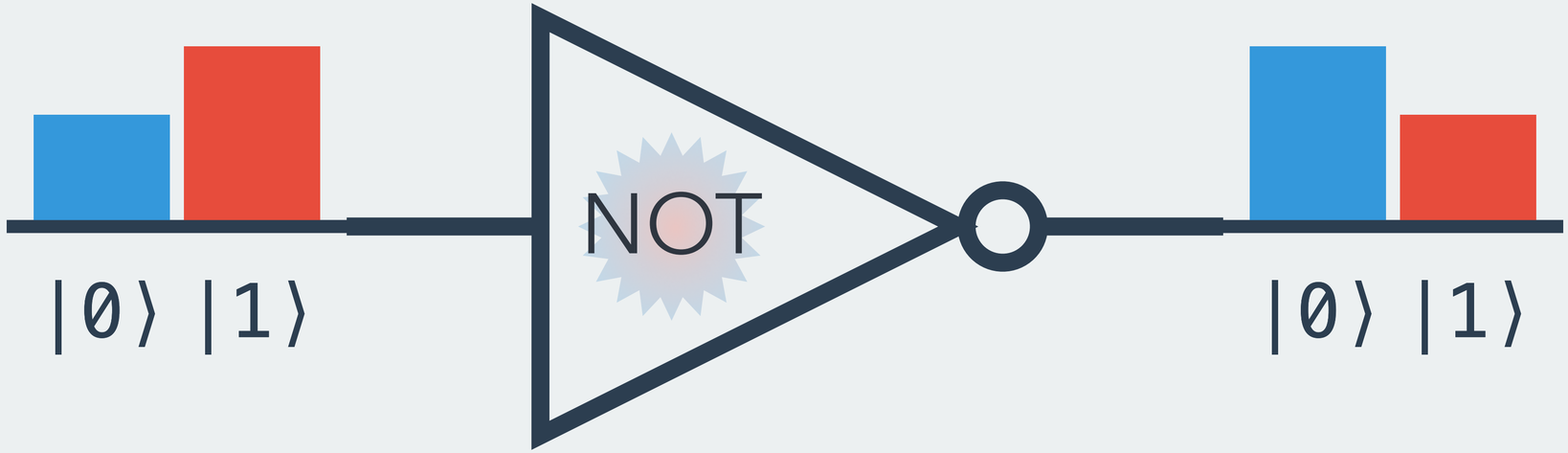
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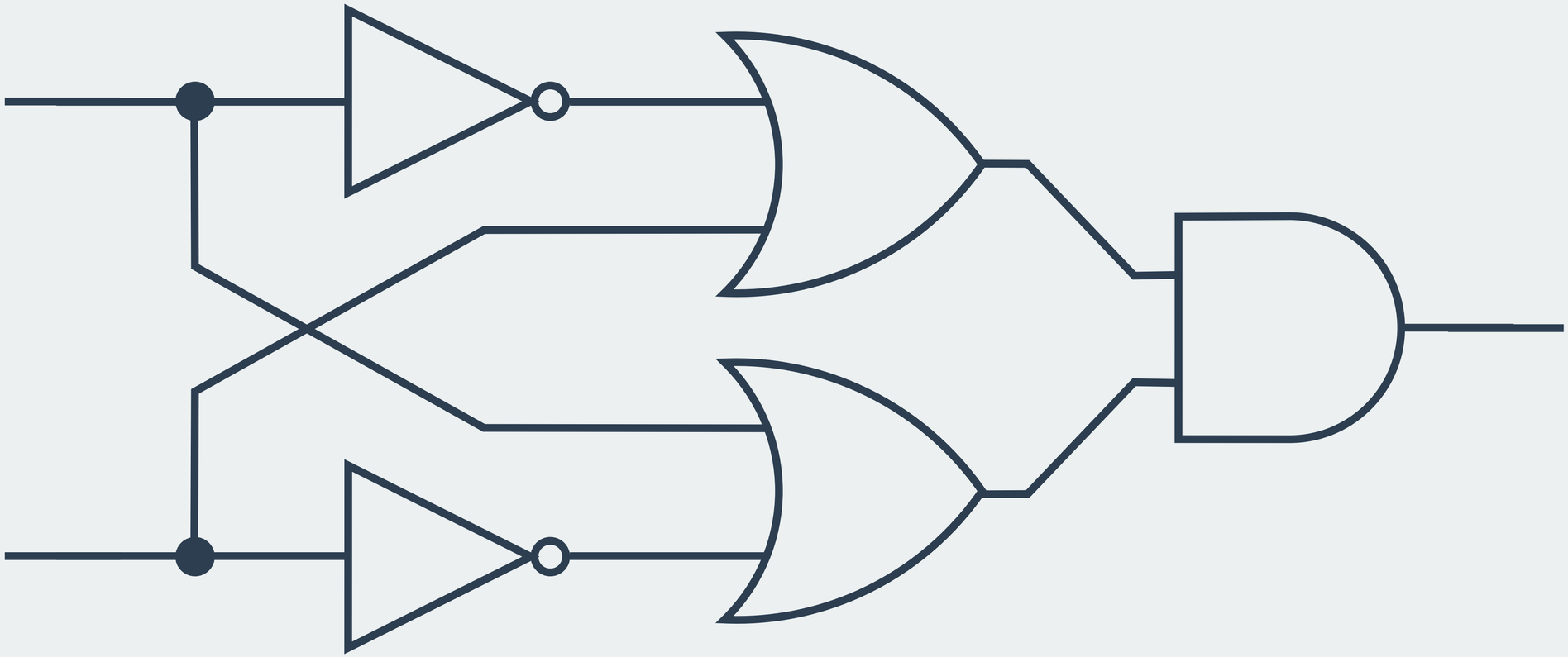
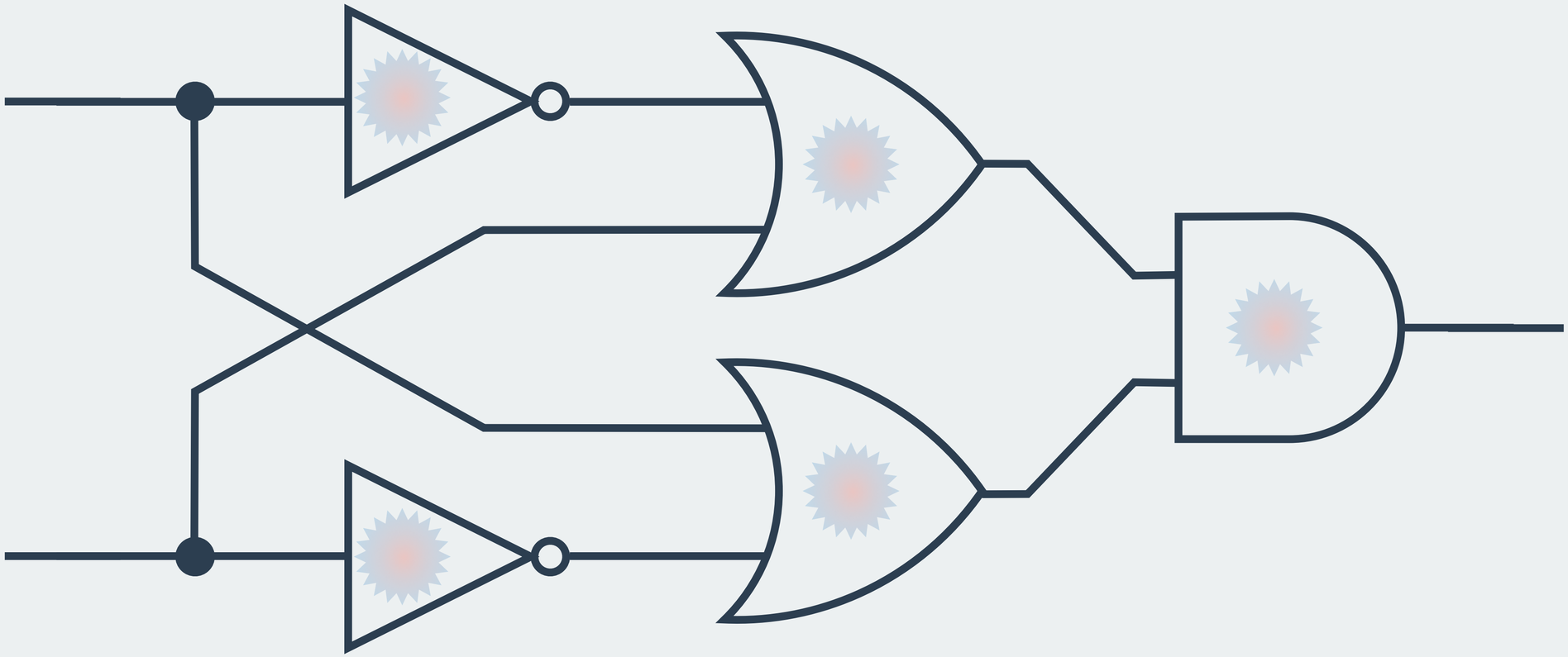
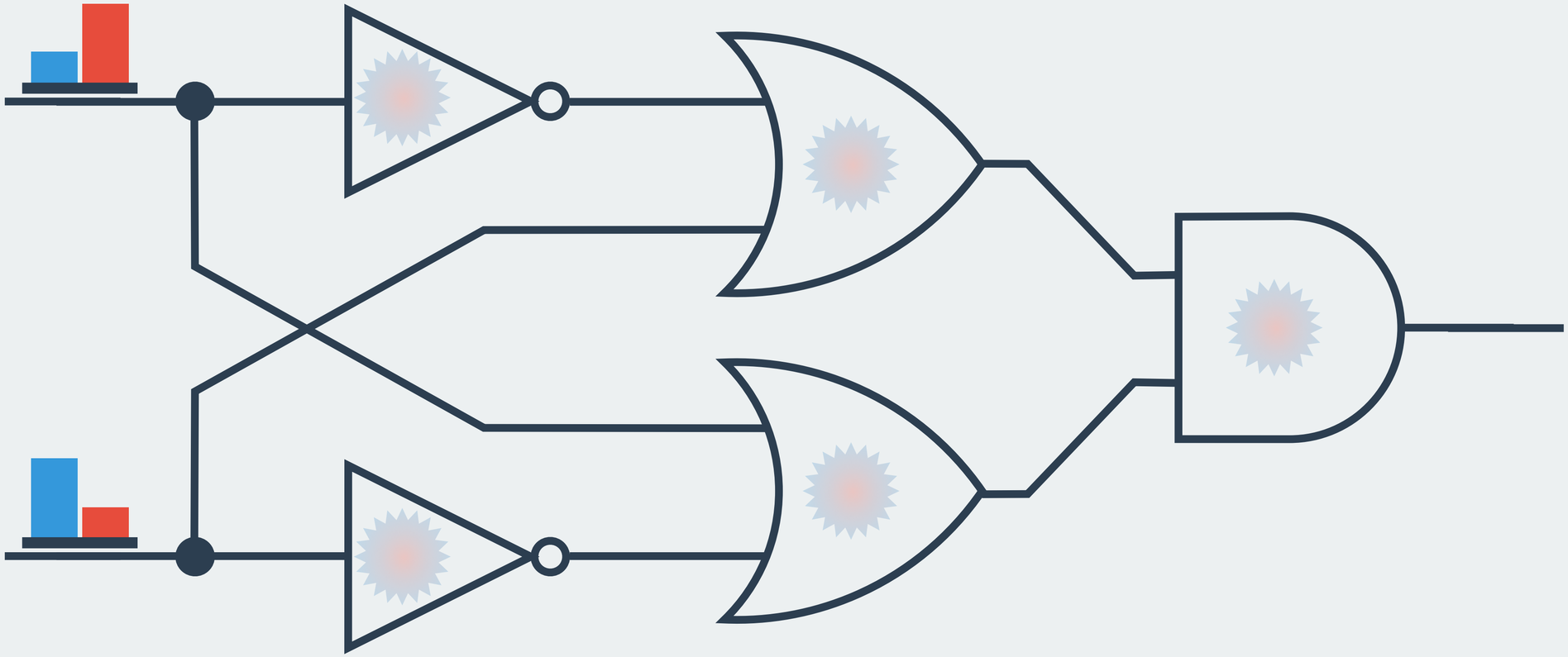
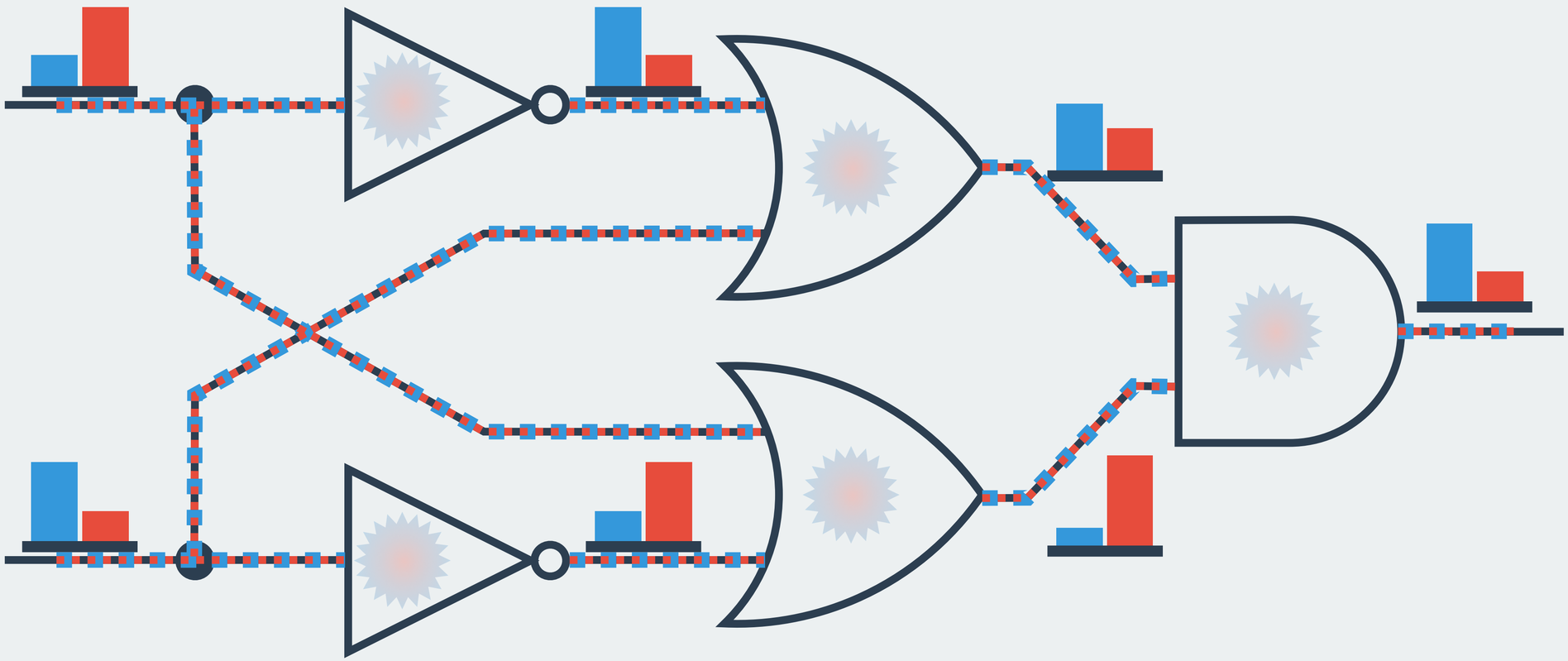
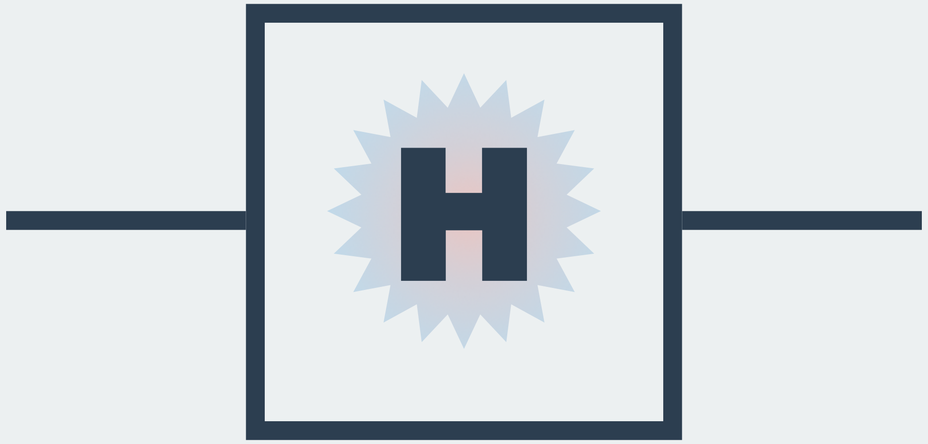
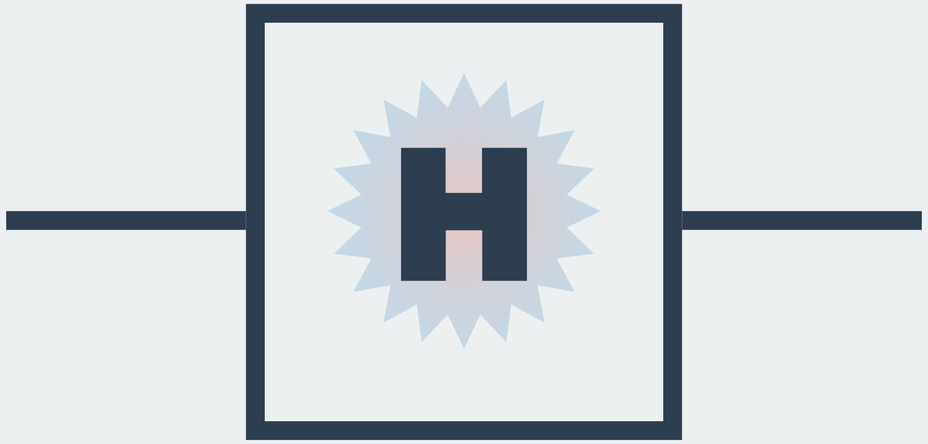




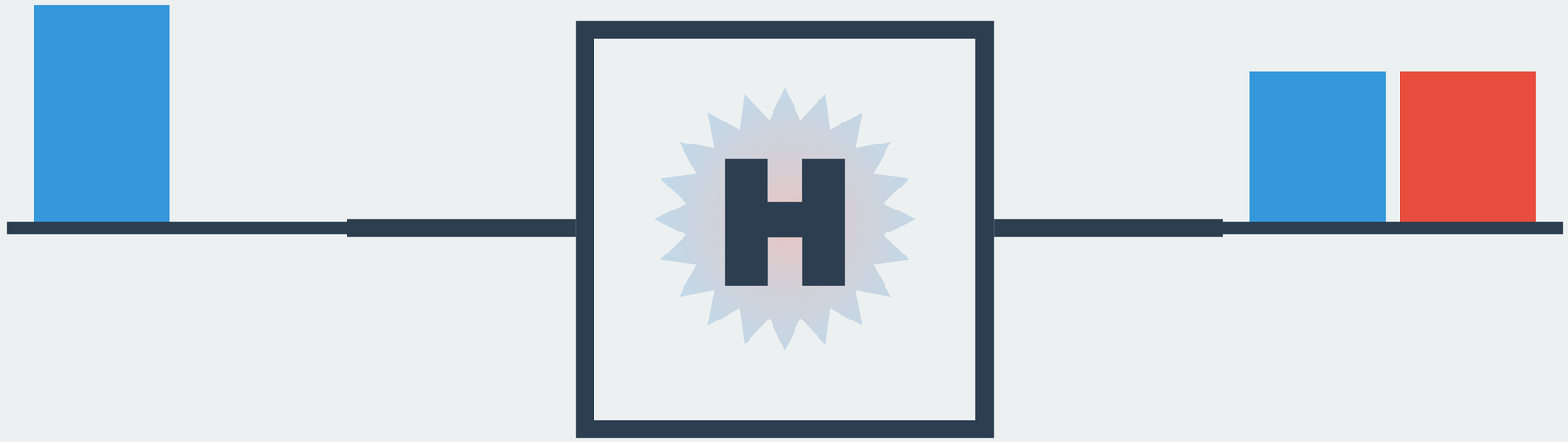








Jacques Hadamard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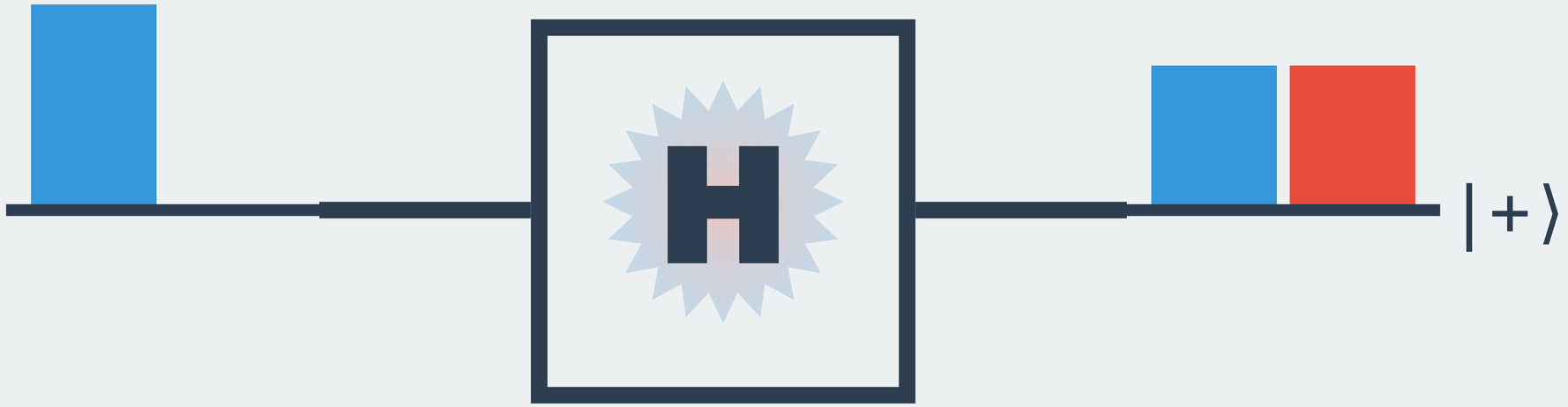
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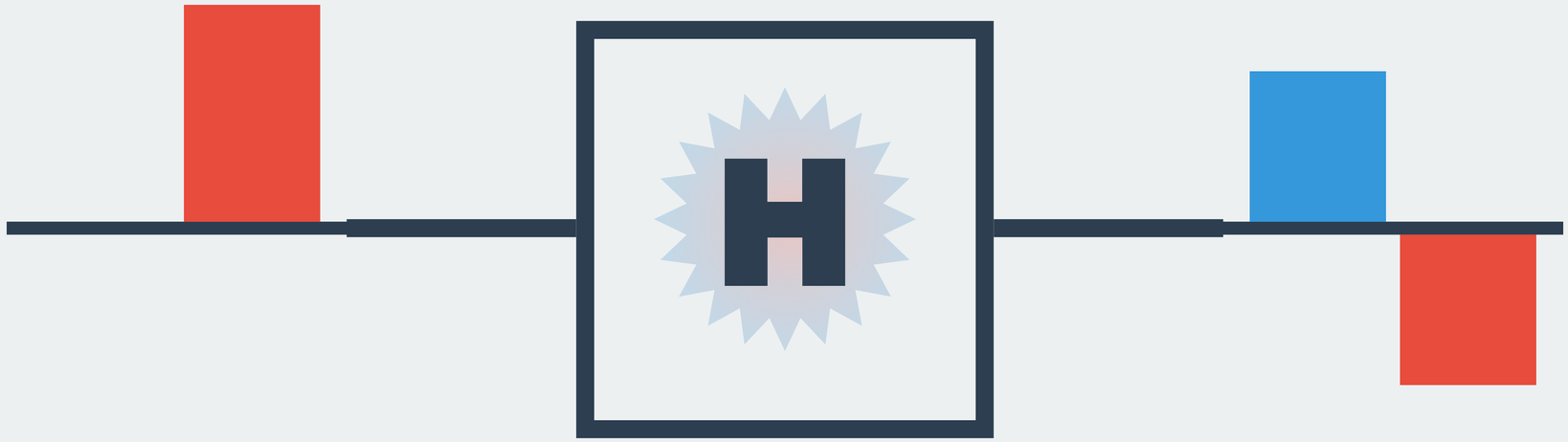
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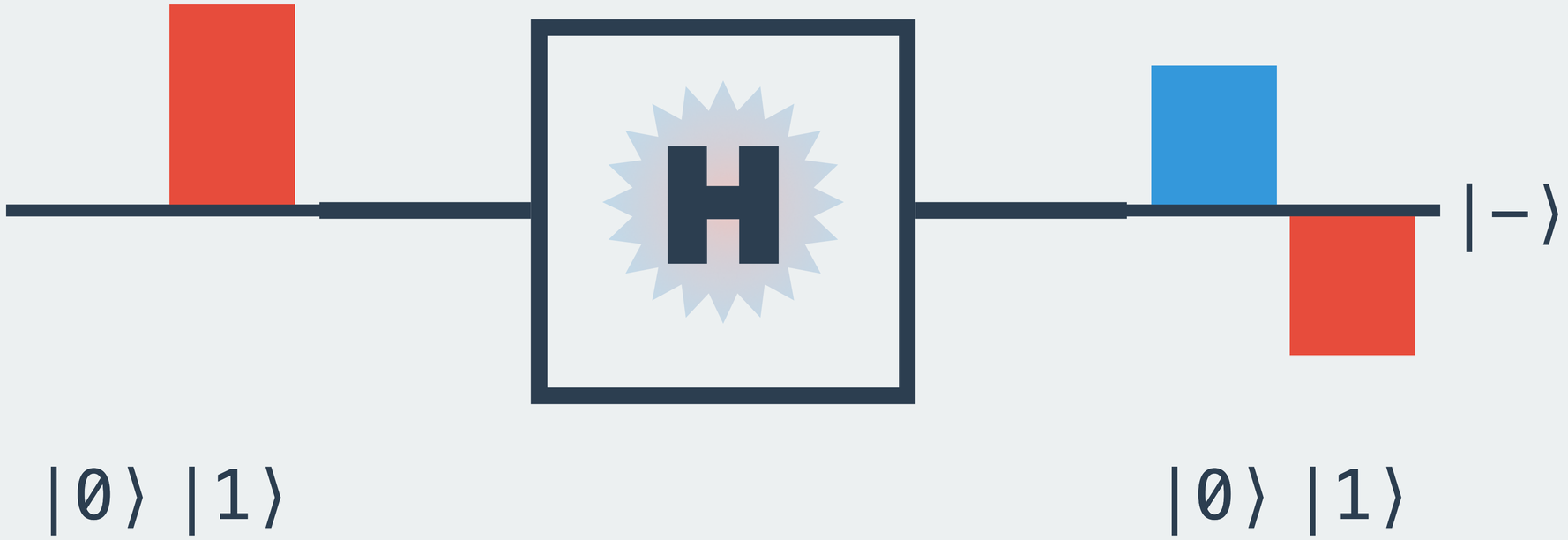
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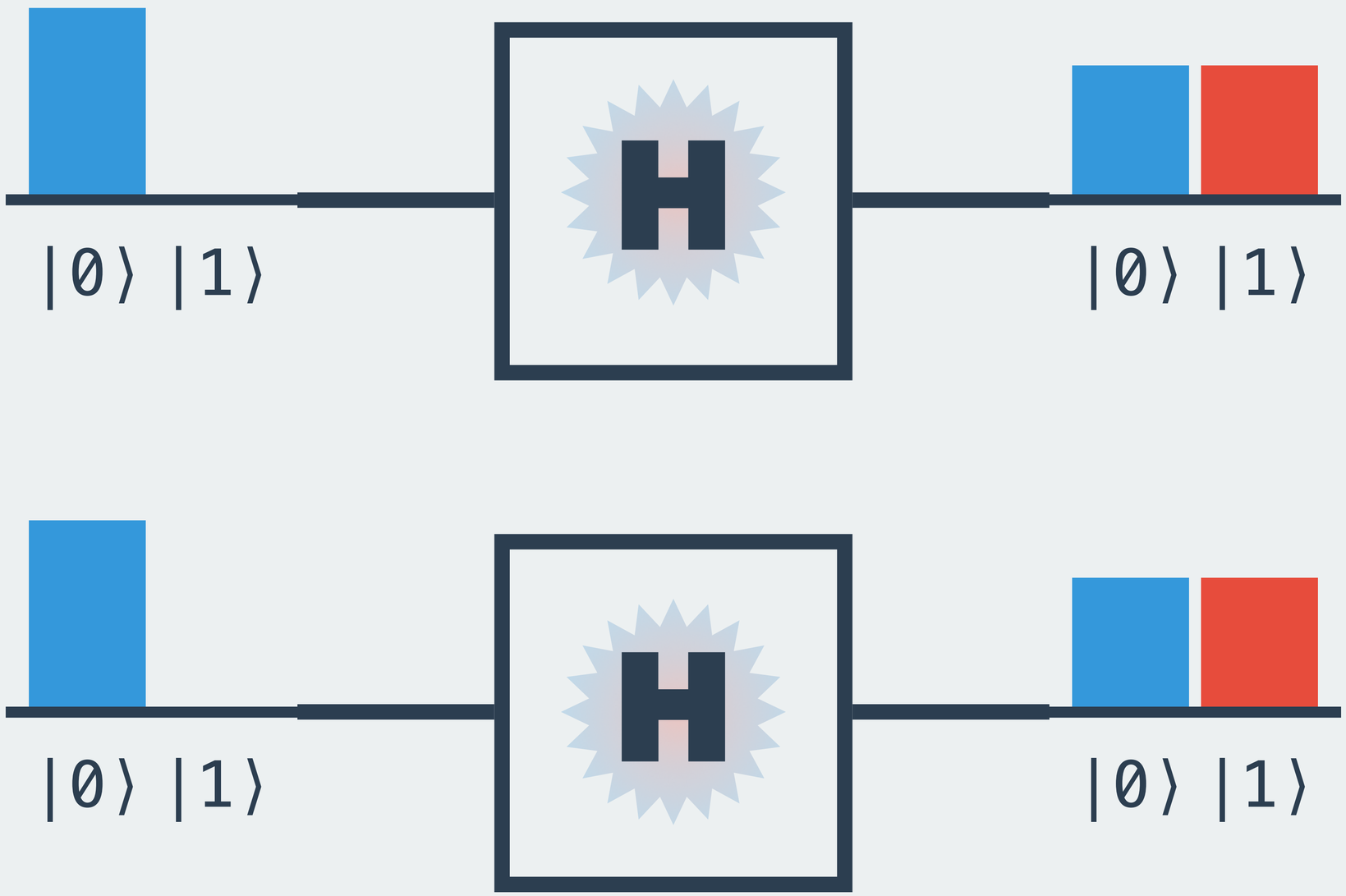
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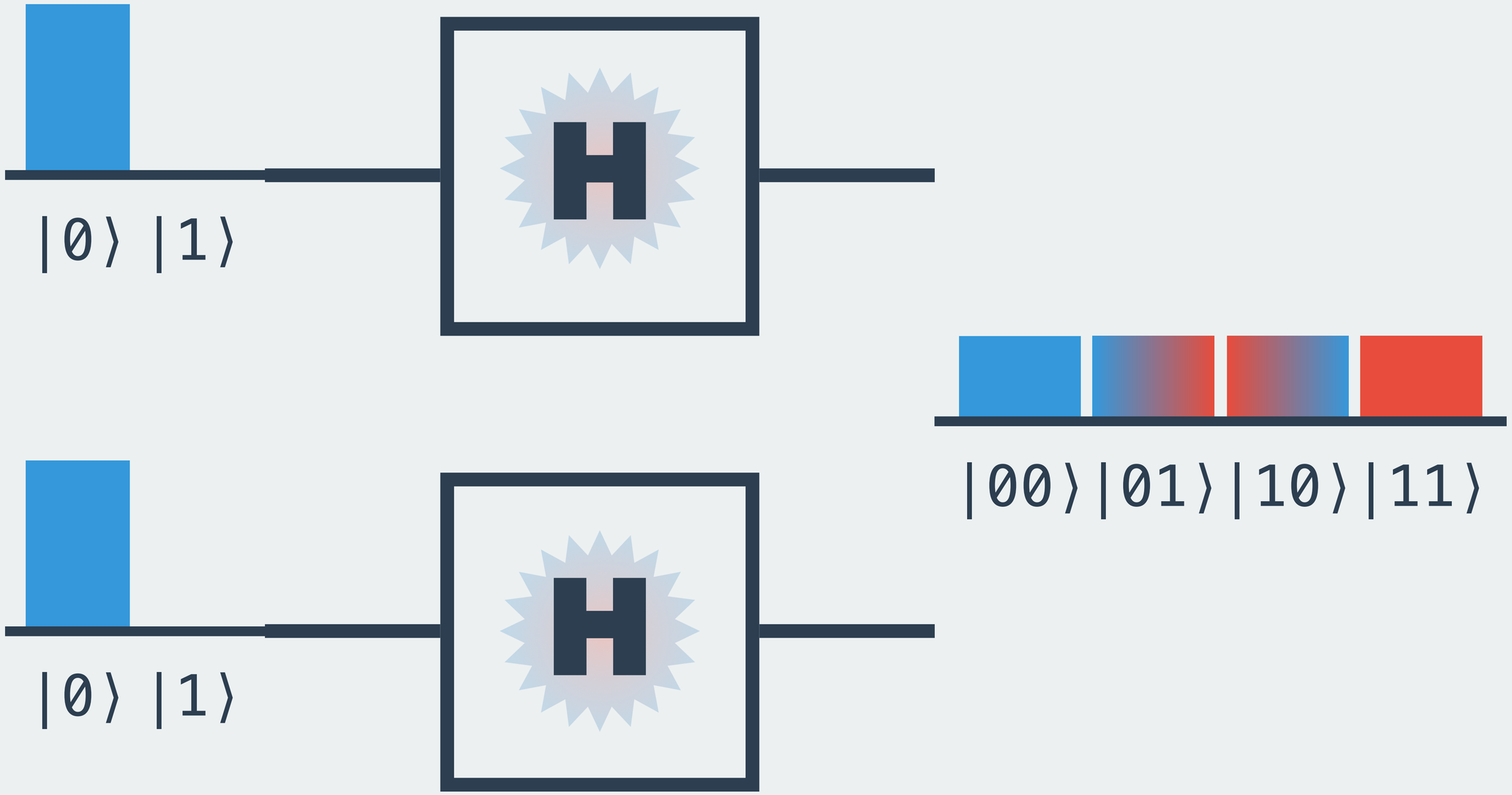
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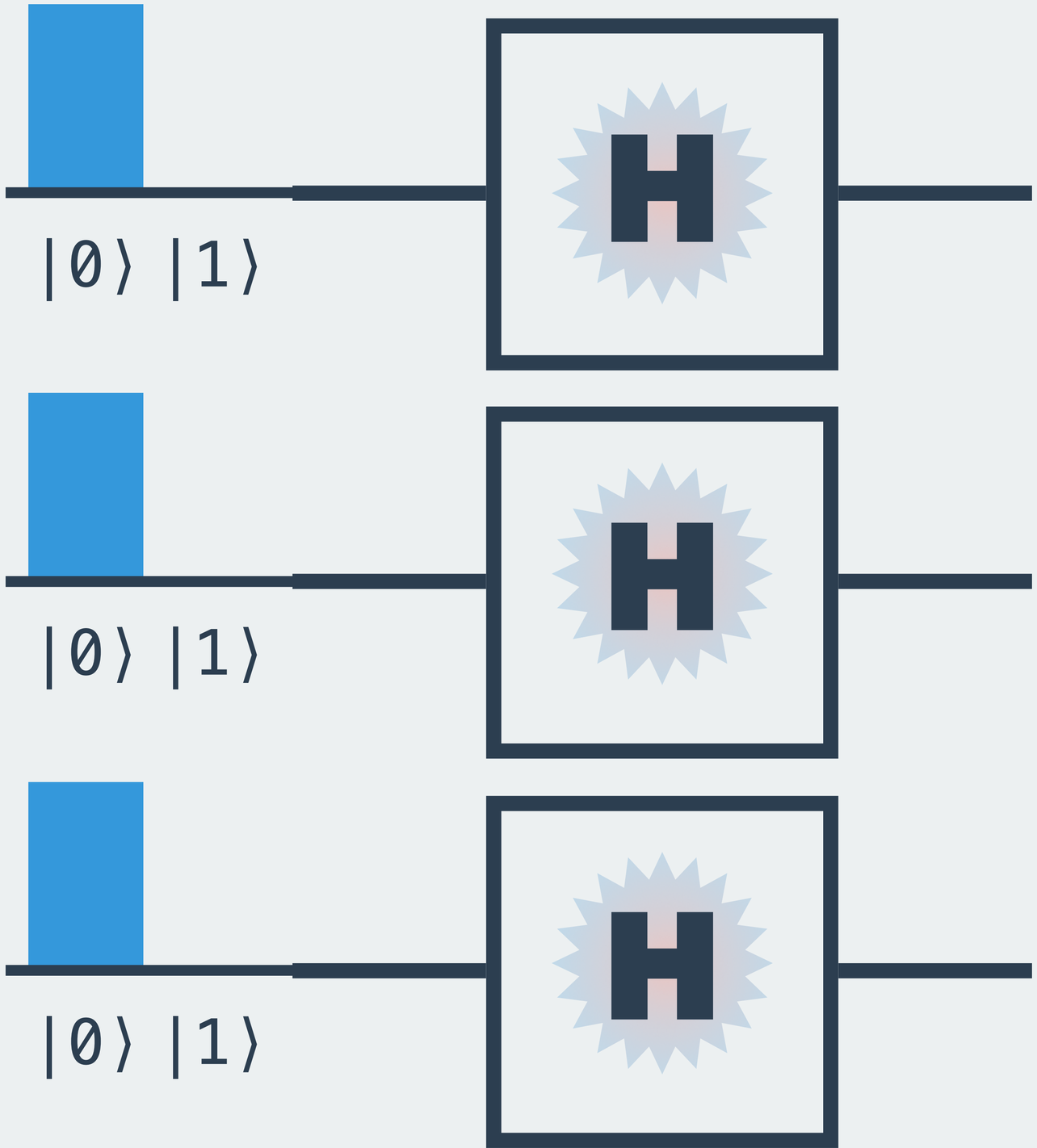
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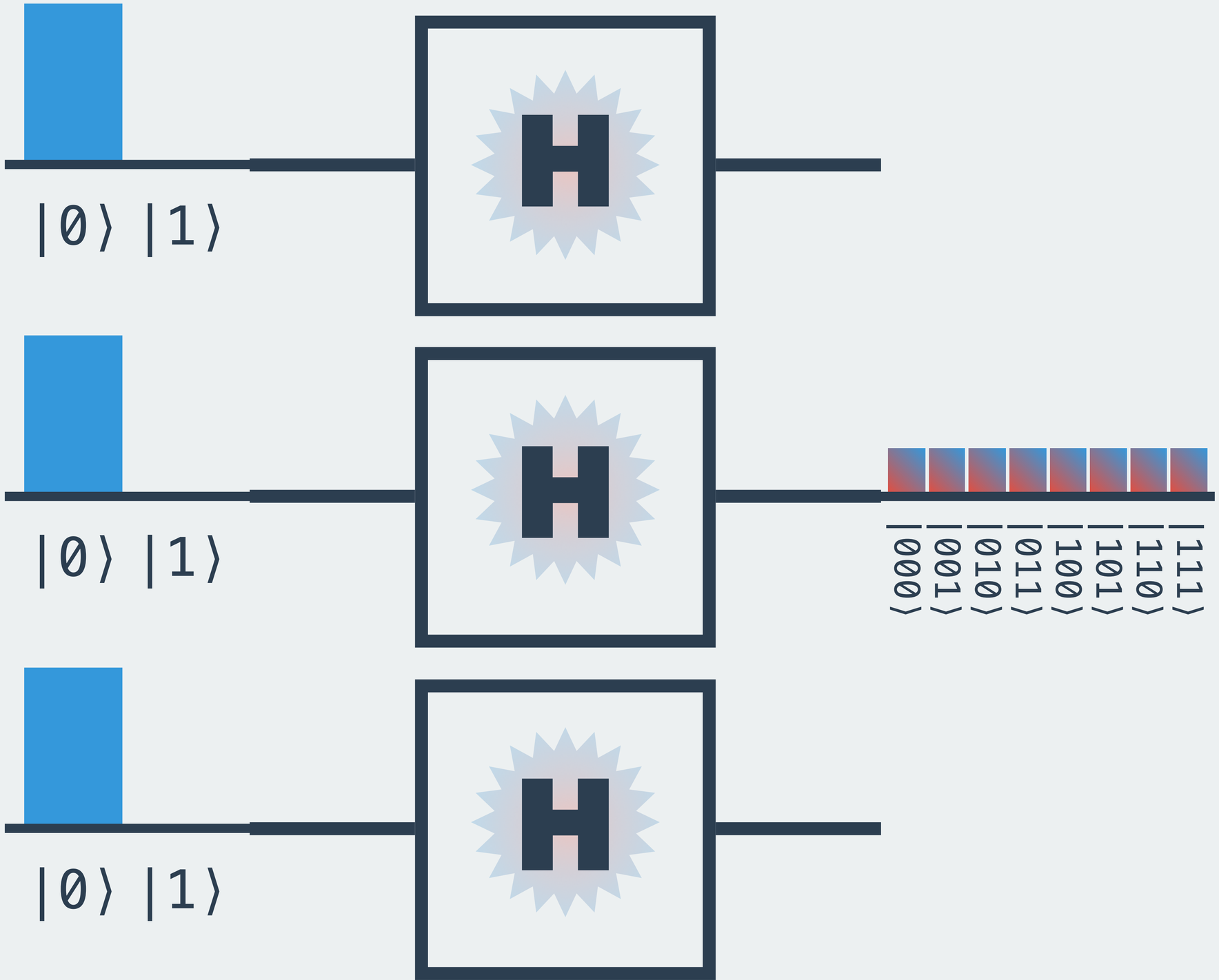
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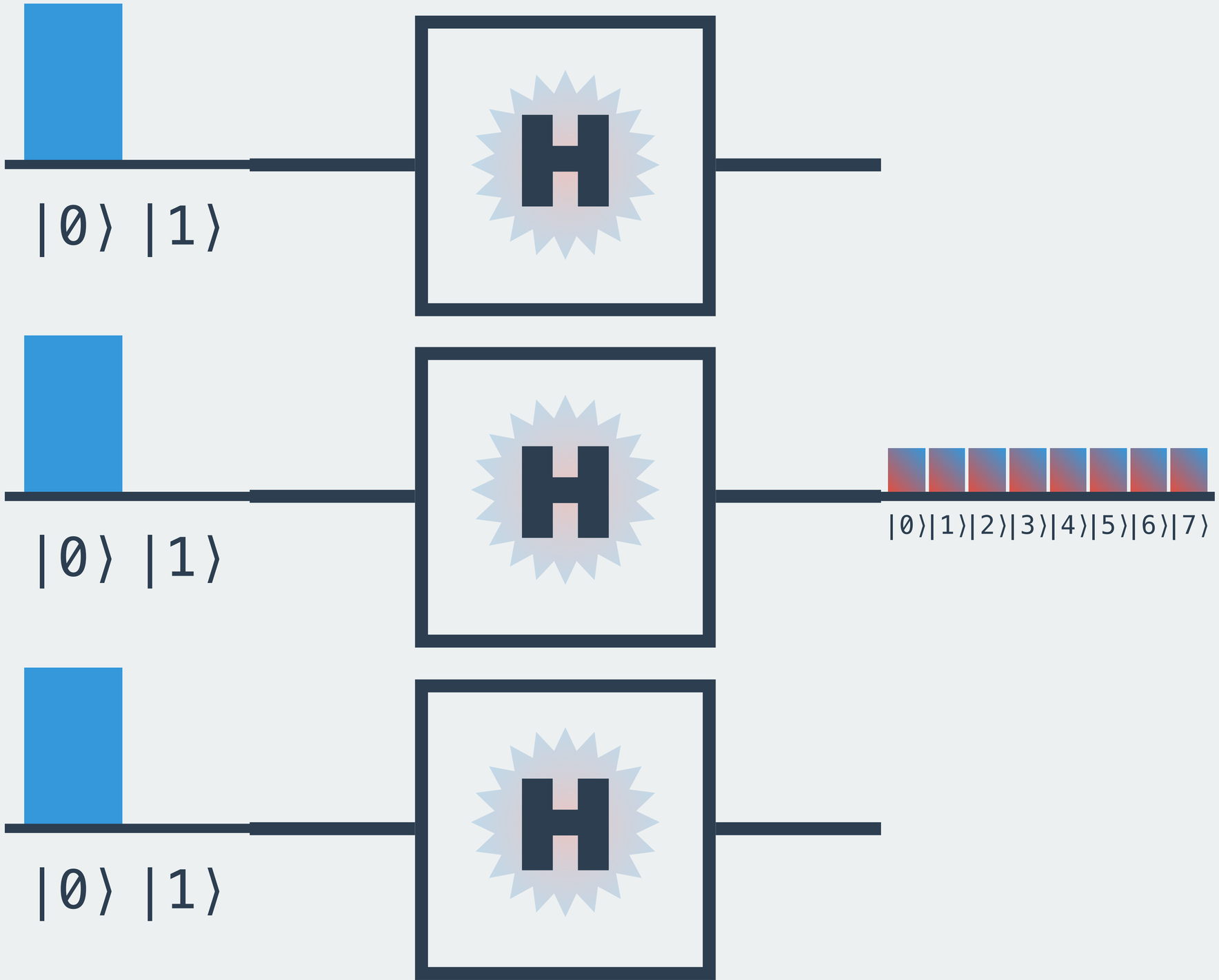
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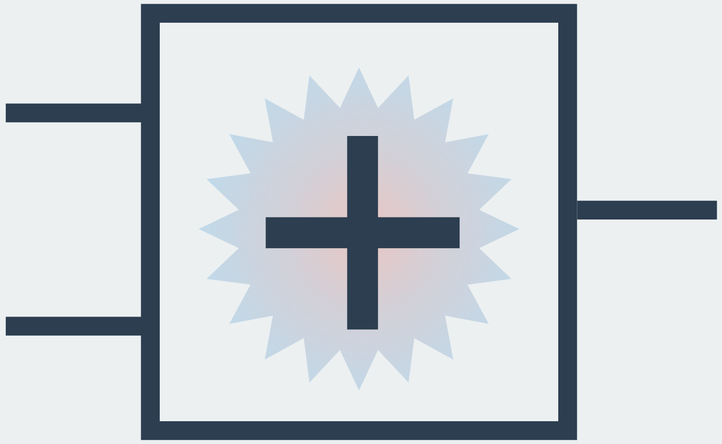

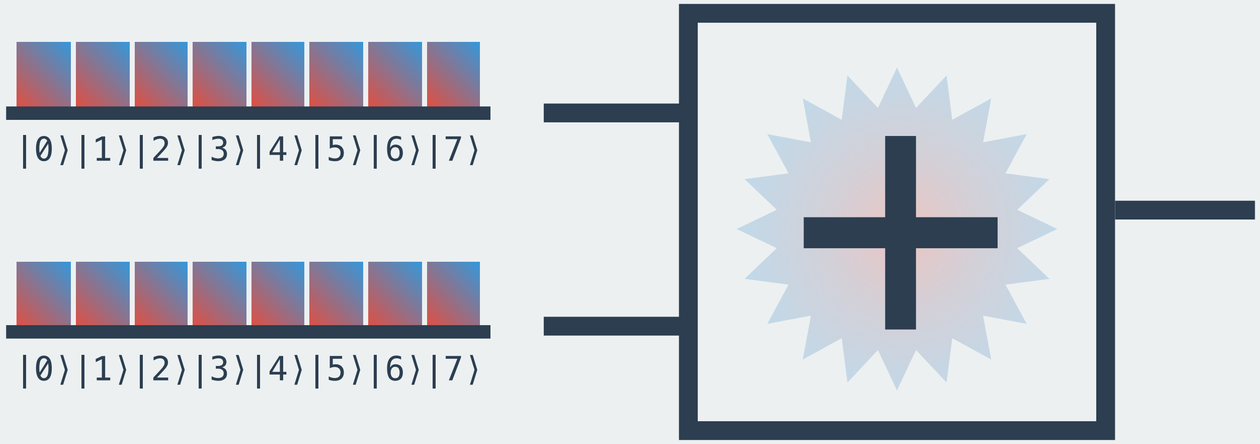
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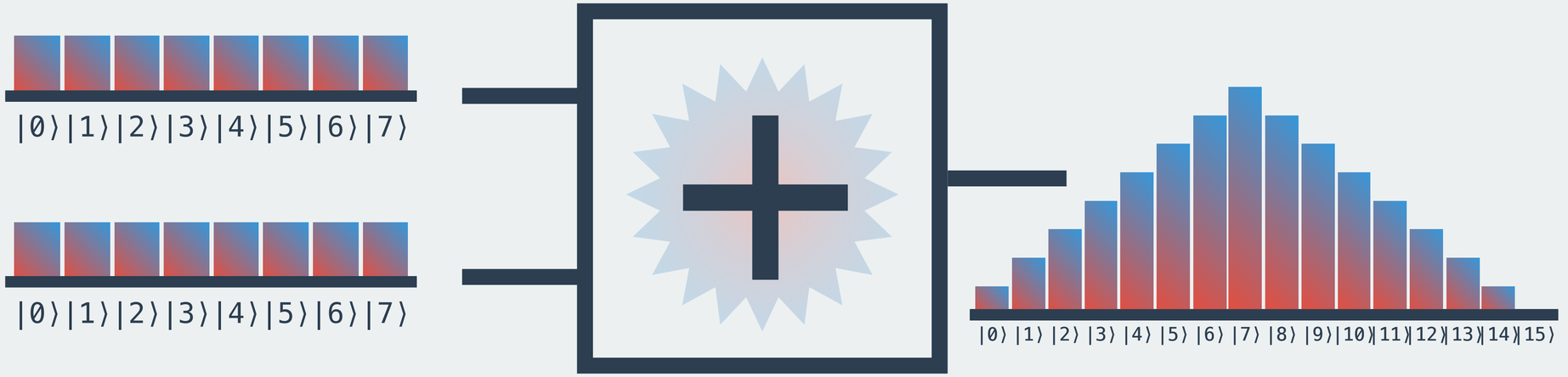
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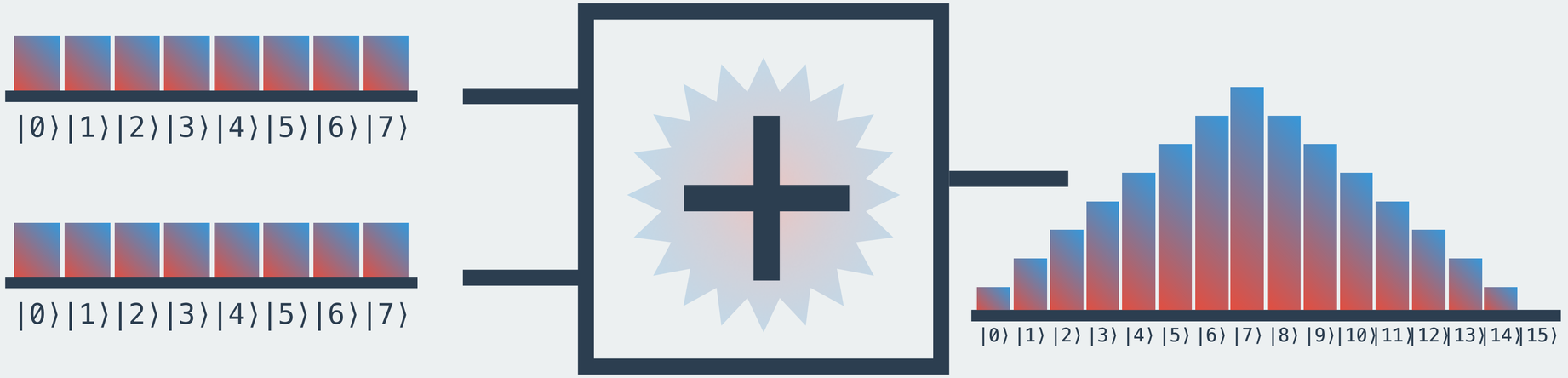
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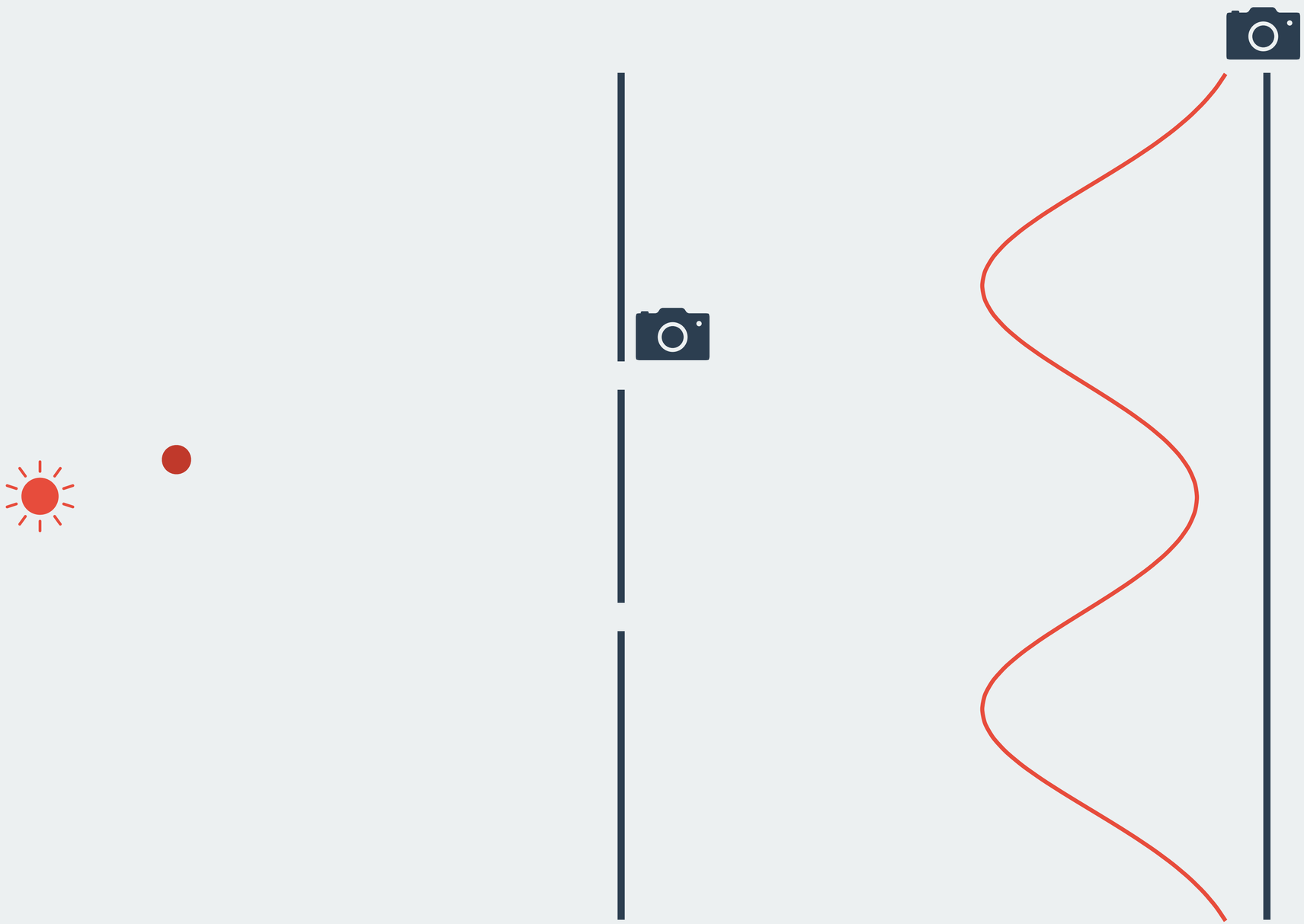

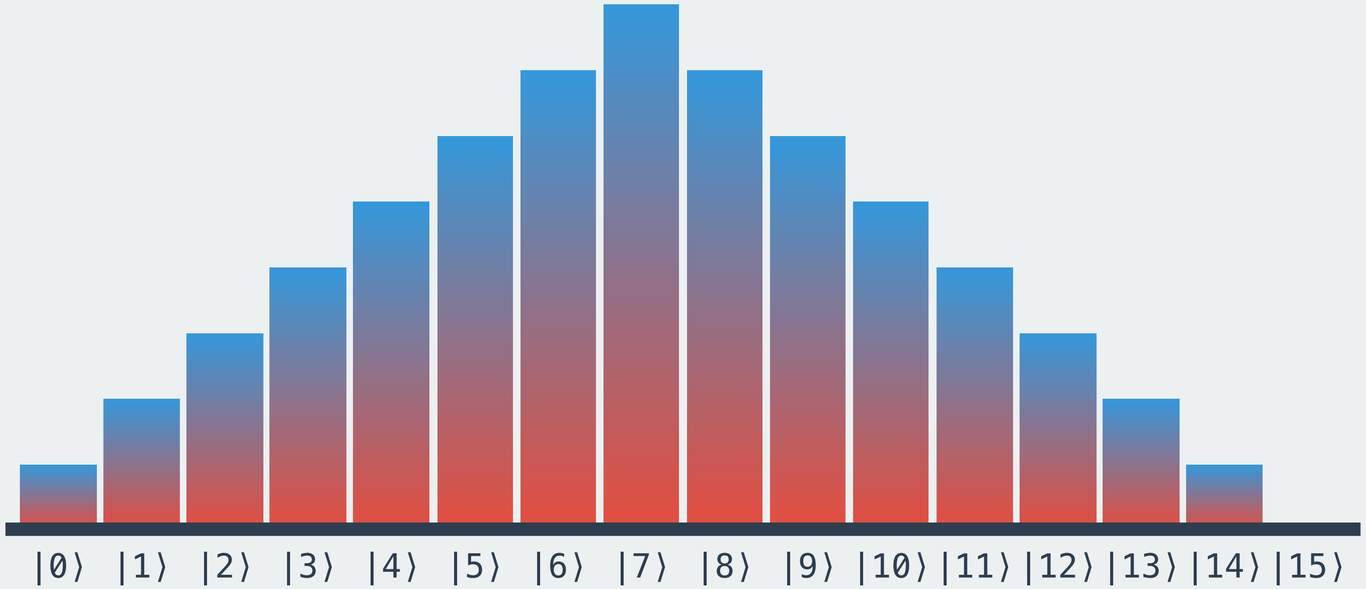
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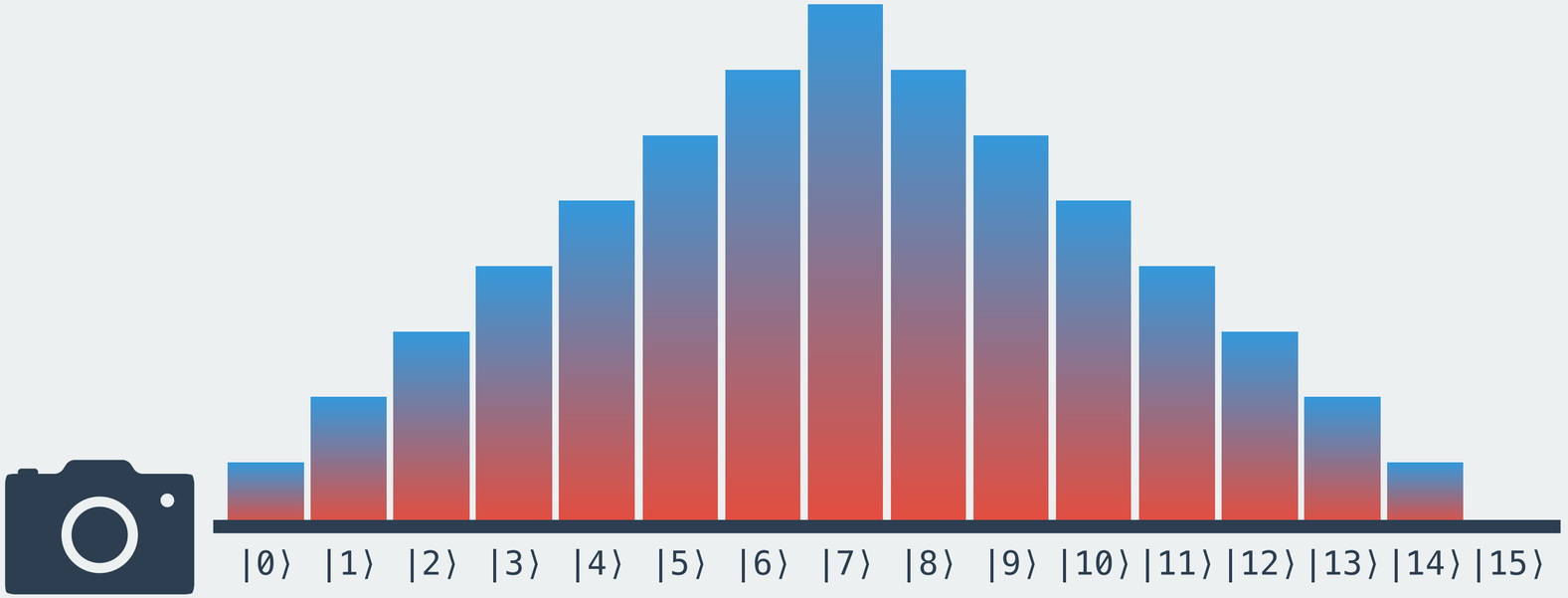
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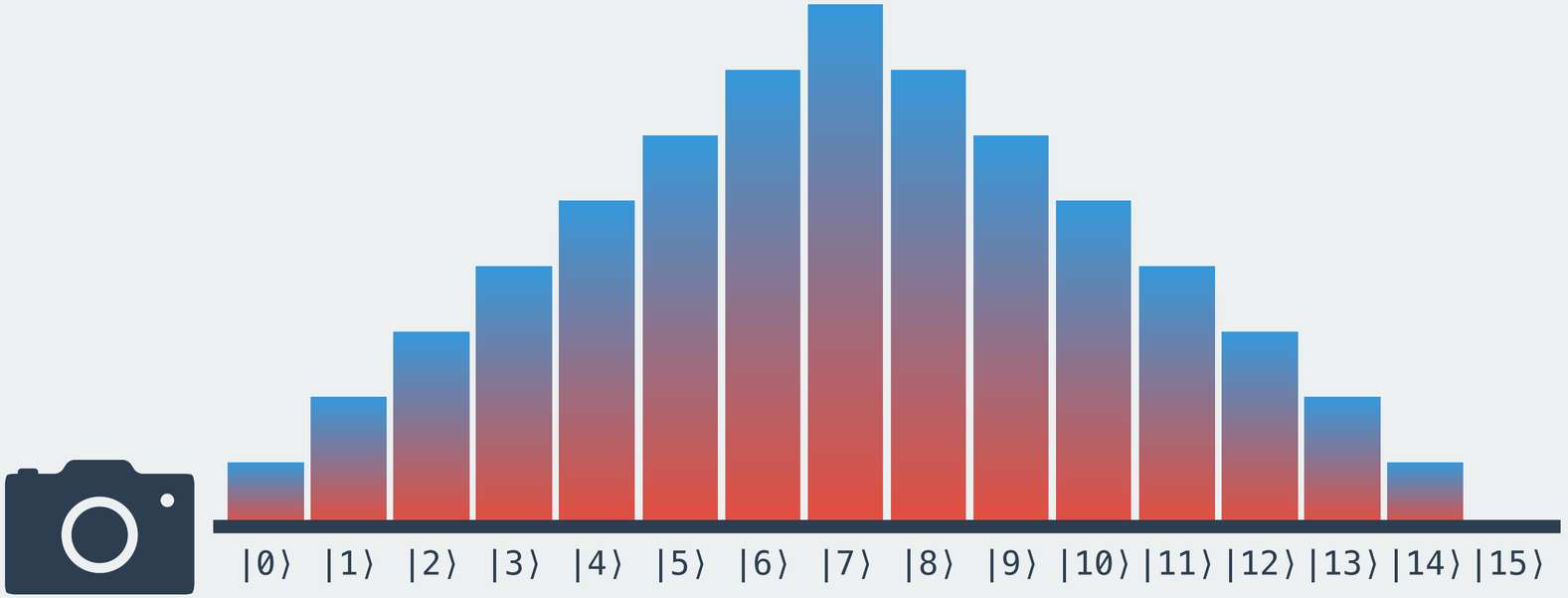
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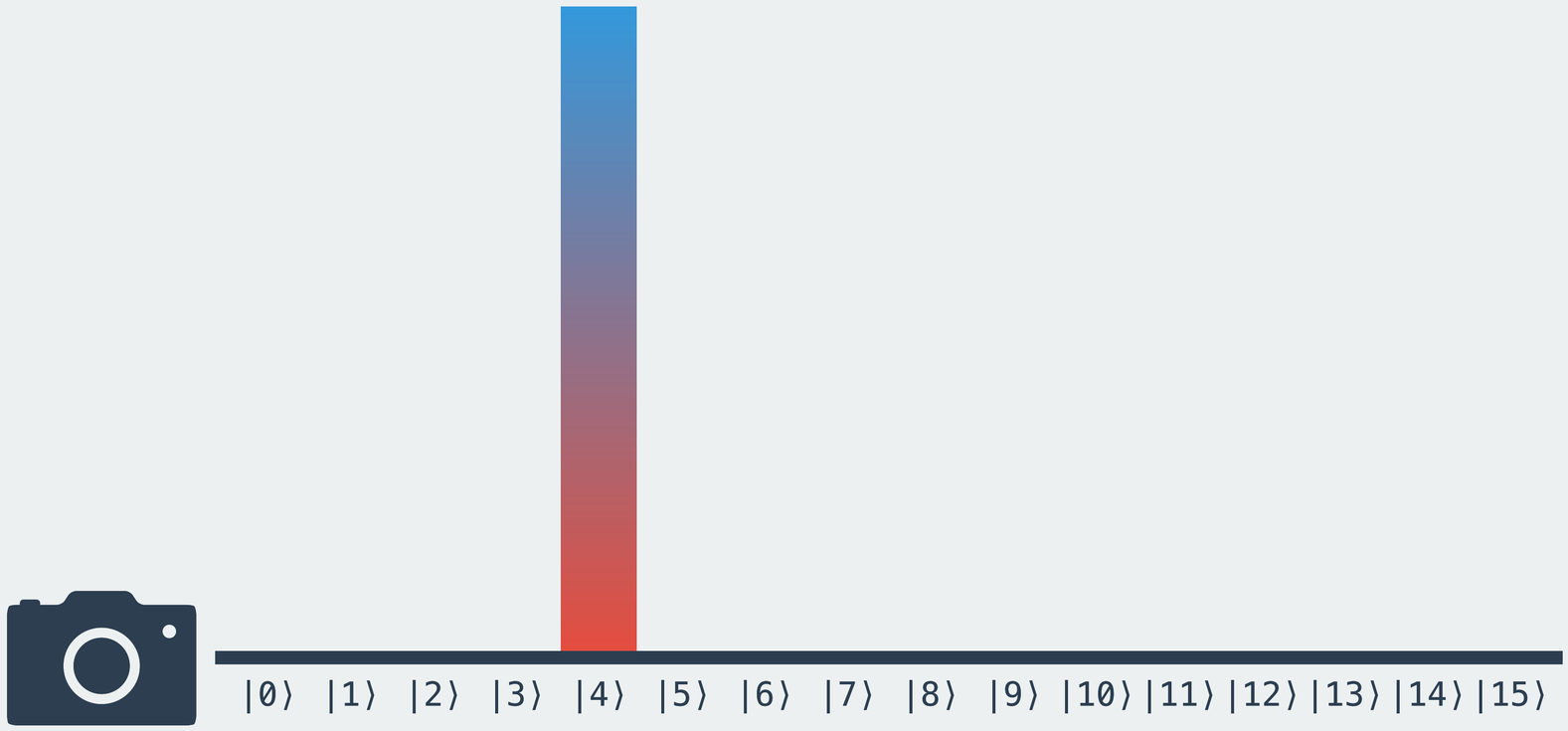
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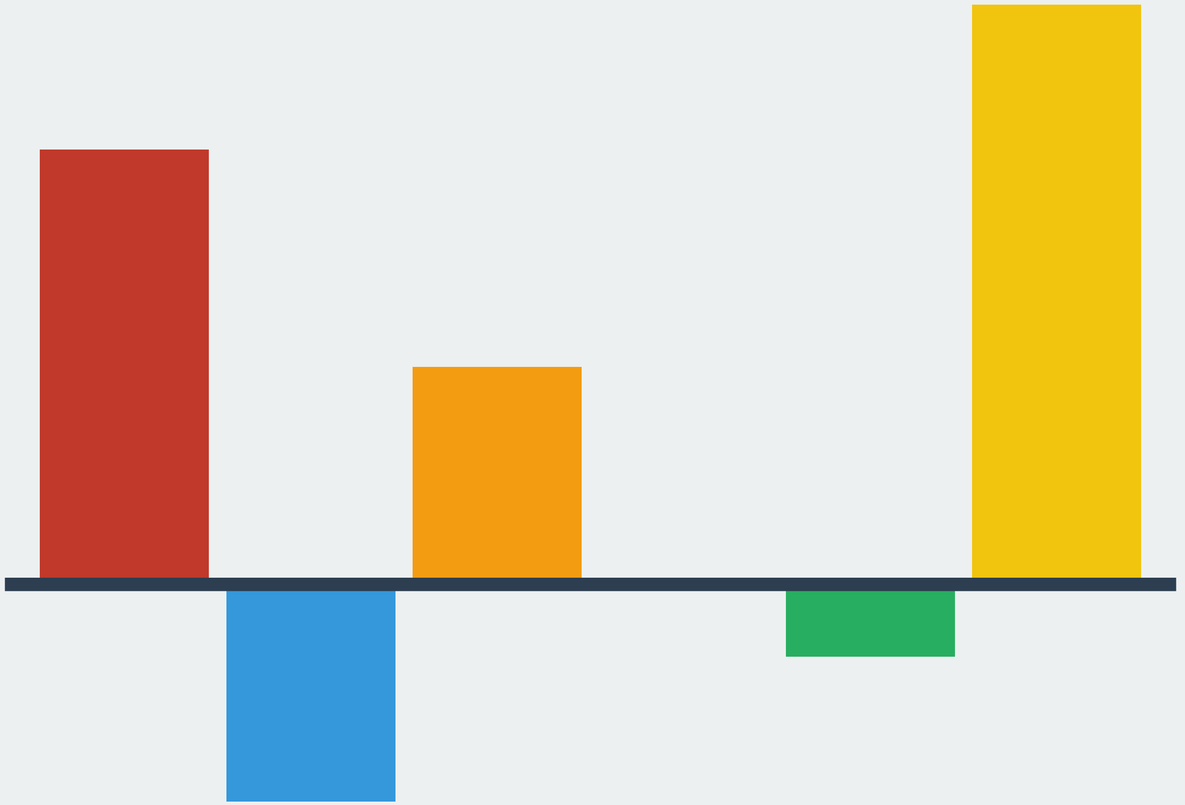
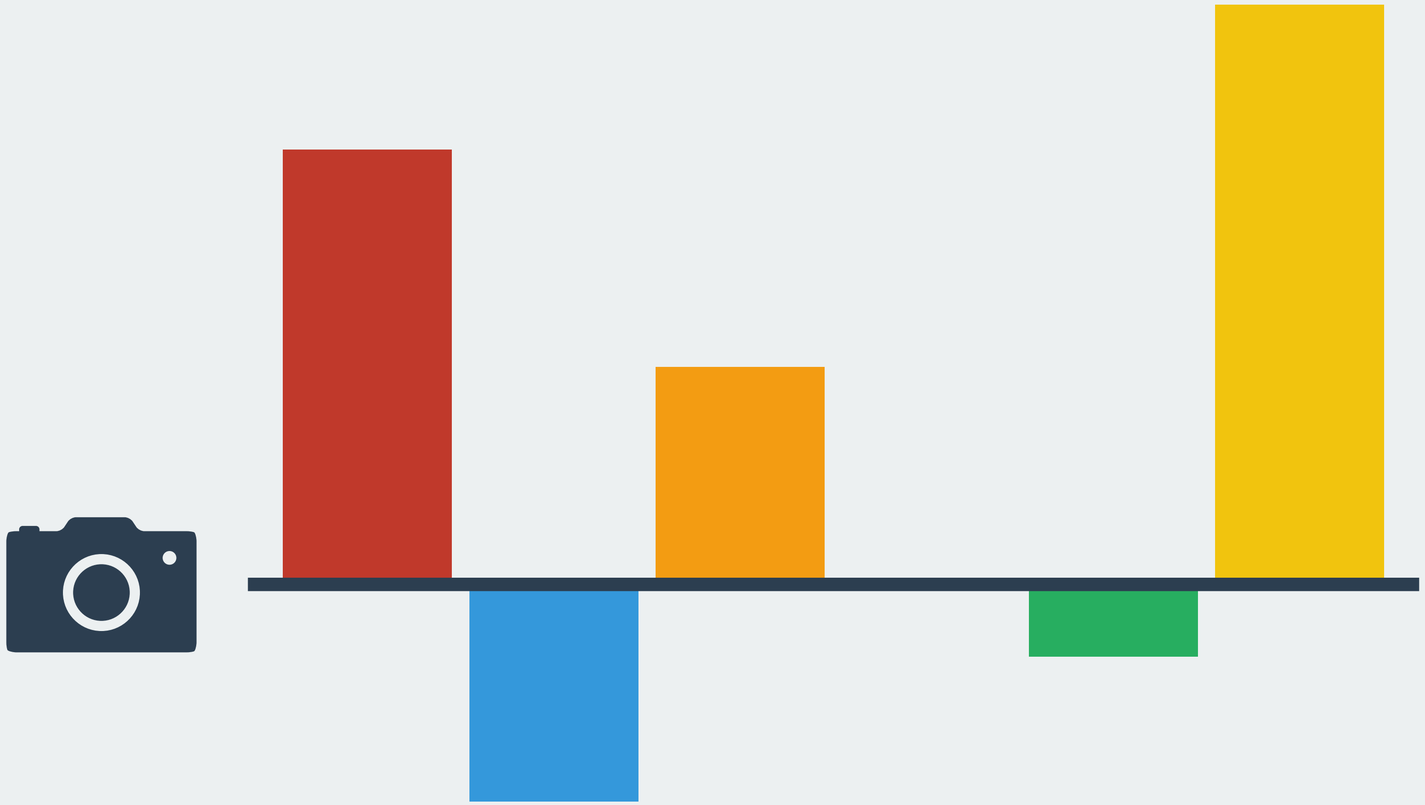
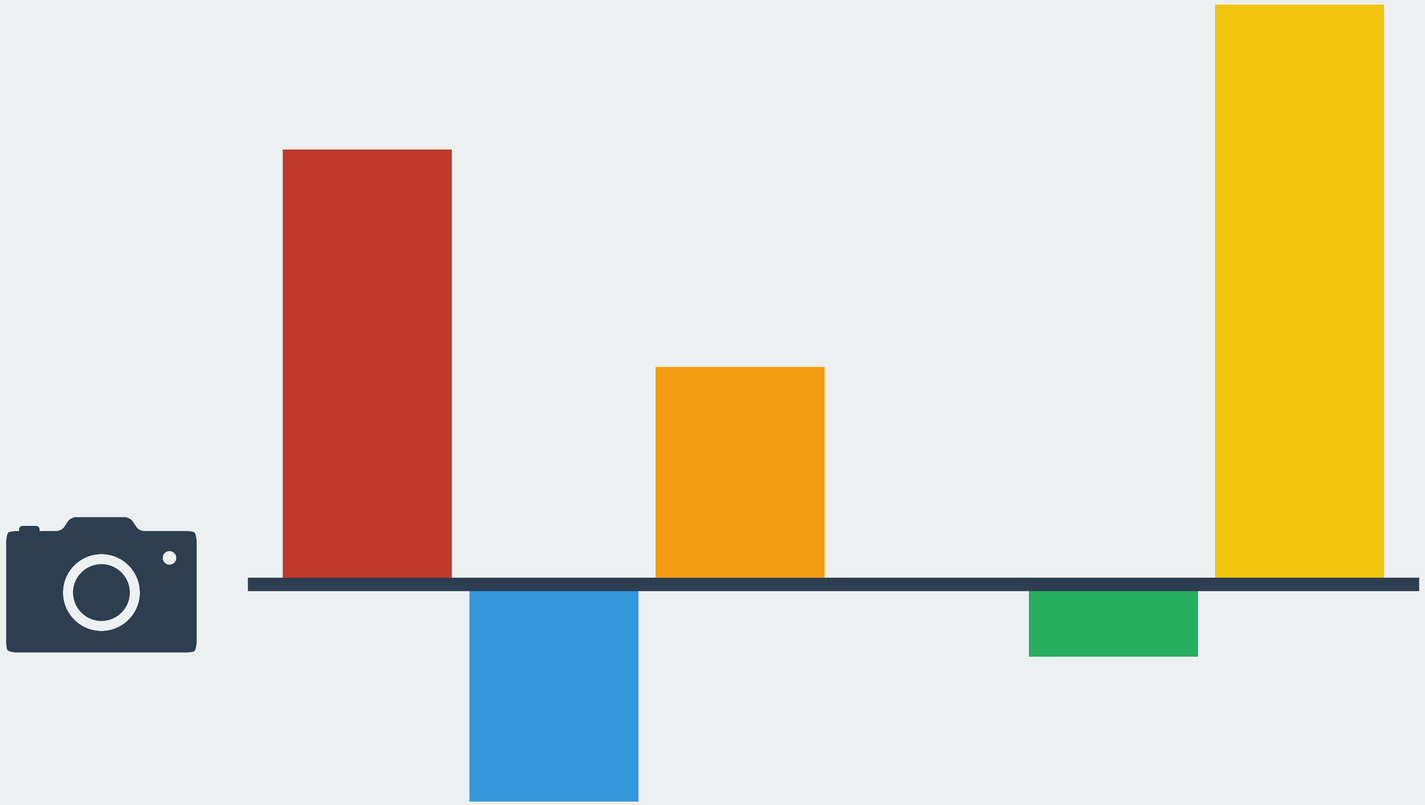


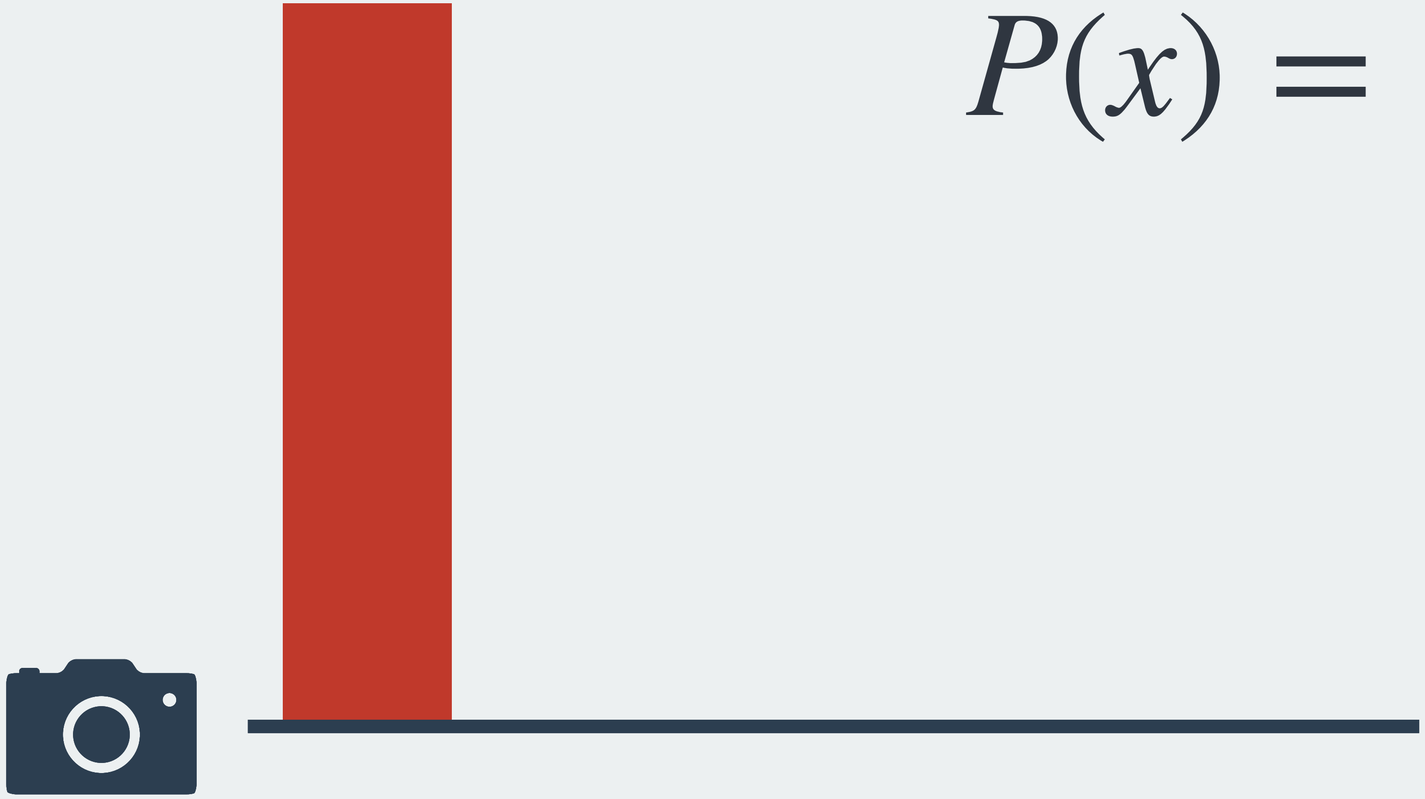


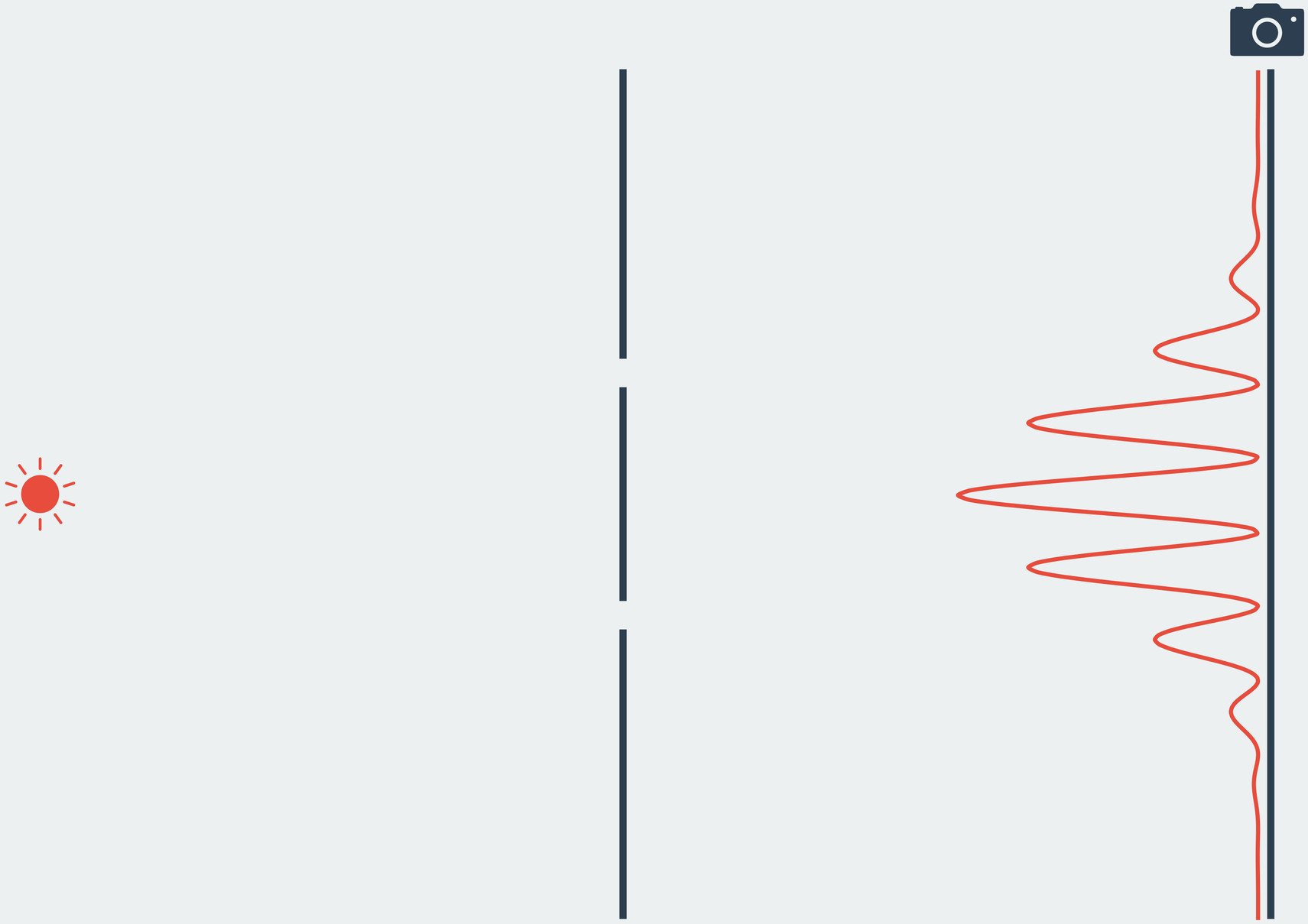


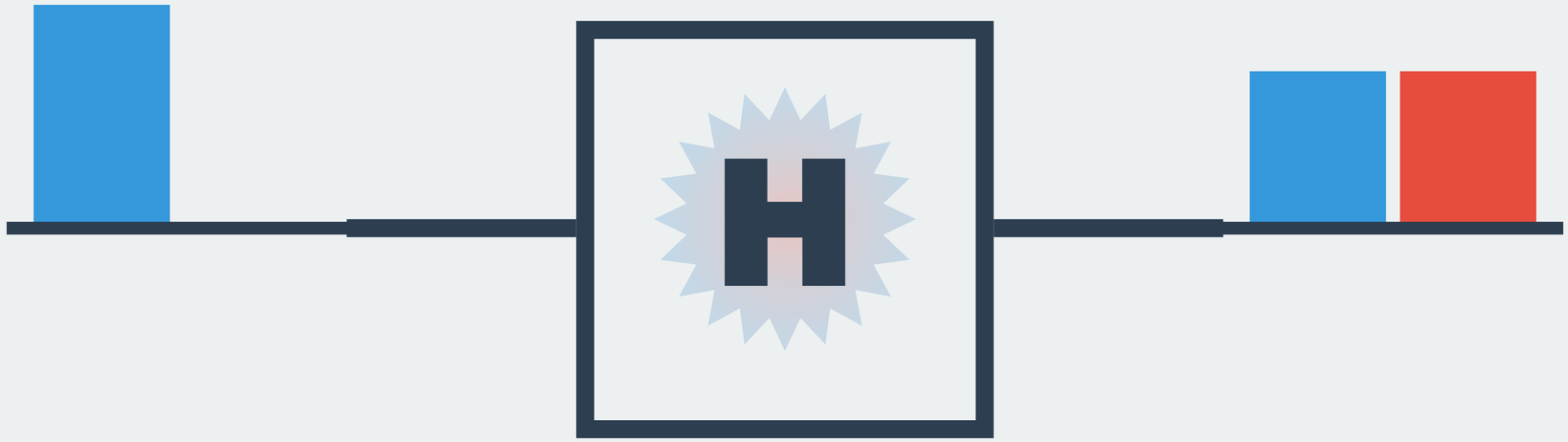
$$|\alpha_1|^2 + \cdots + |\alpha_n|^2 = 1$$

$$|\alpha_1|^2 + \cdots + |\alpha_n|^2 = 1$$

$$P(x) = |\alpha_x|^2$$



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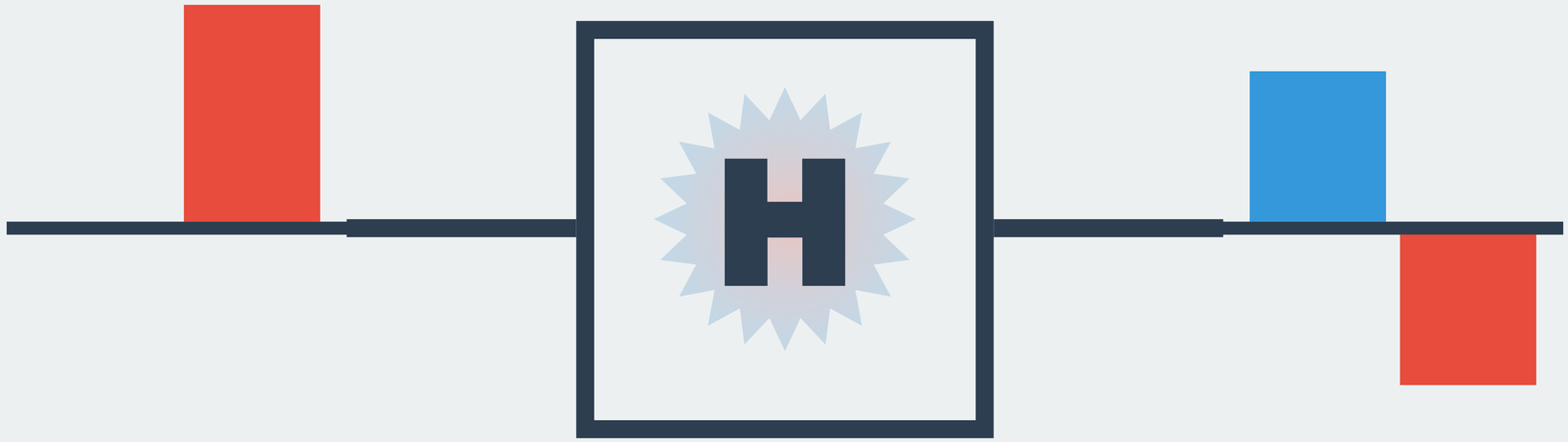
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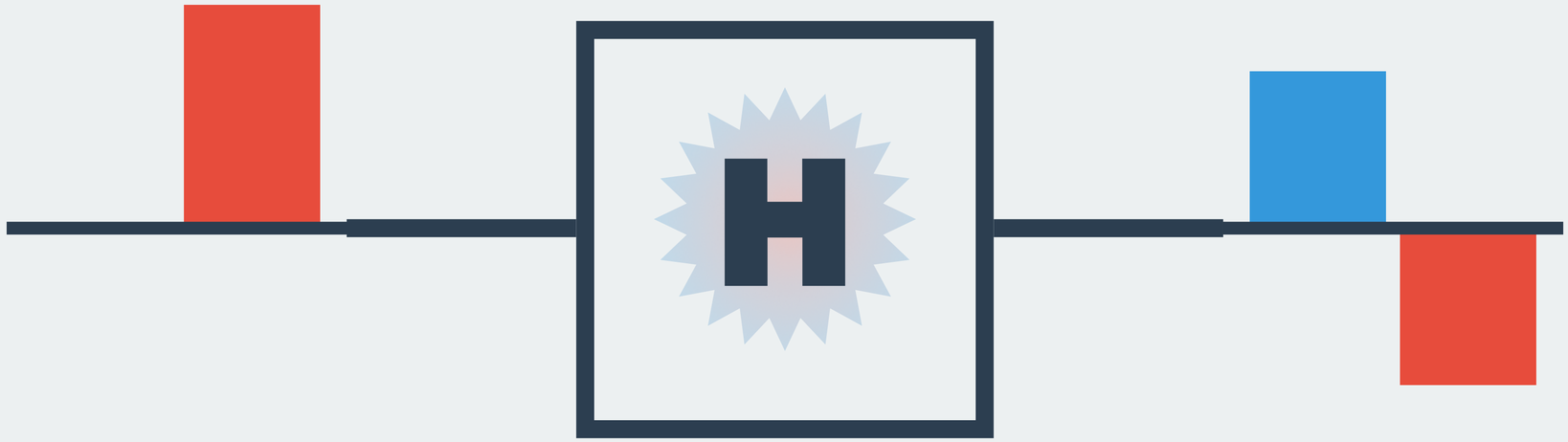
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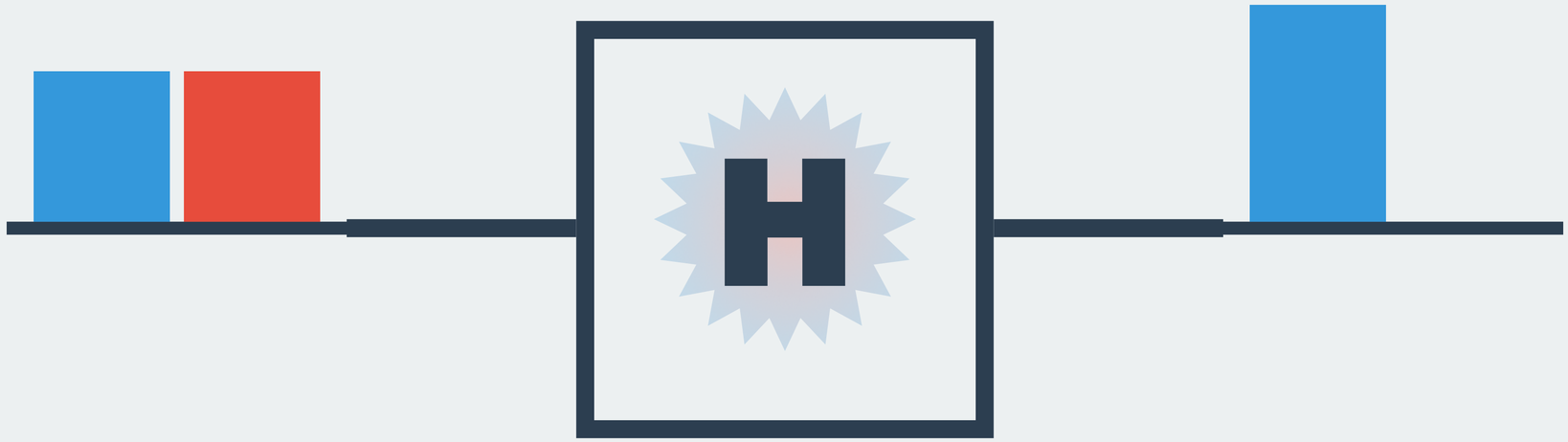
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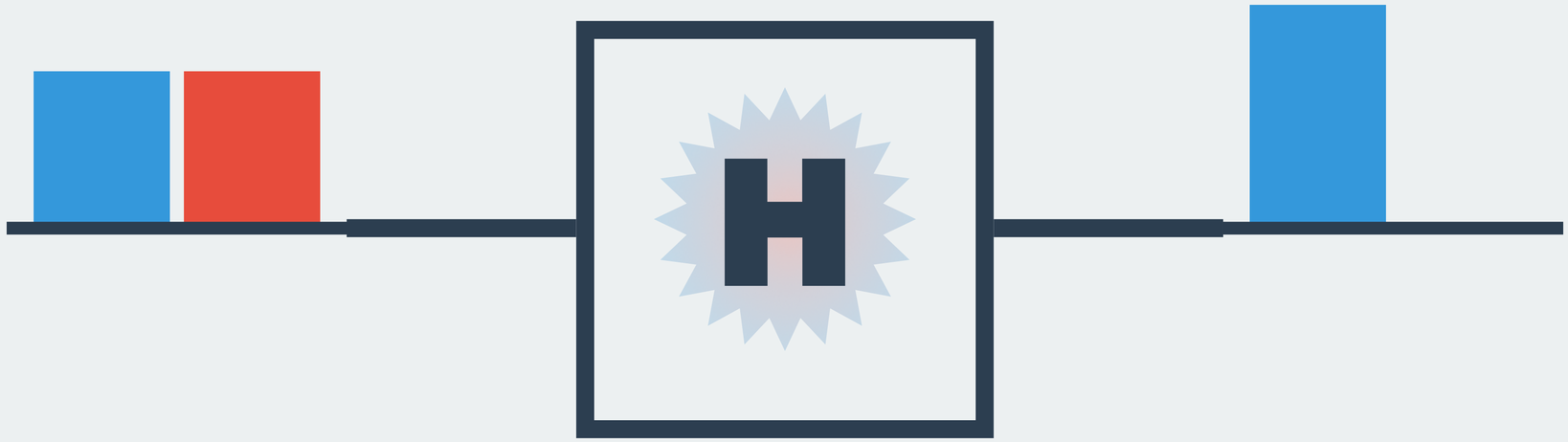
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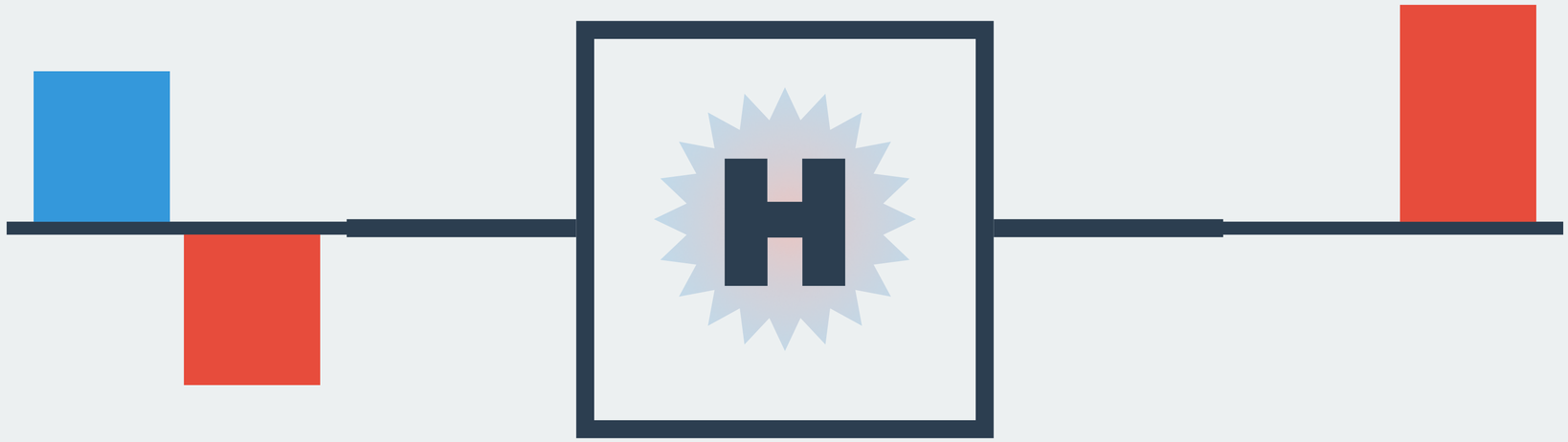
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DEUTSCHEV ALGORITEM

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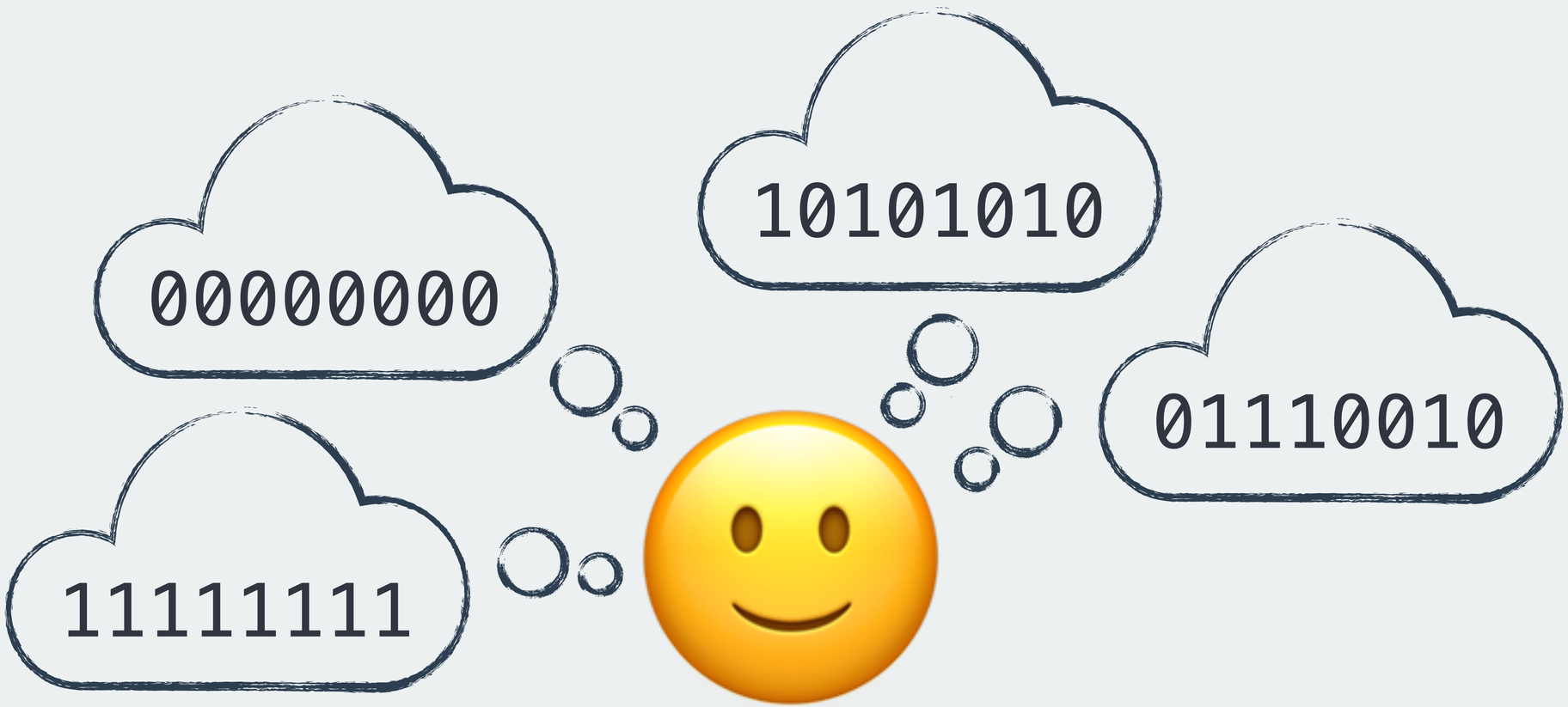
1953-

David Deutsch
1953-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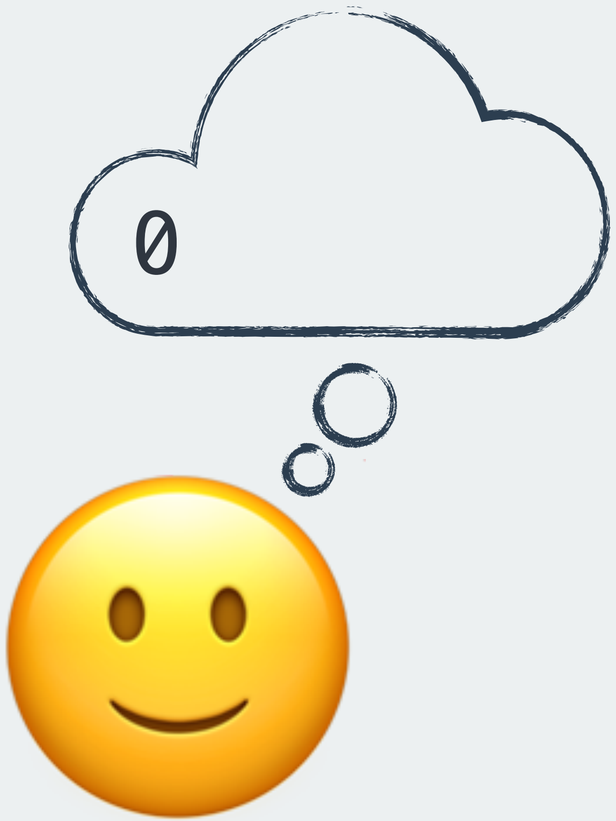
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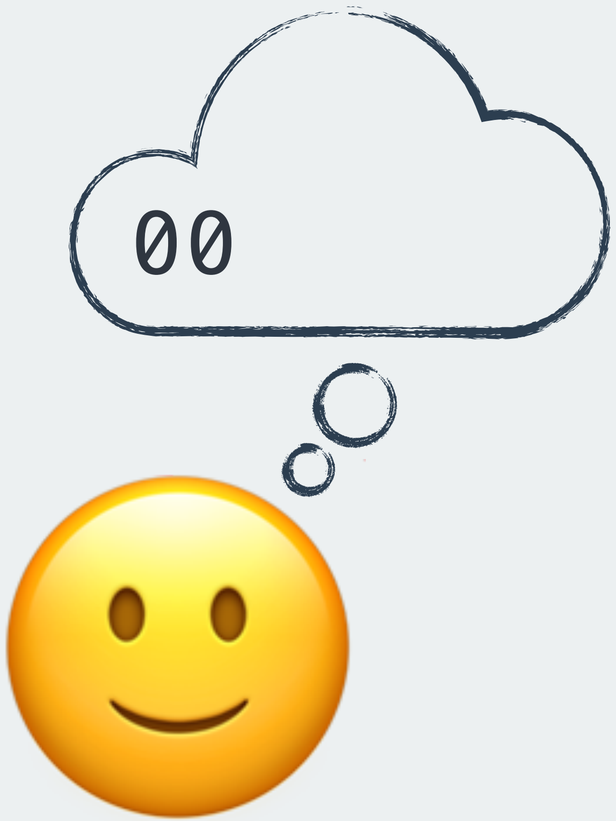
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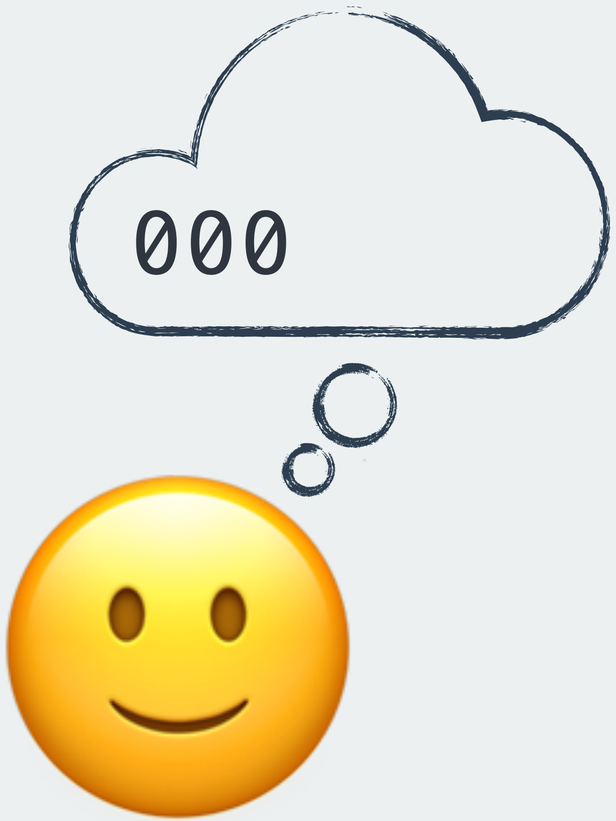
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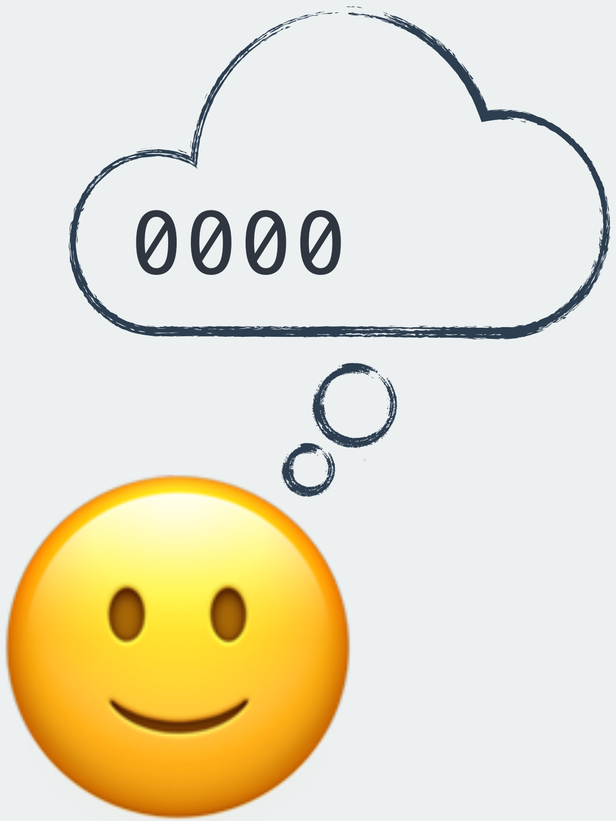
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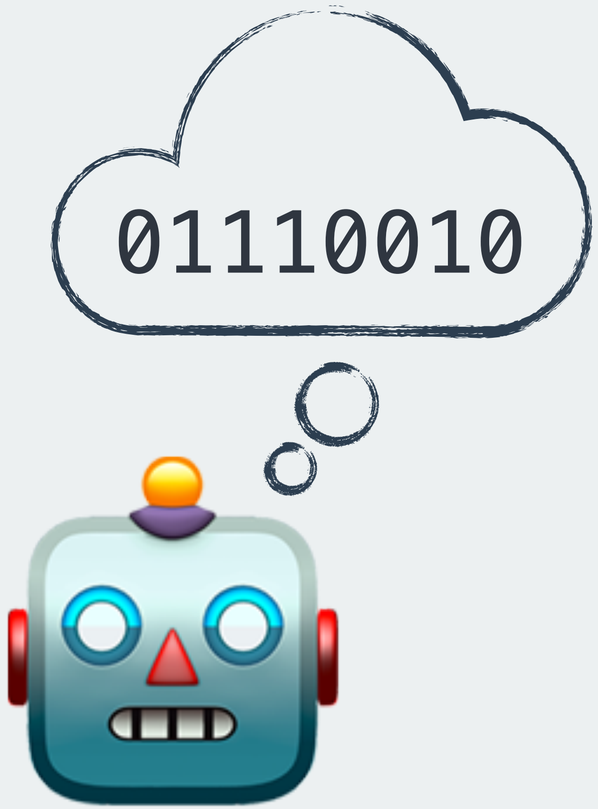
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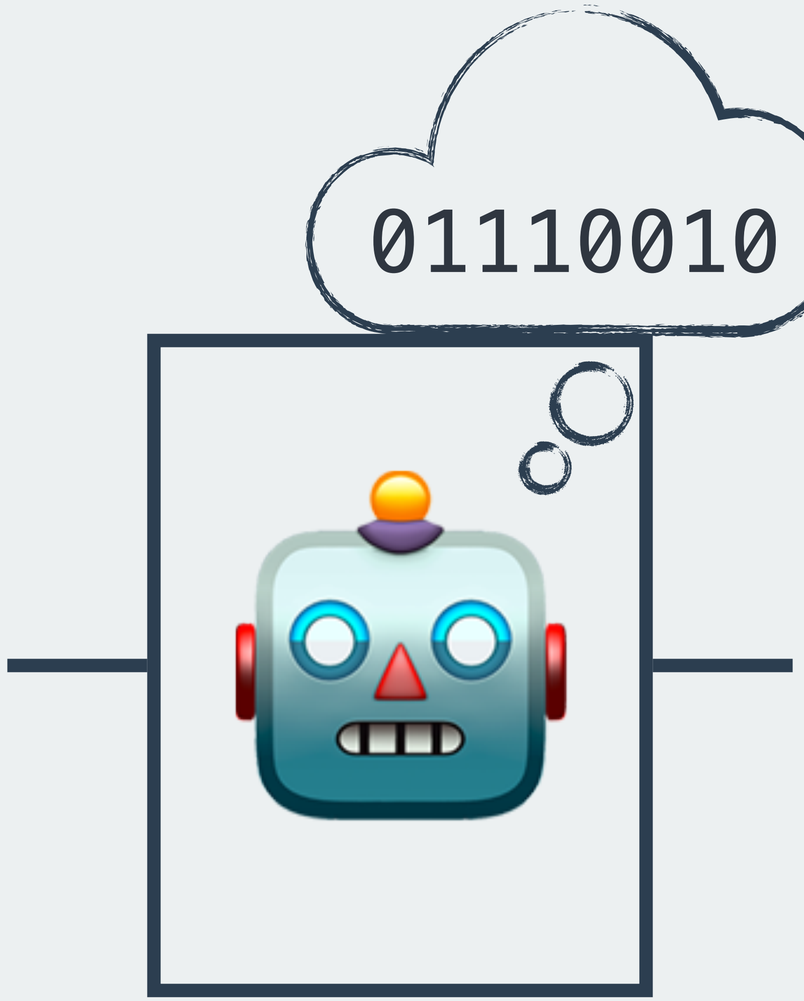
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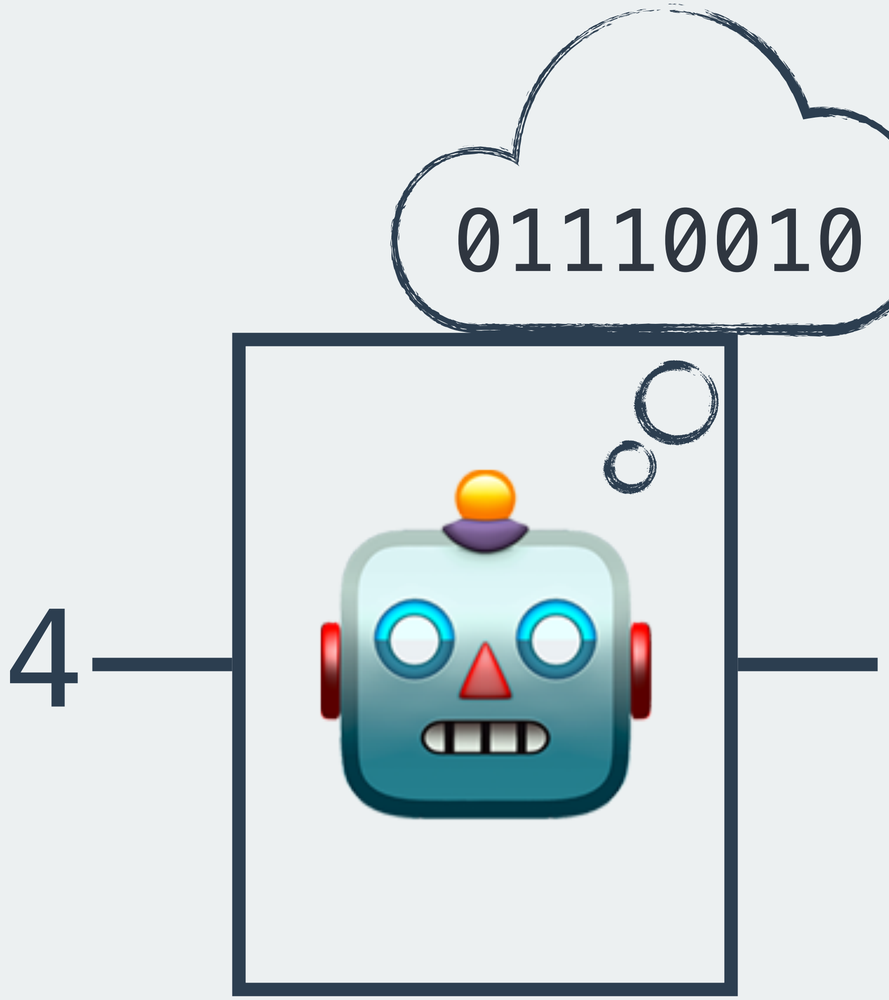
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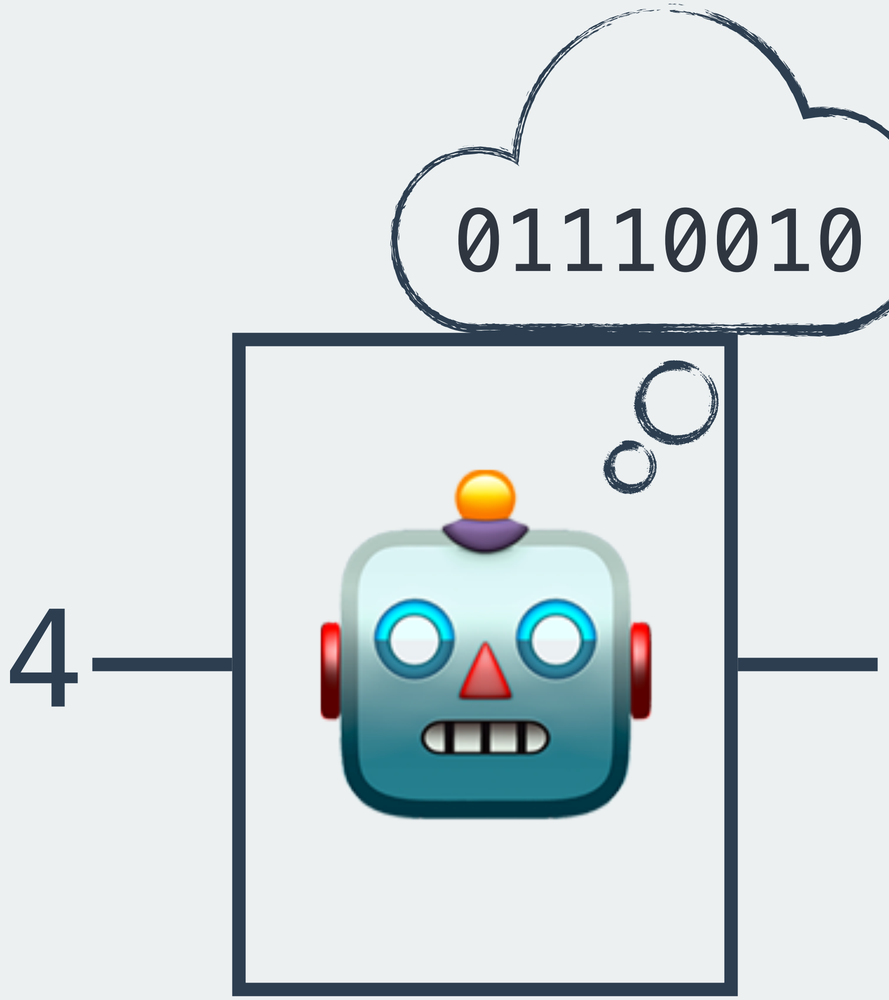
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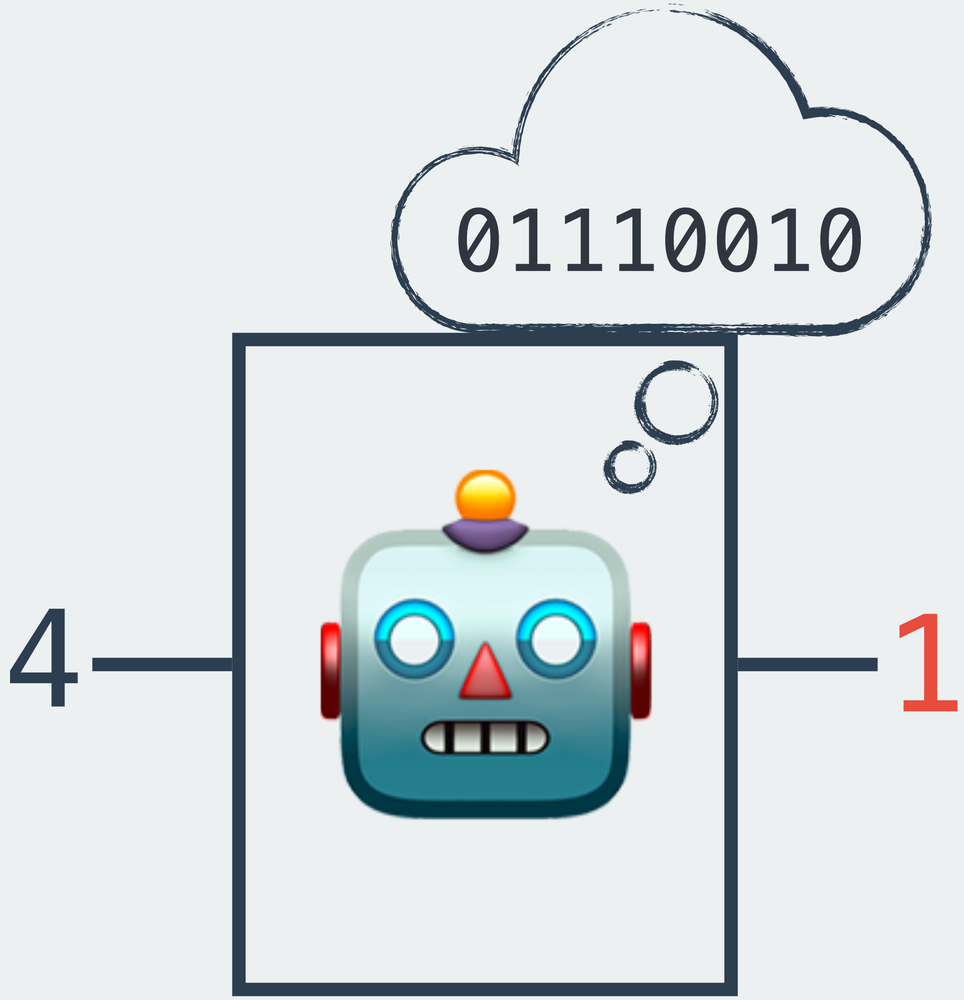
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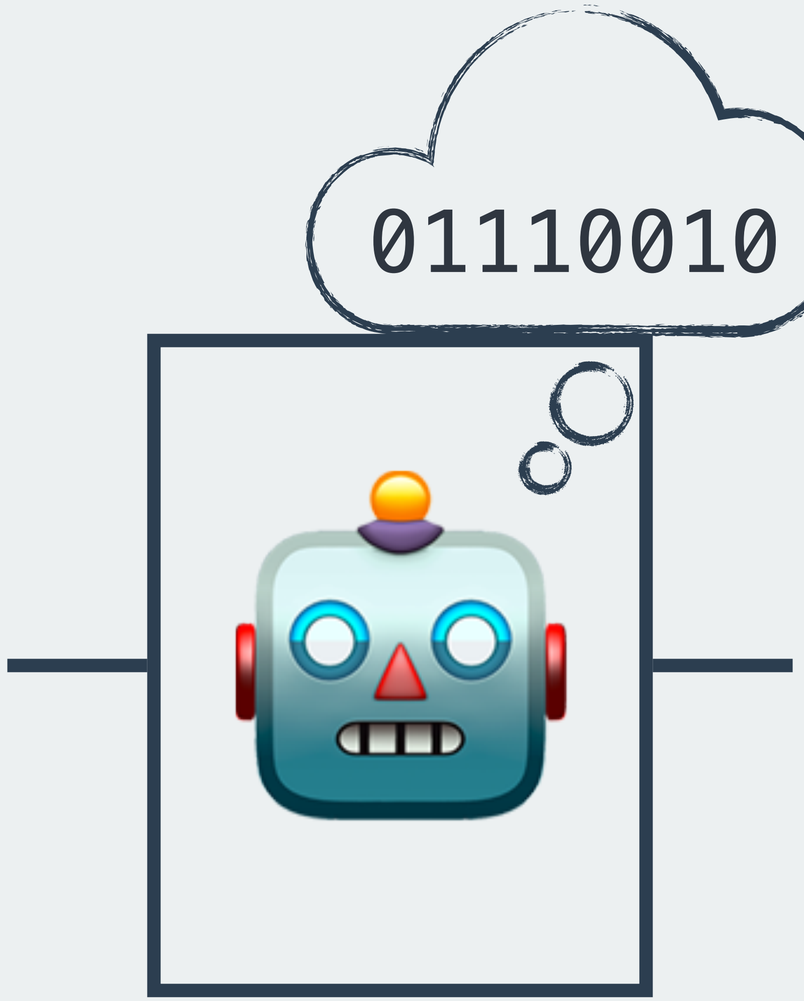
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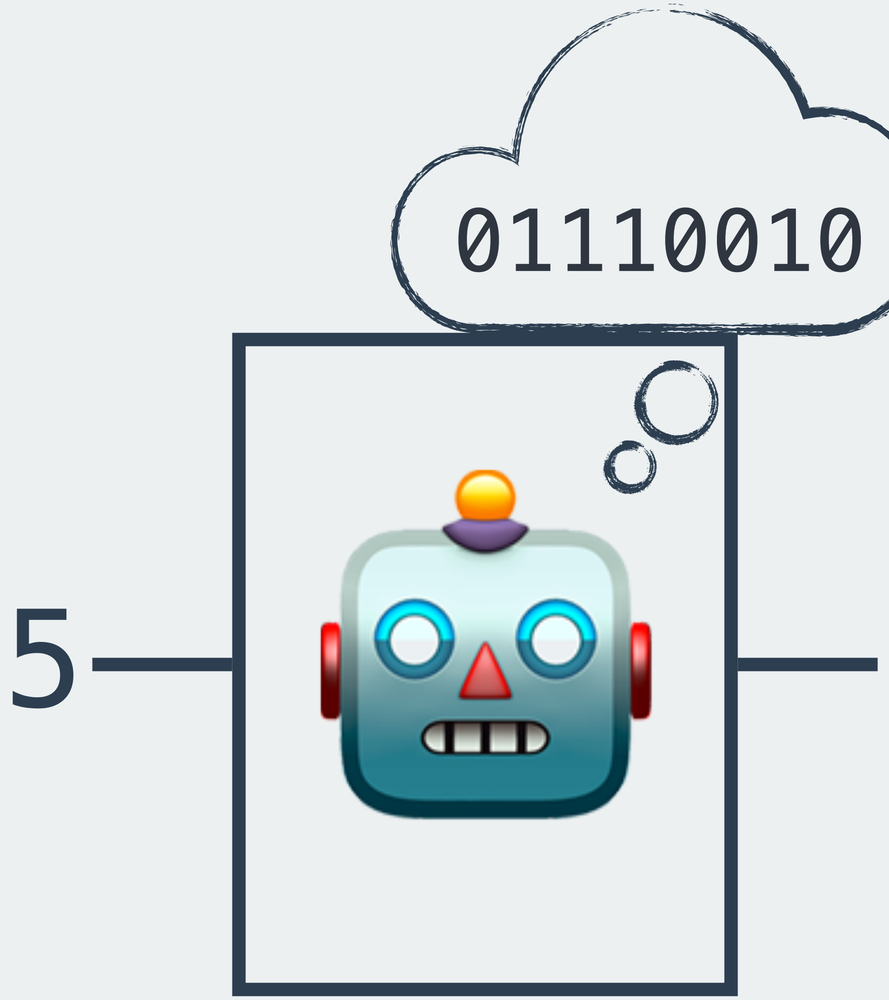
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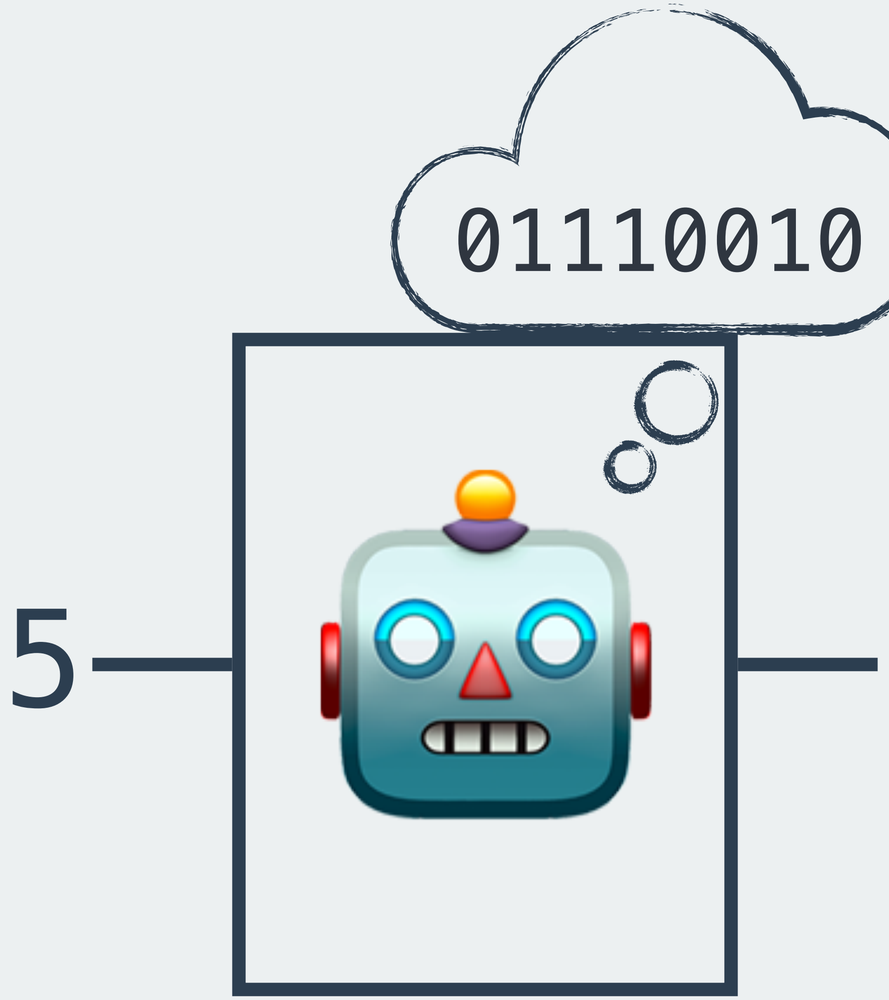
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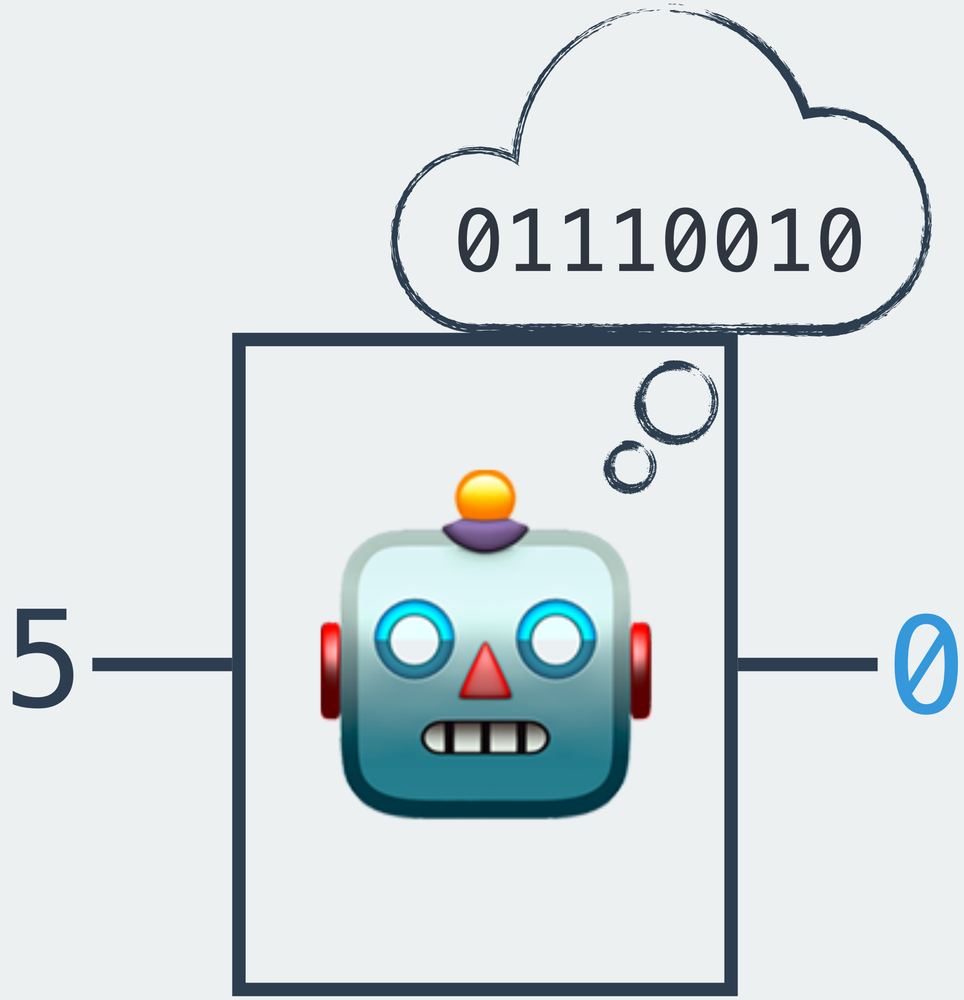
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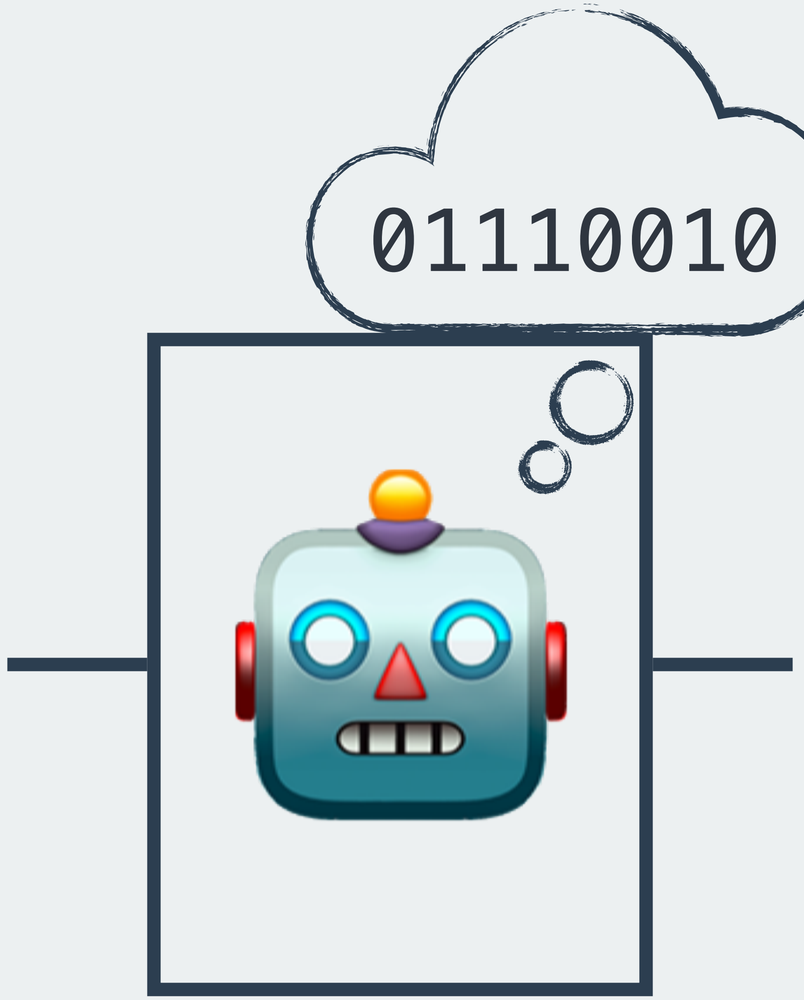
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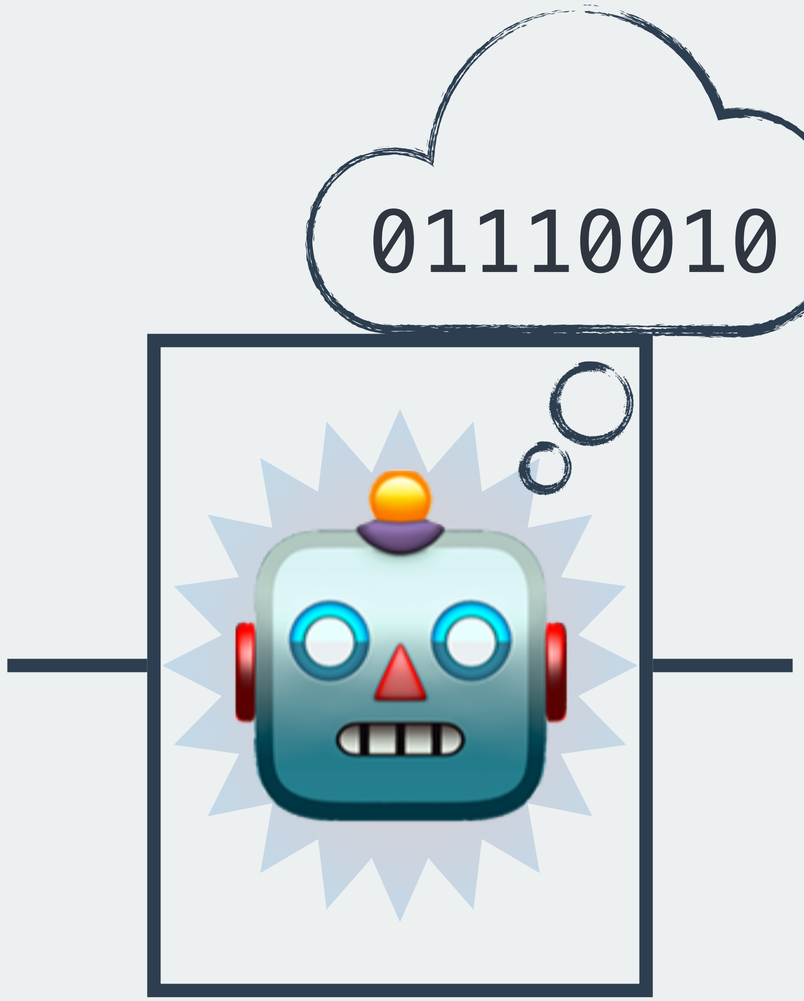
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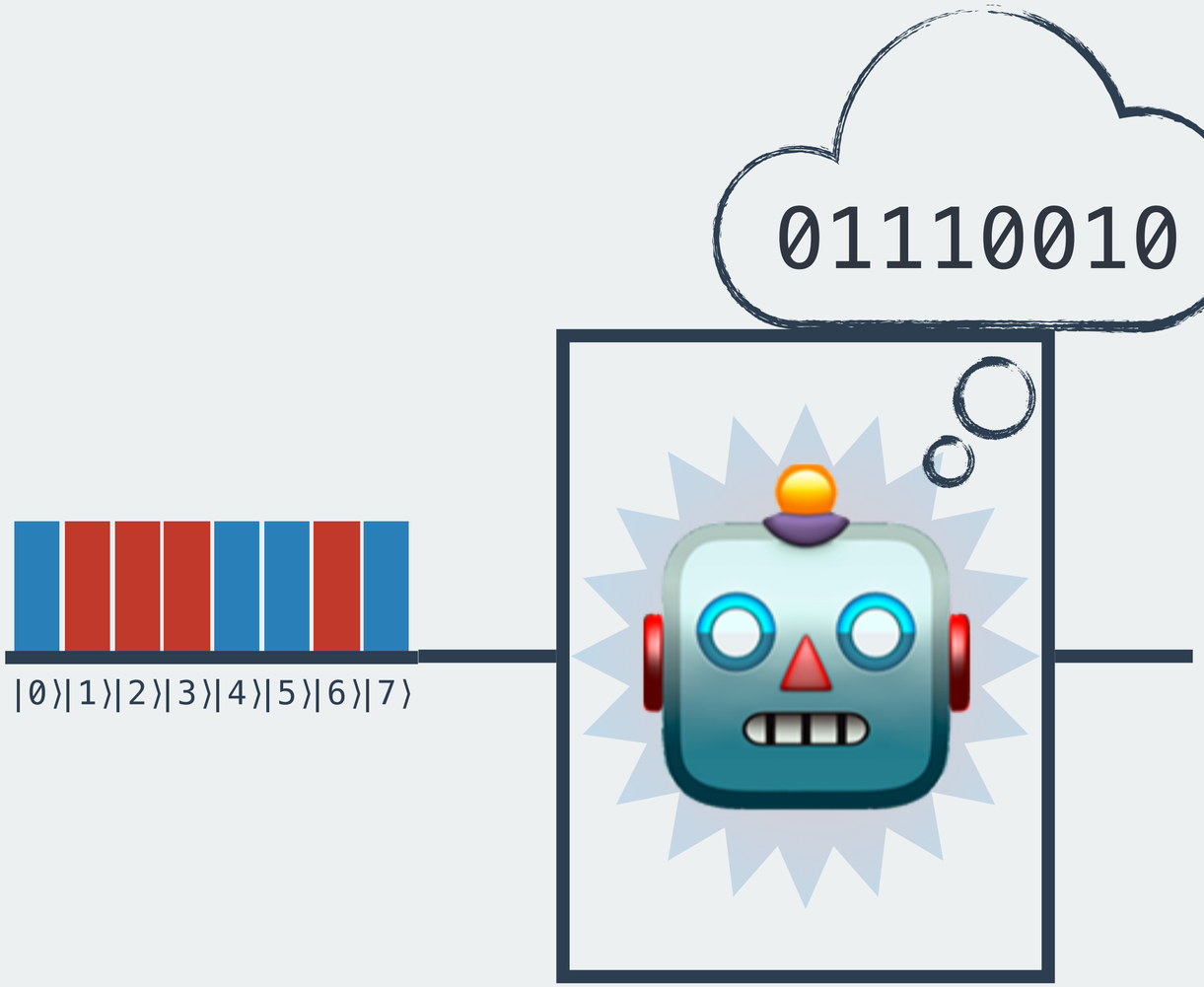
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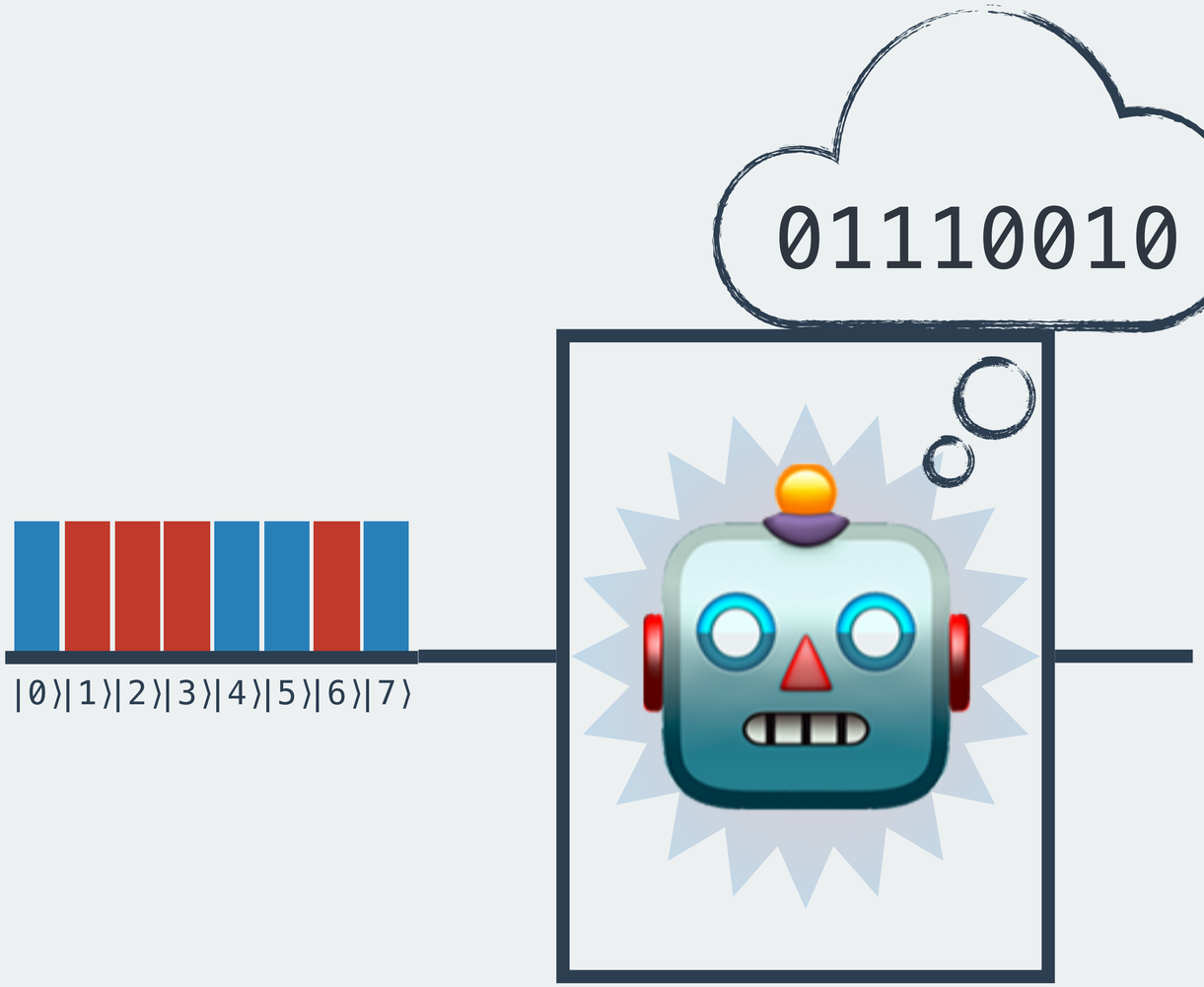
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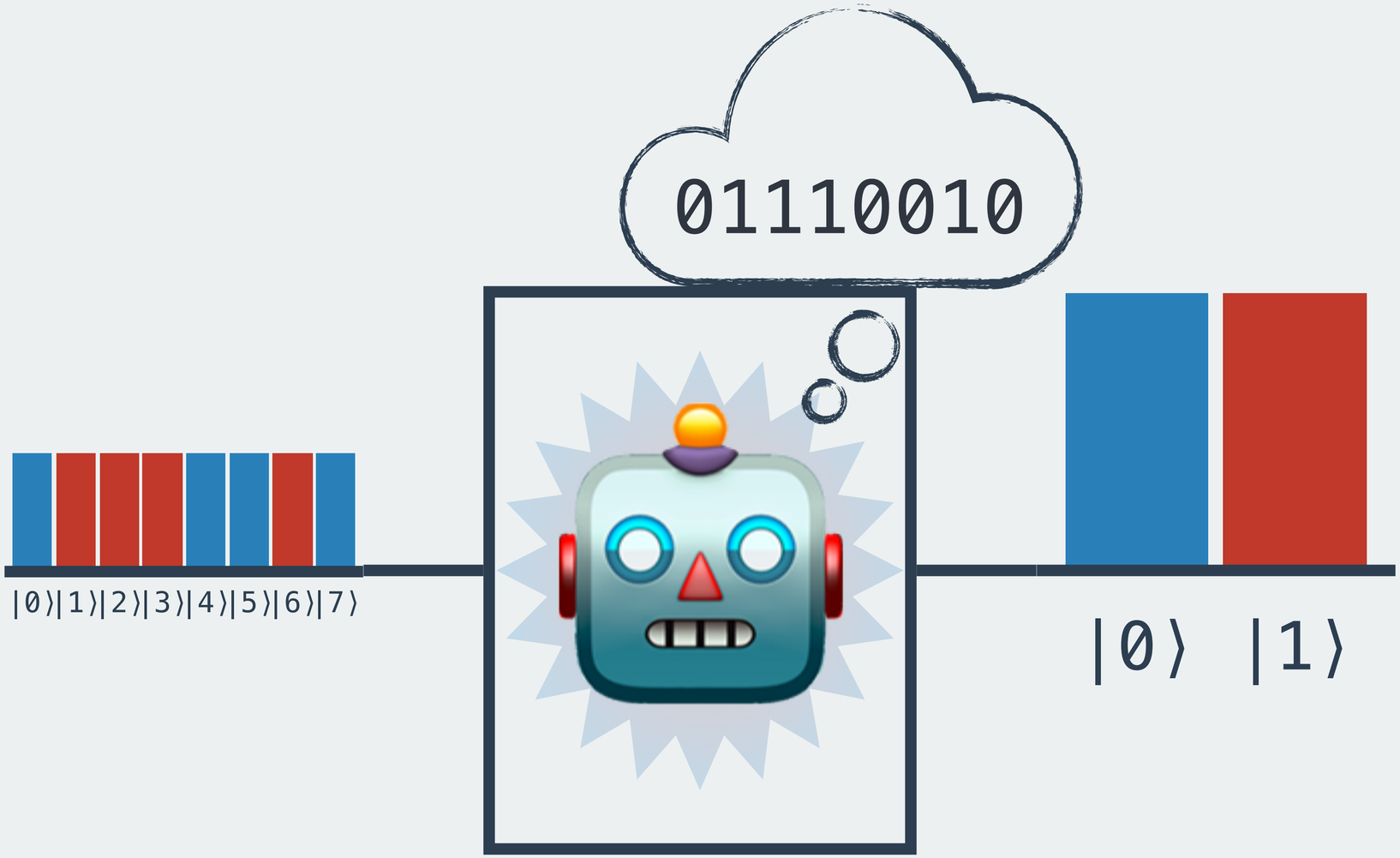
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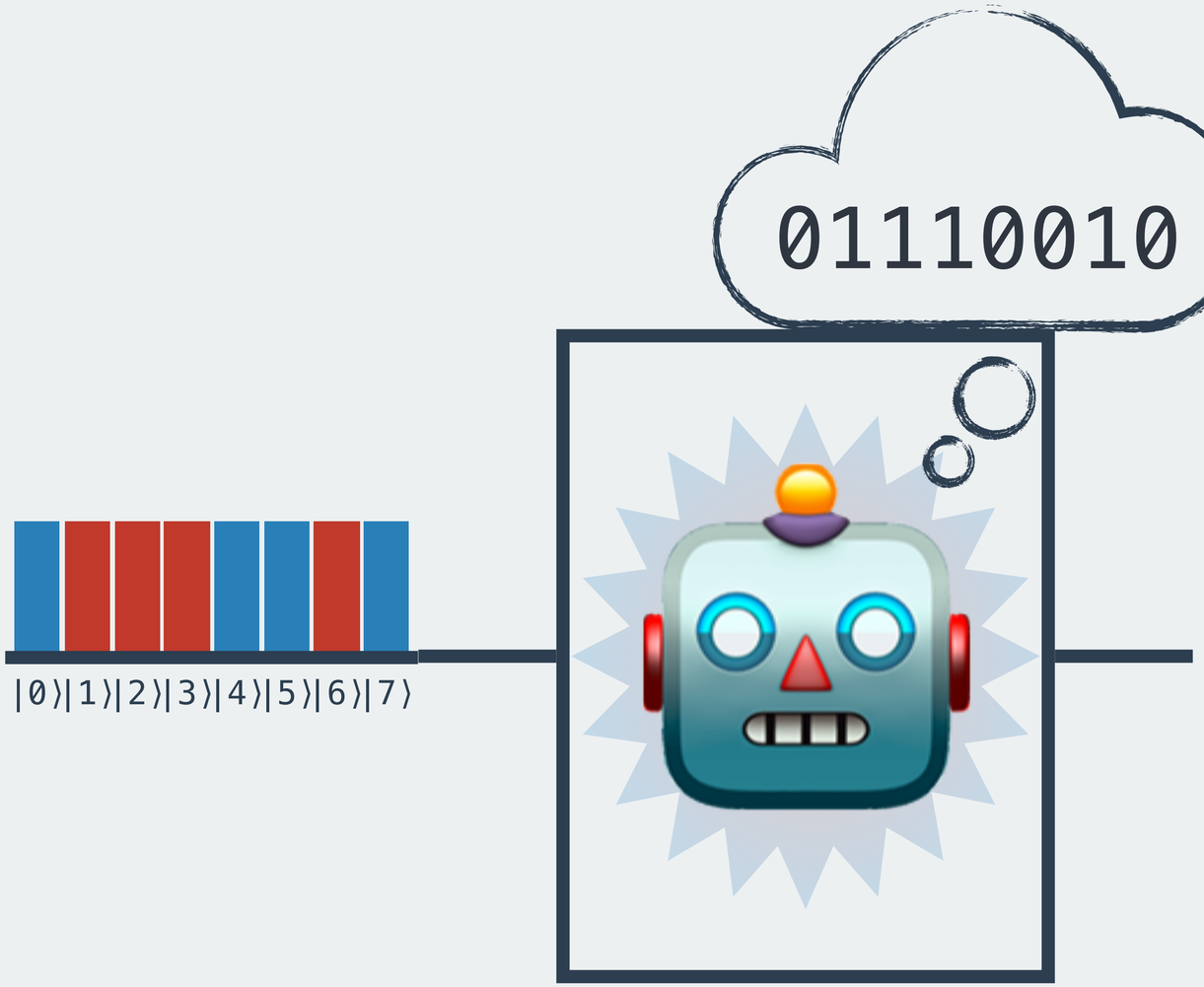
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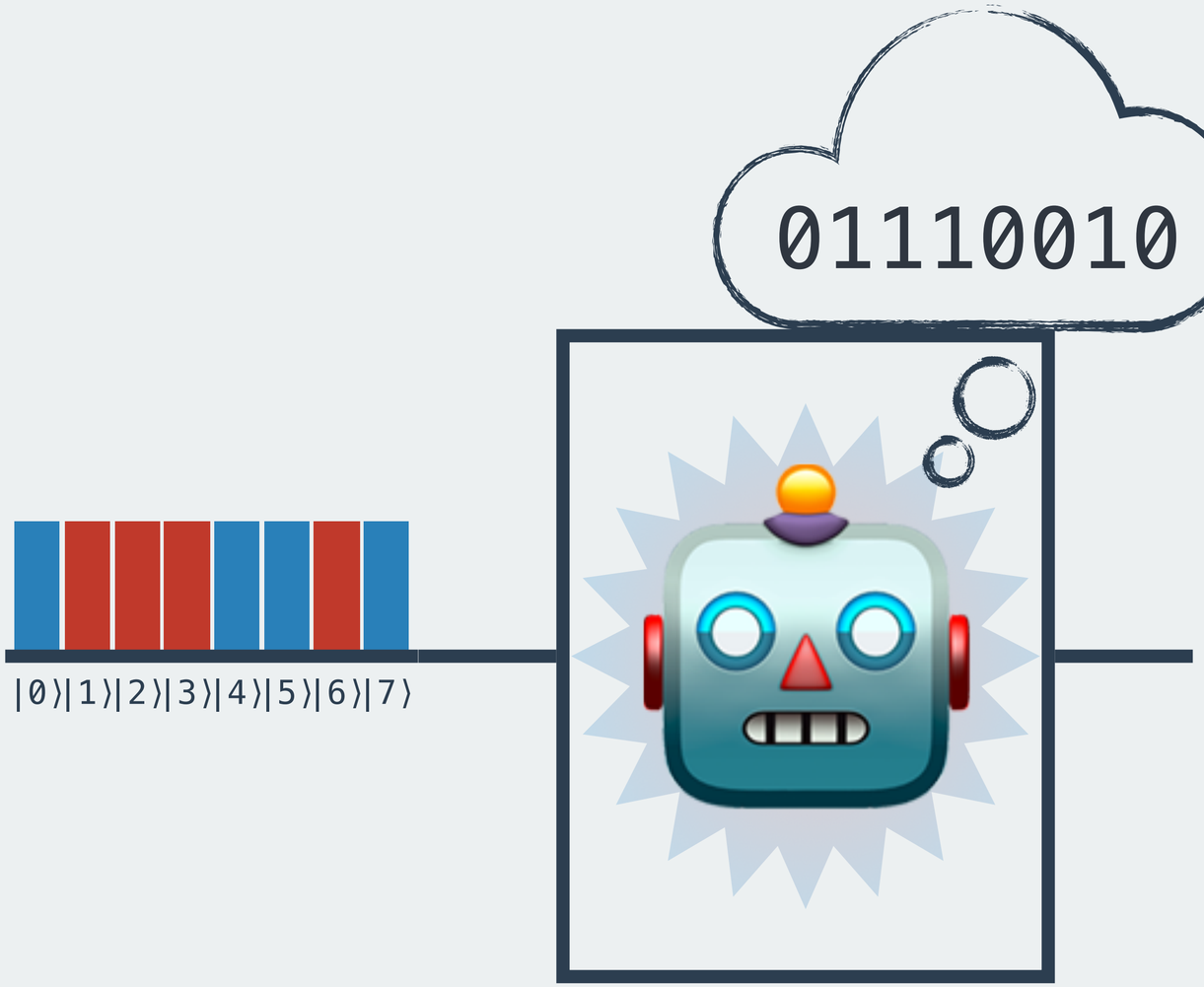
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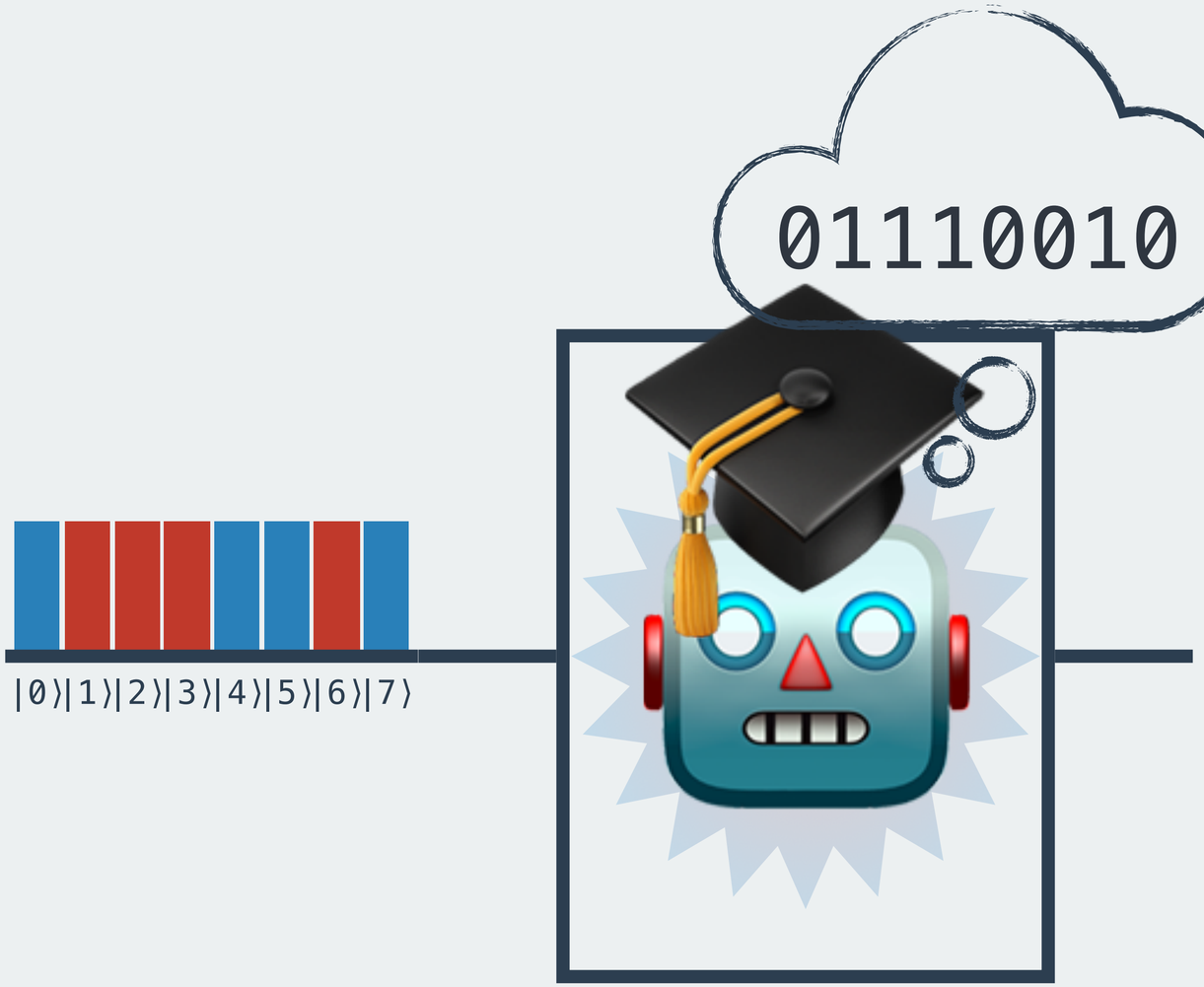
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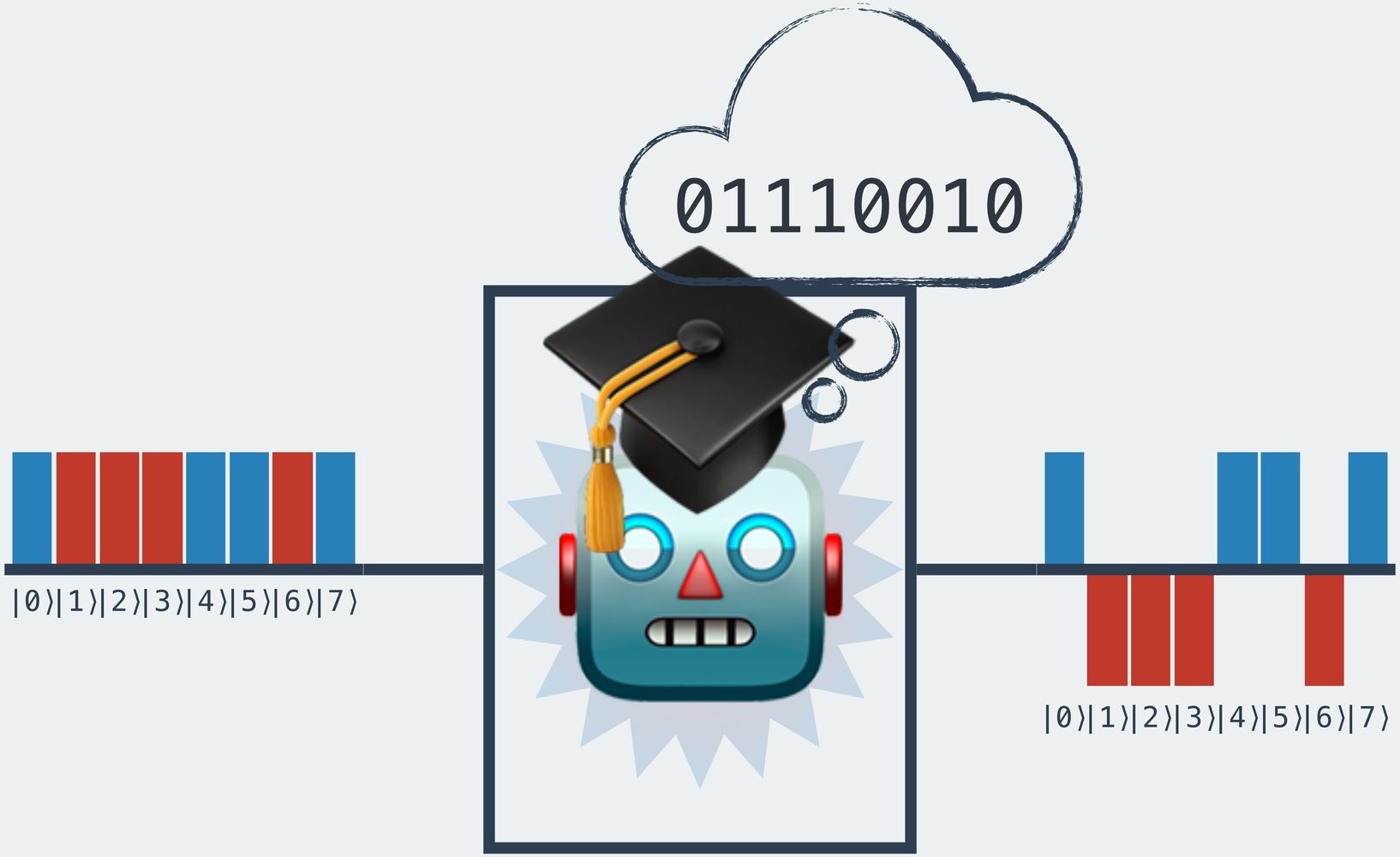
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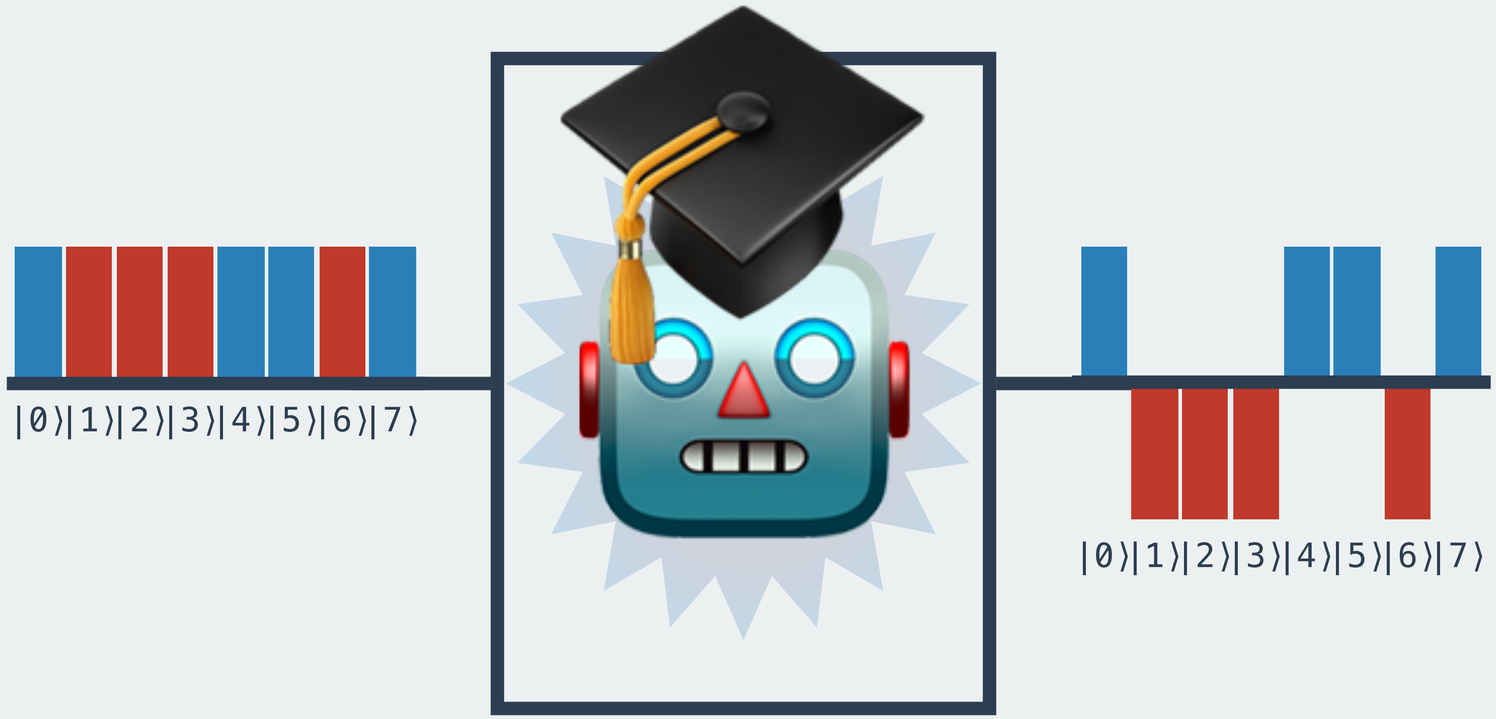
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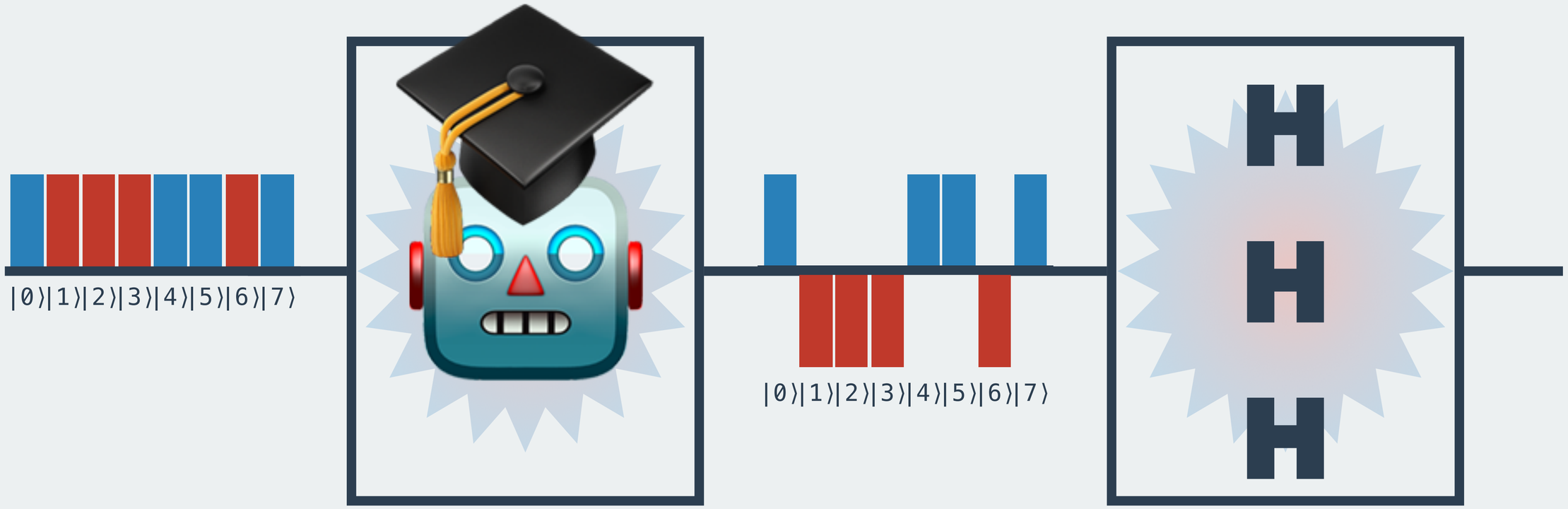
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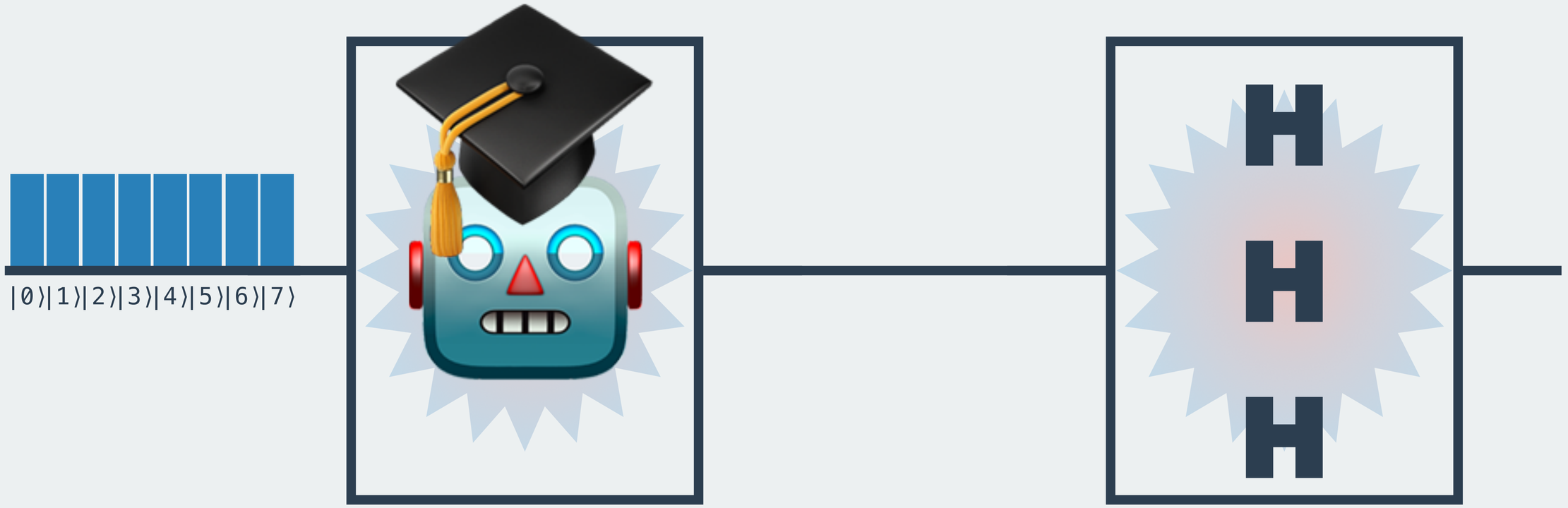
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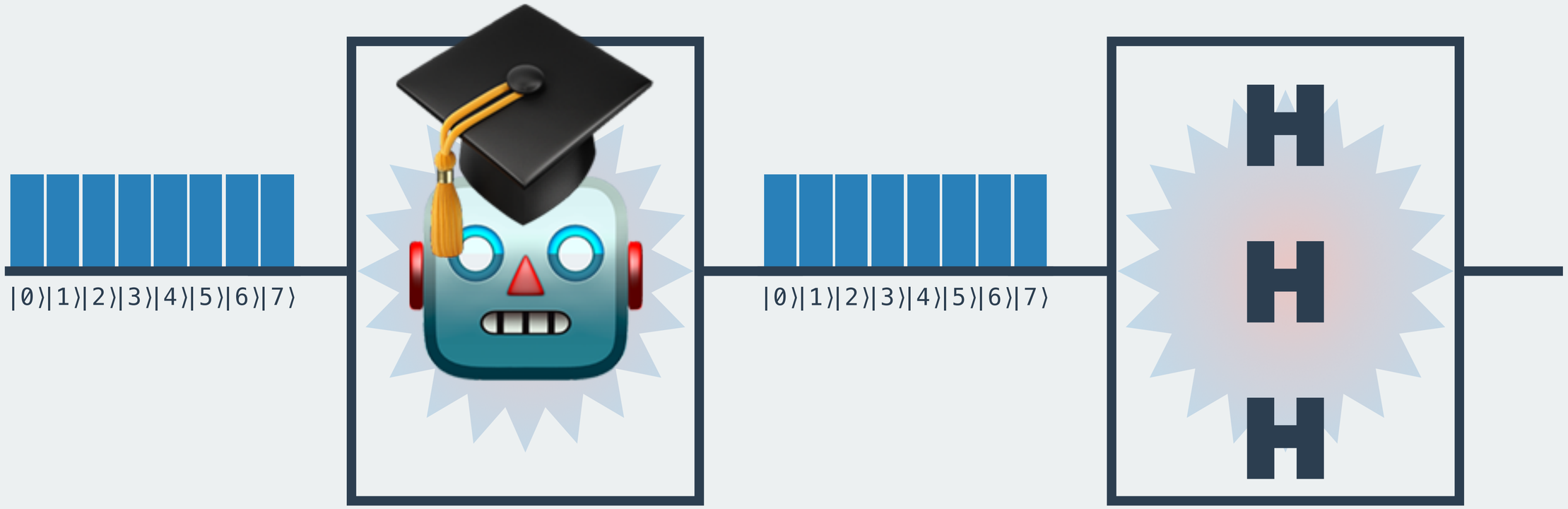
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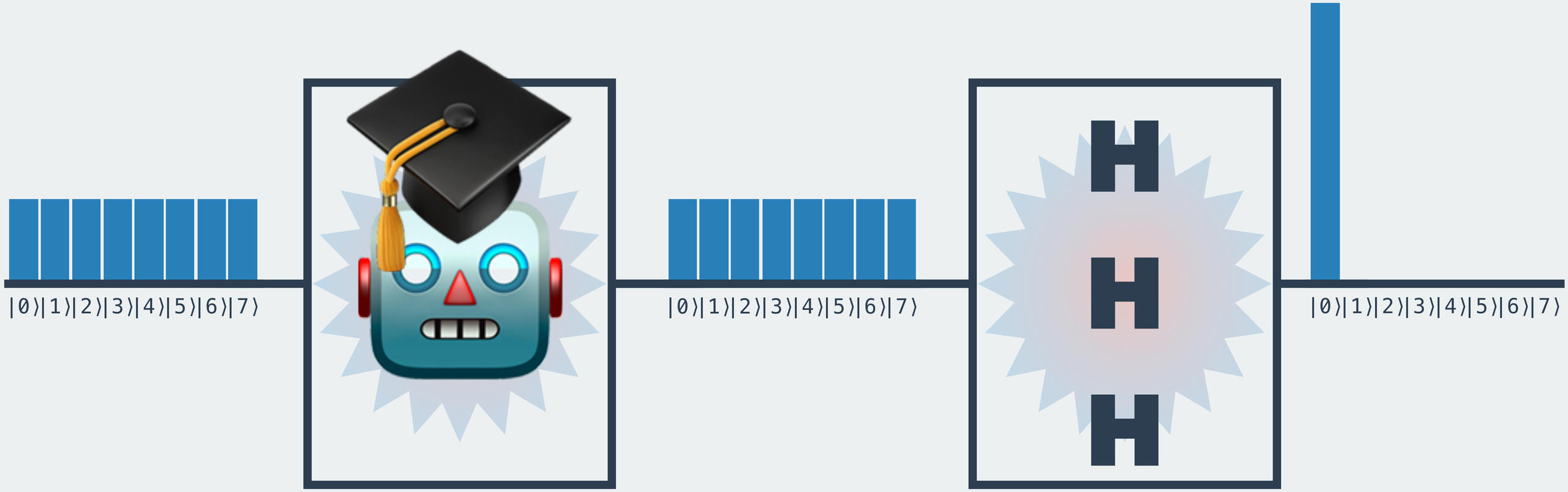
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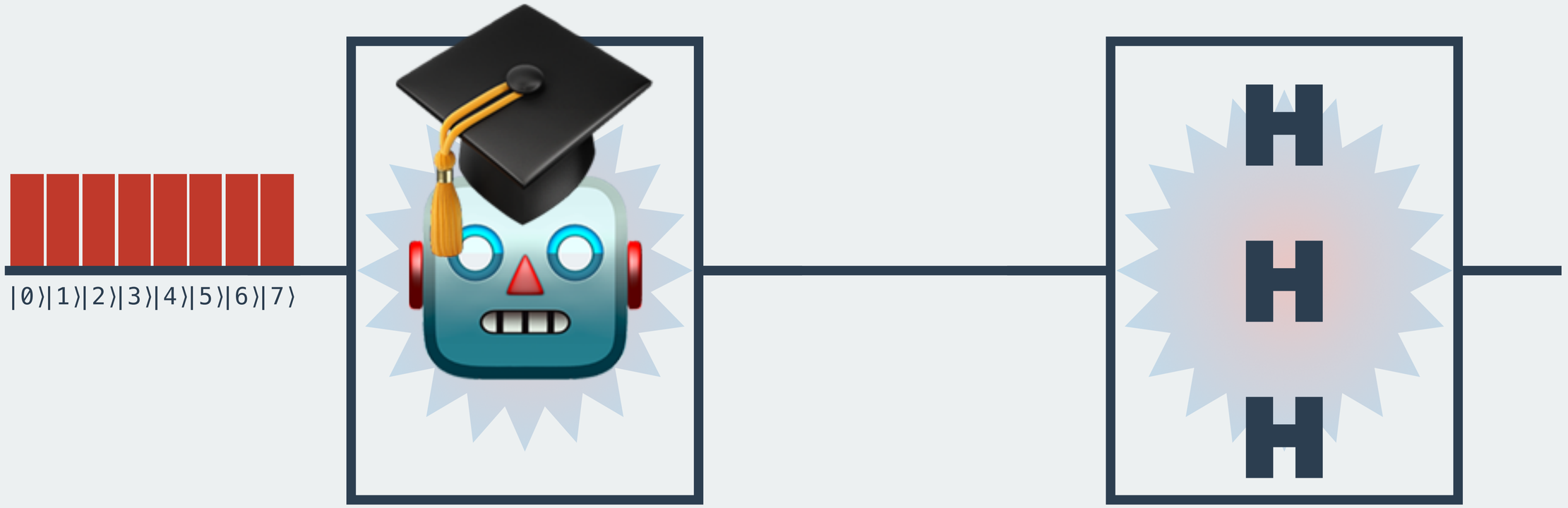
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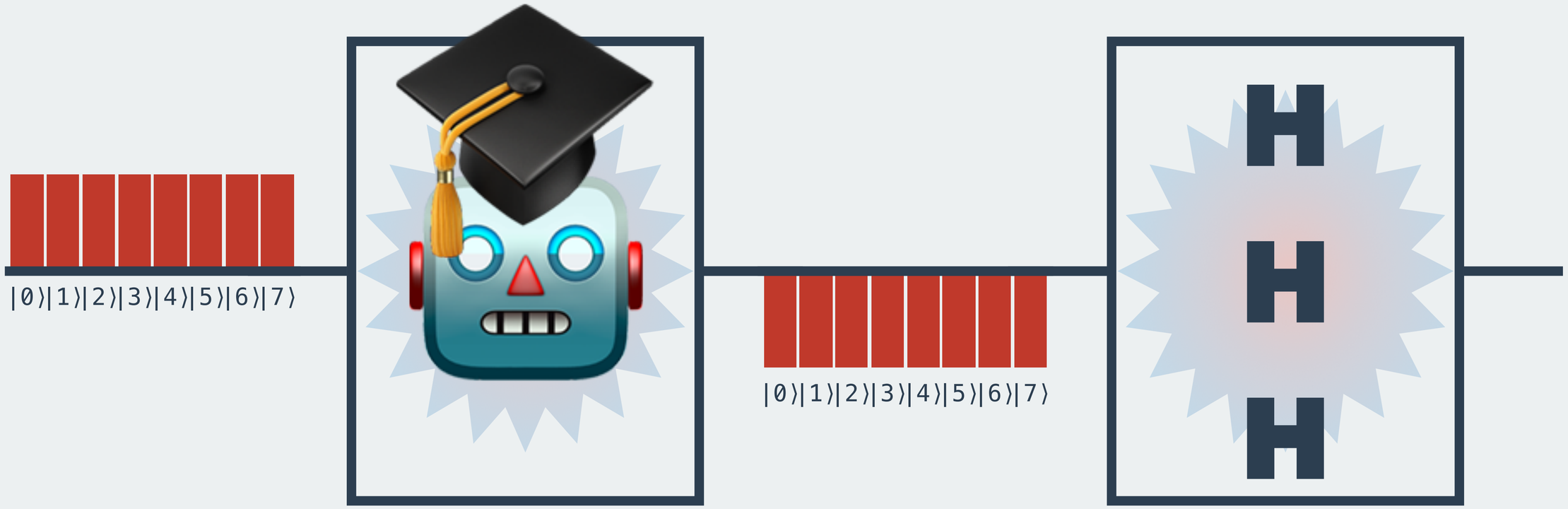
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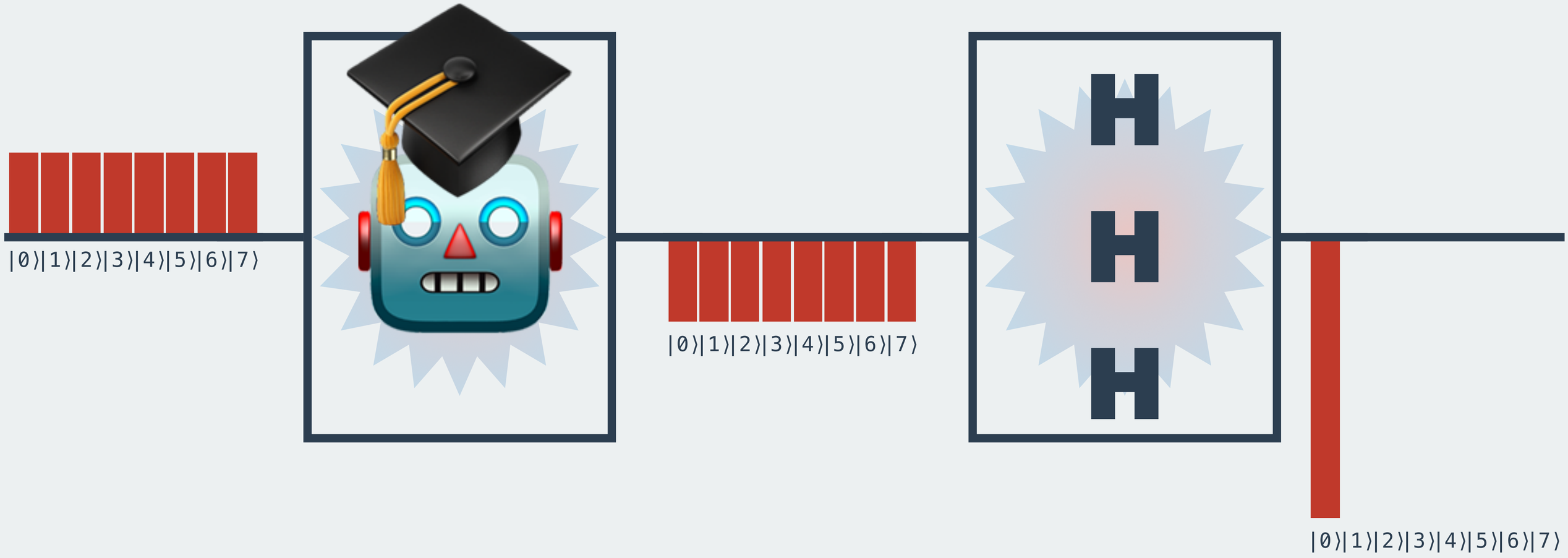
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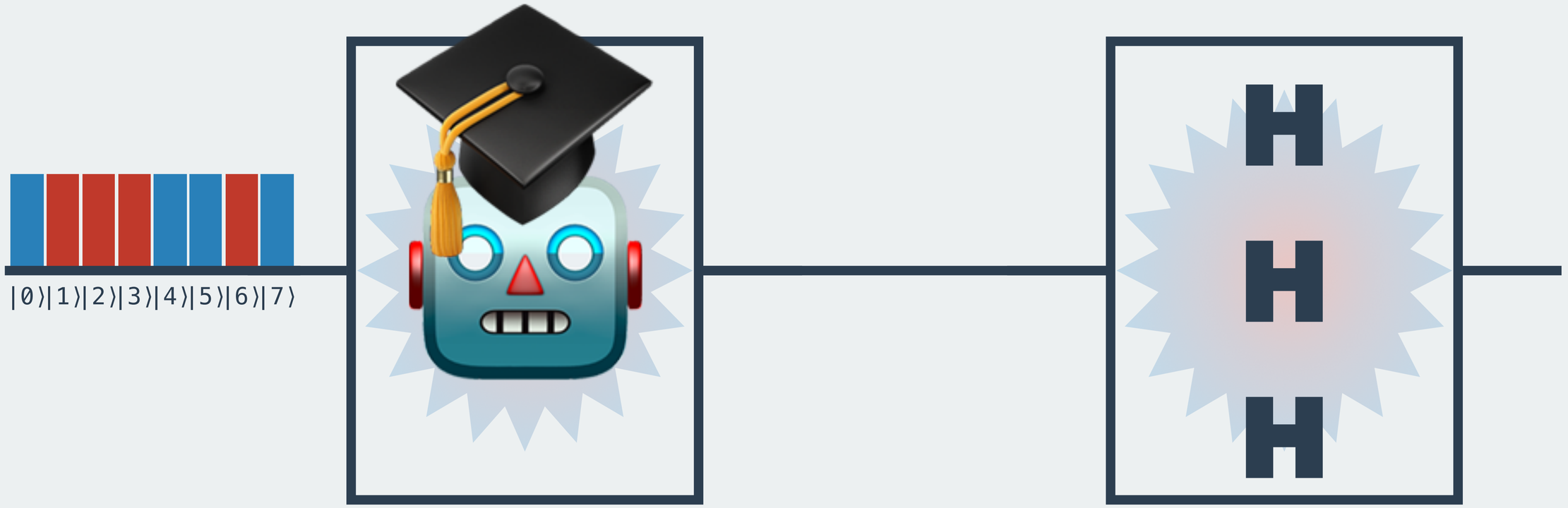
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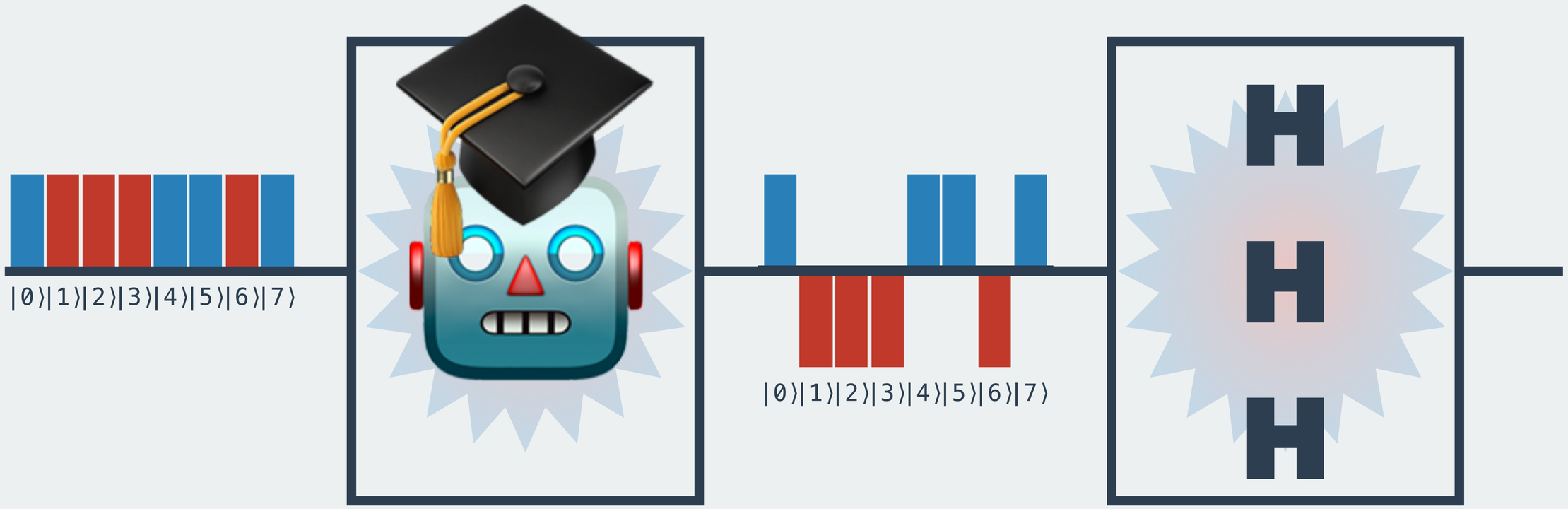
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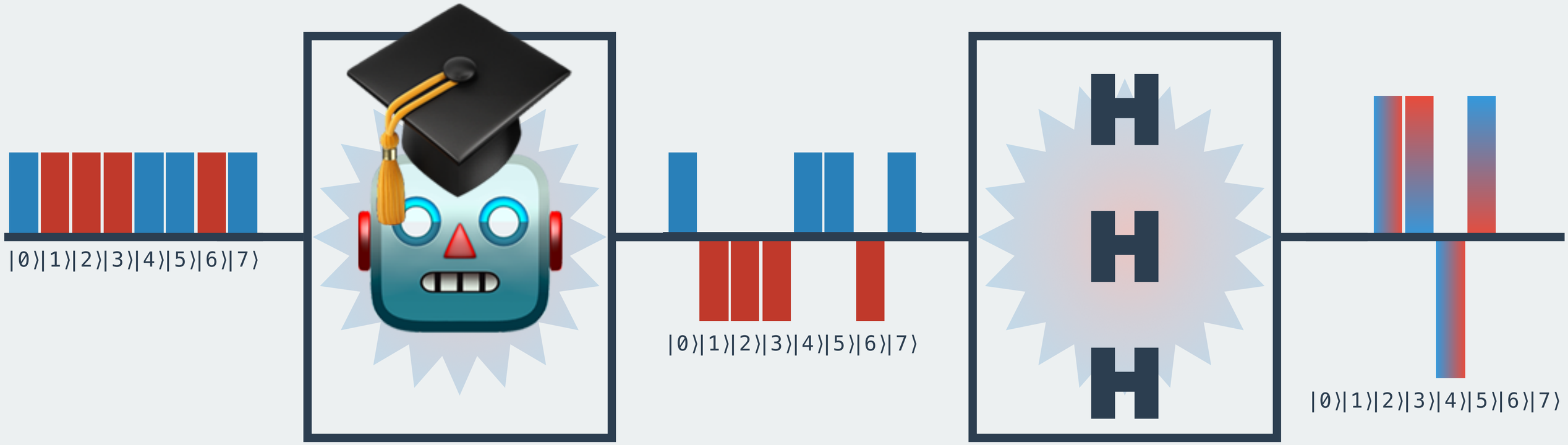
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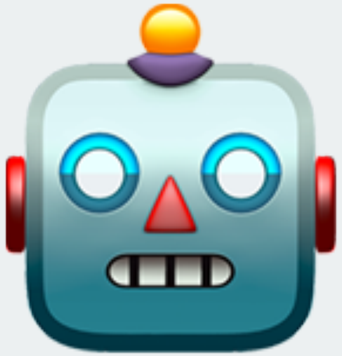
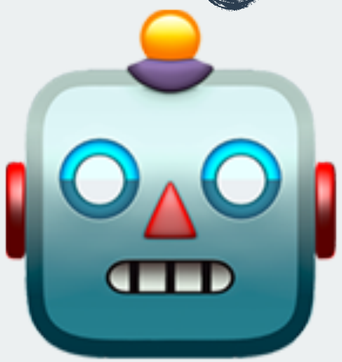


ali je **x**
pravi delitelj **15**?



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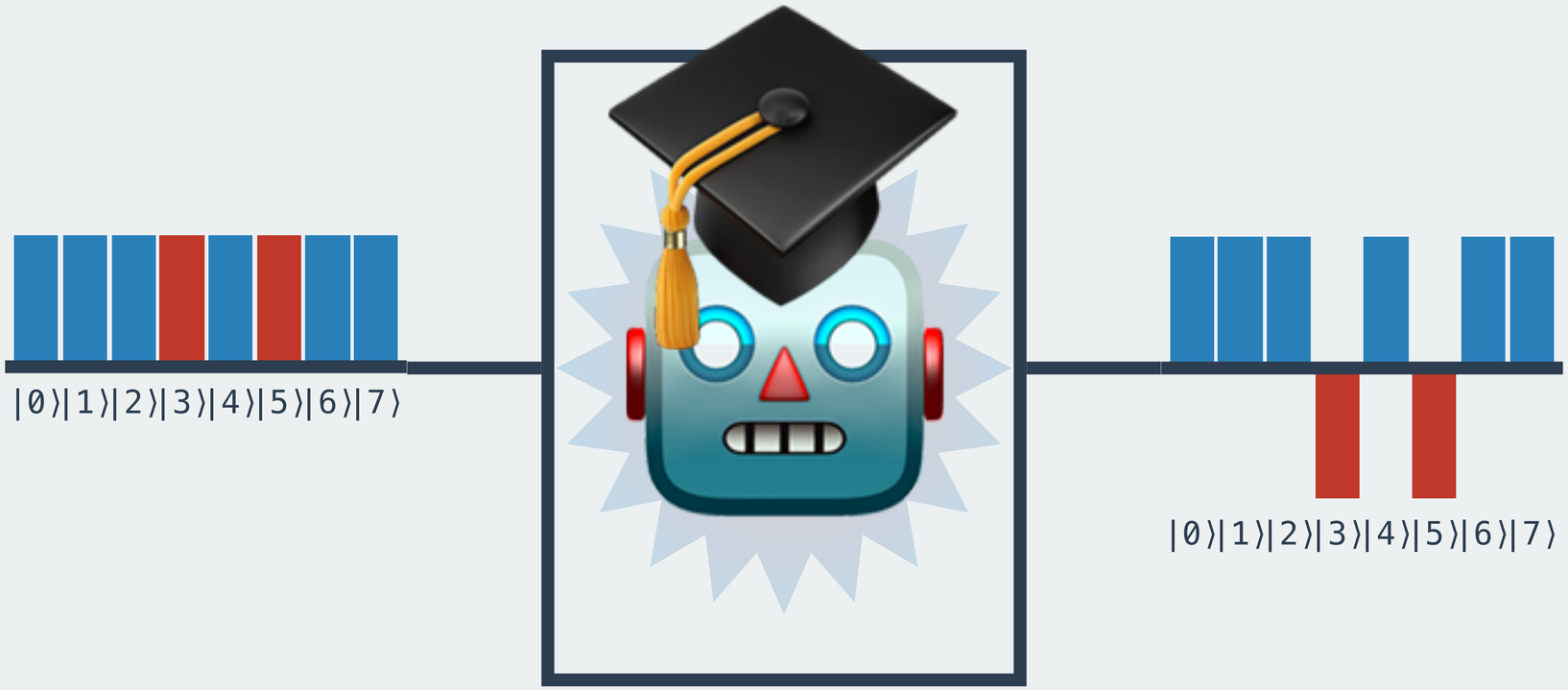
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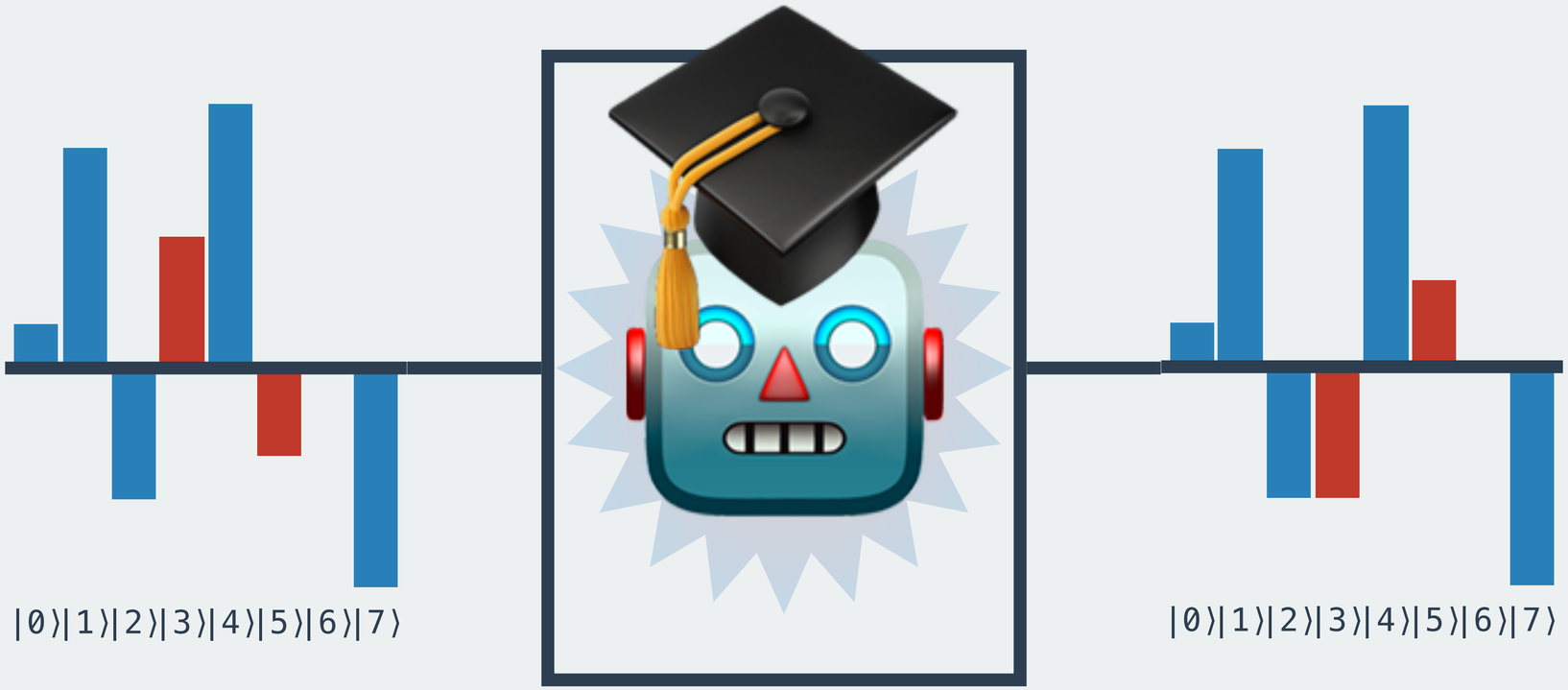
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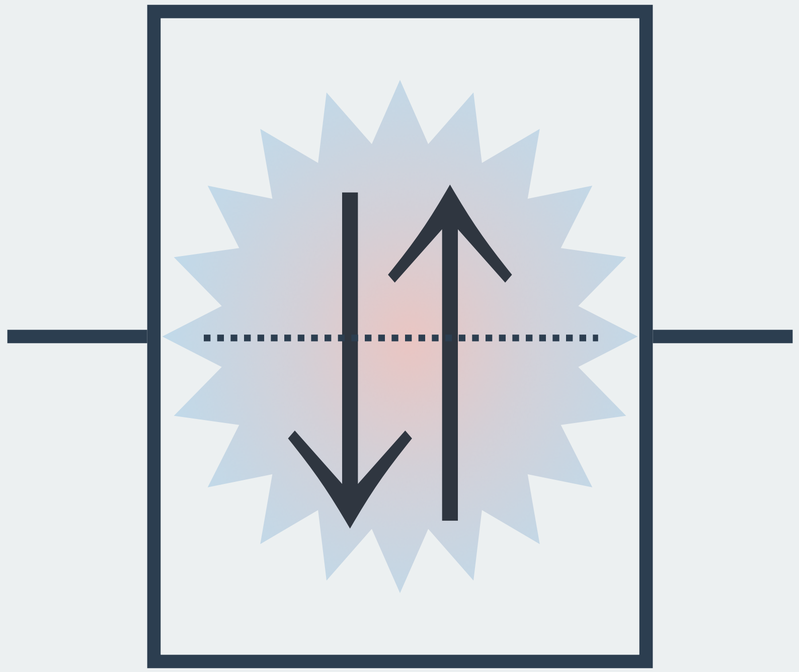

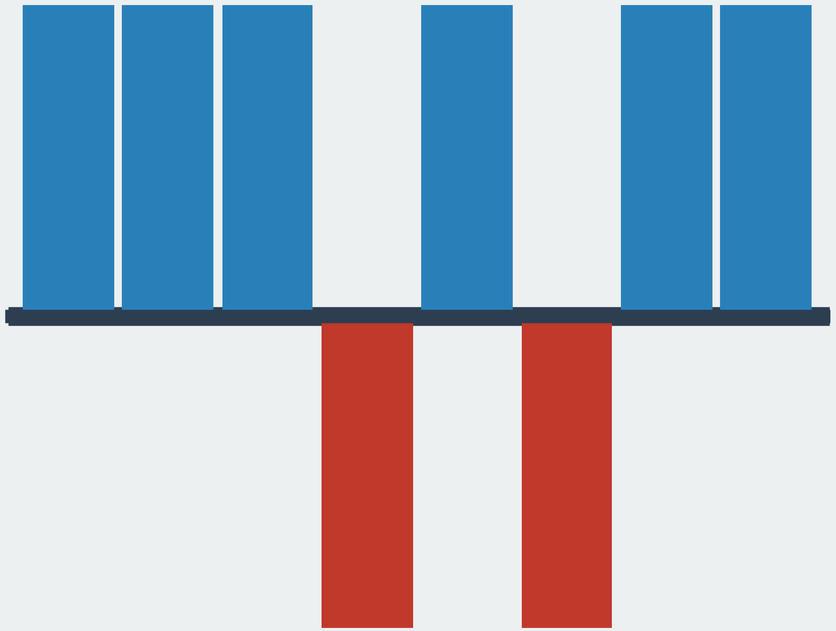

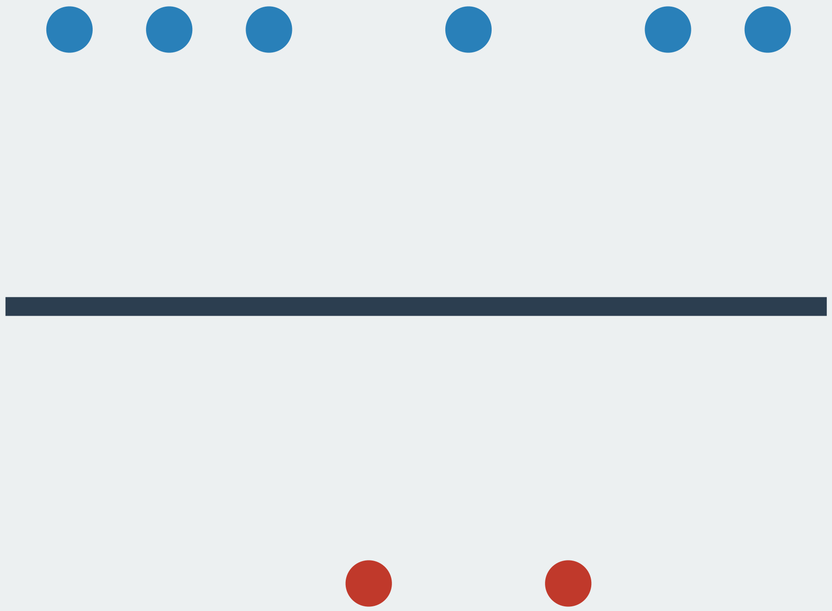

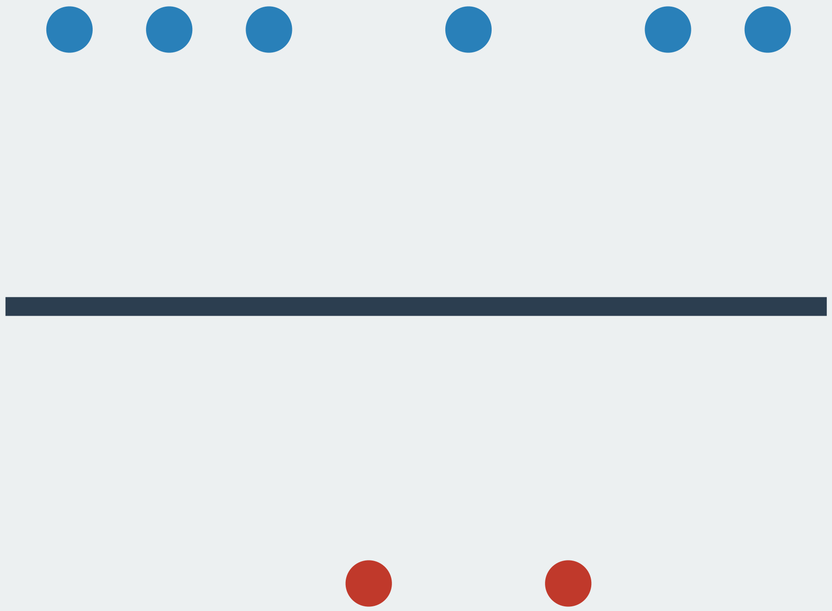

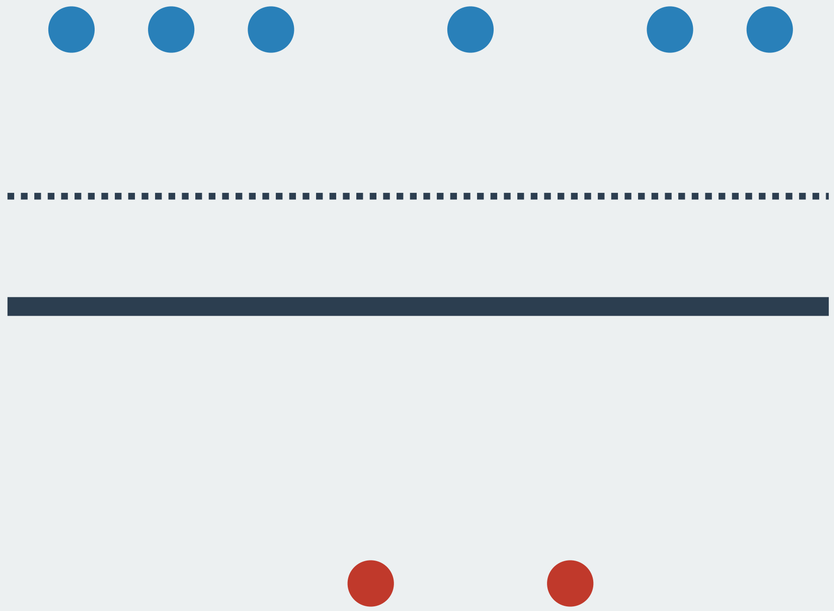

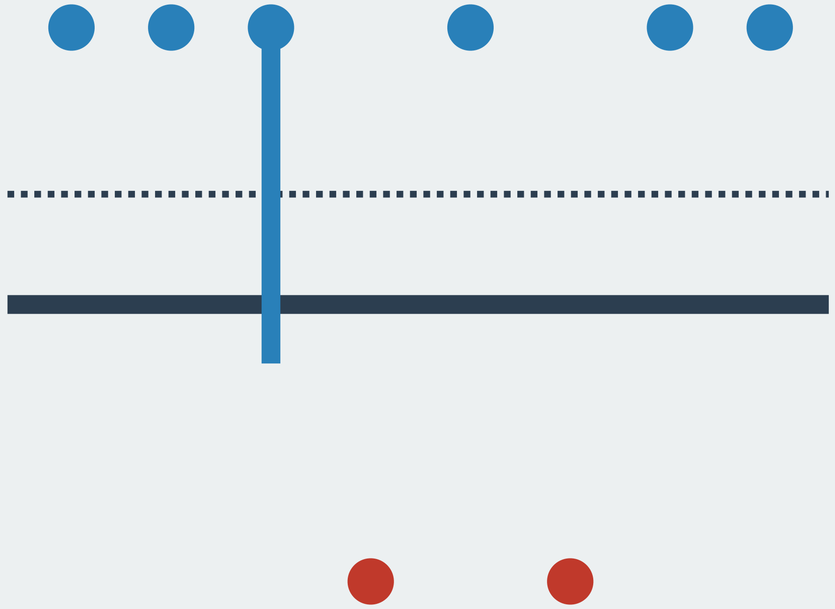

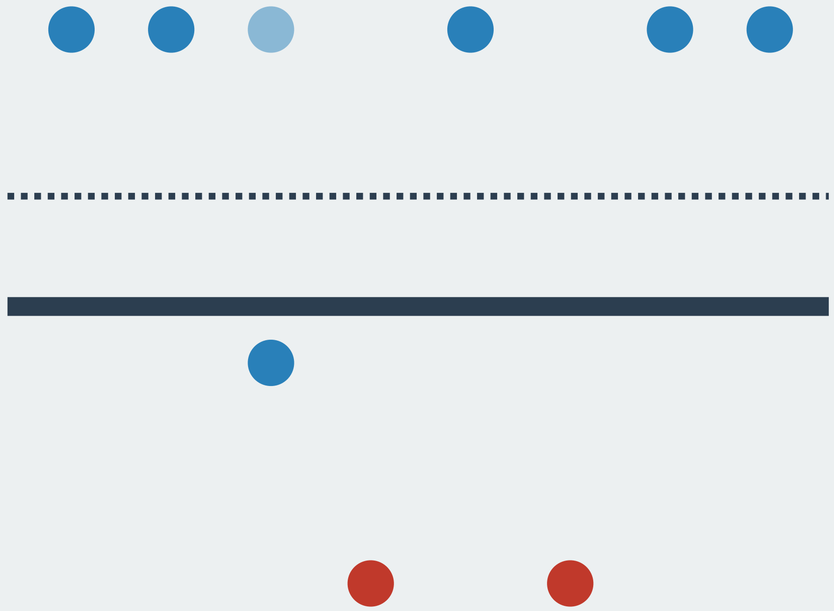

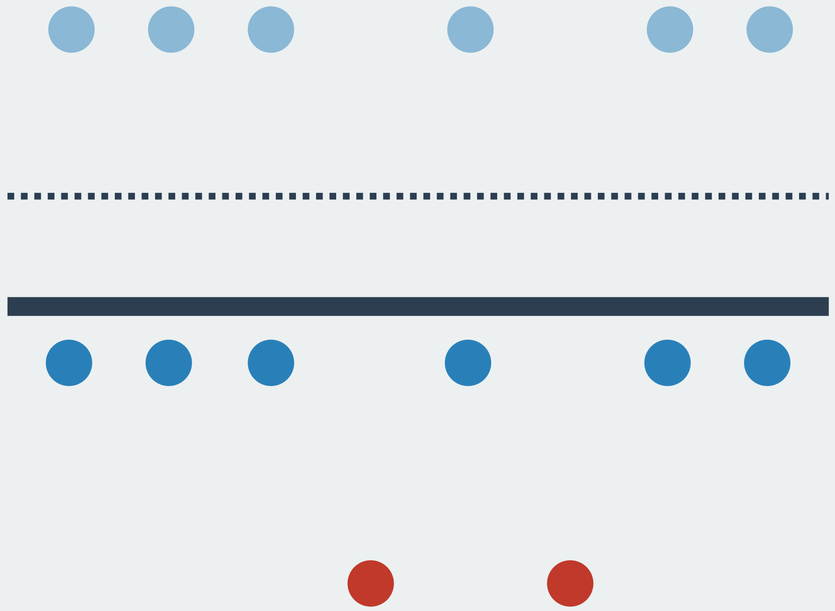

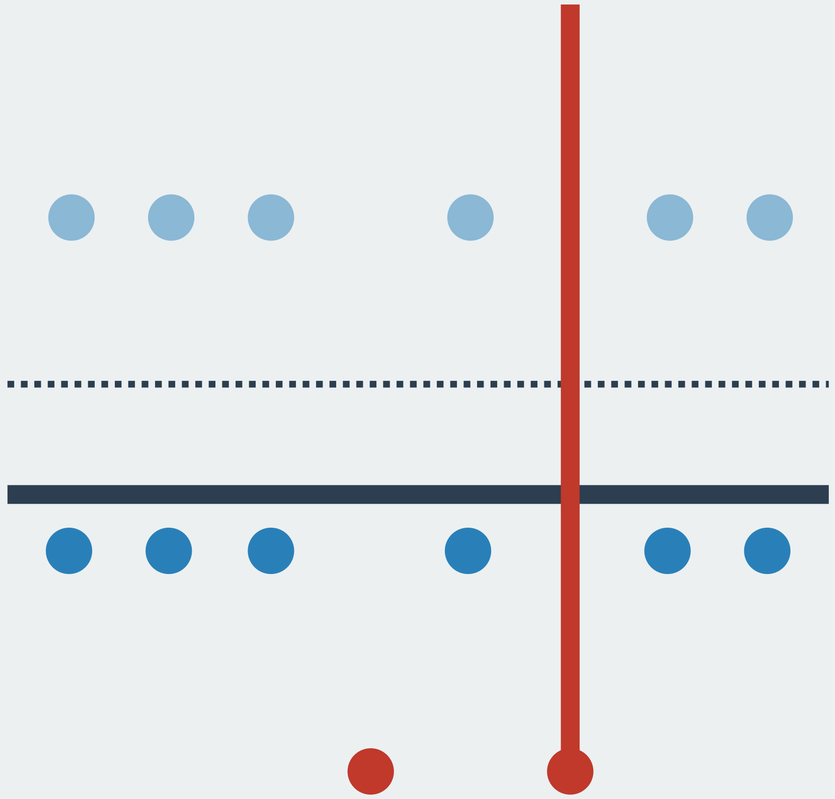

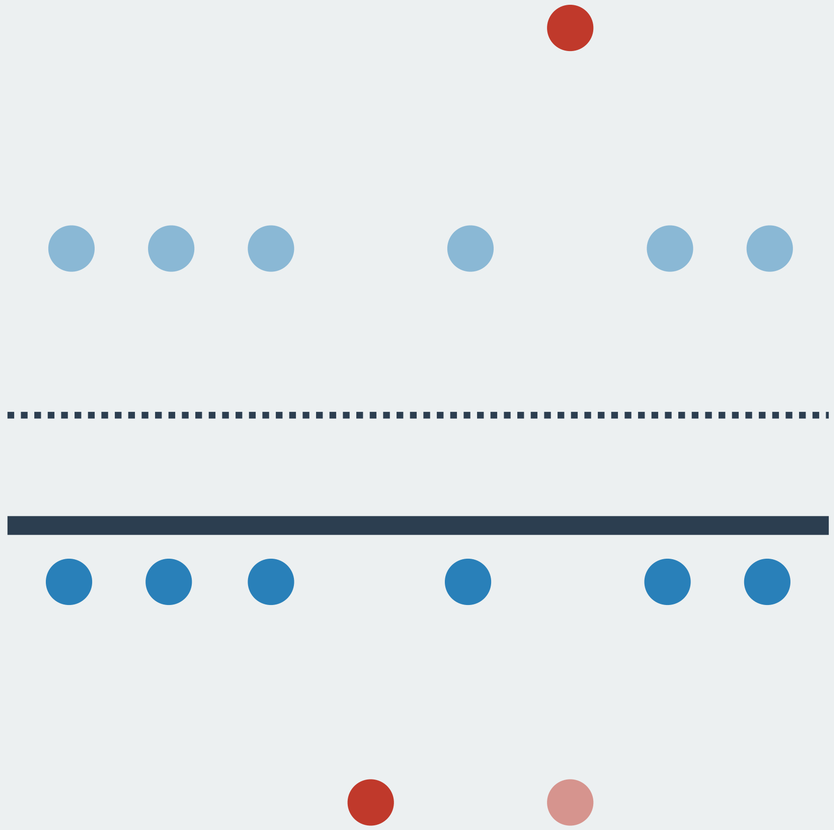

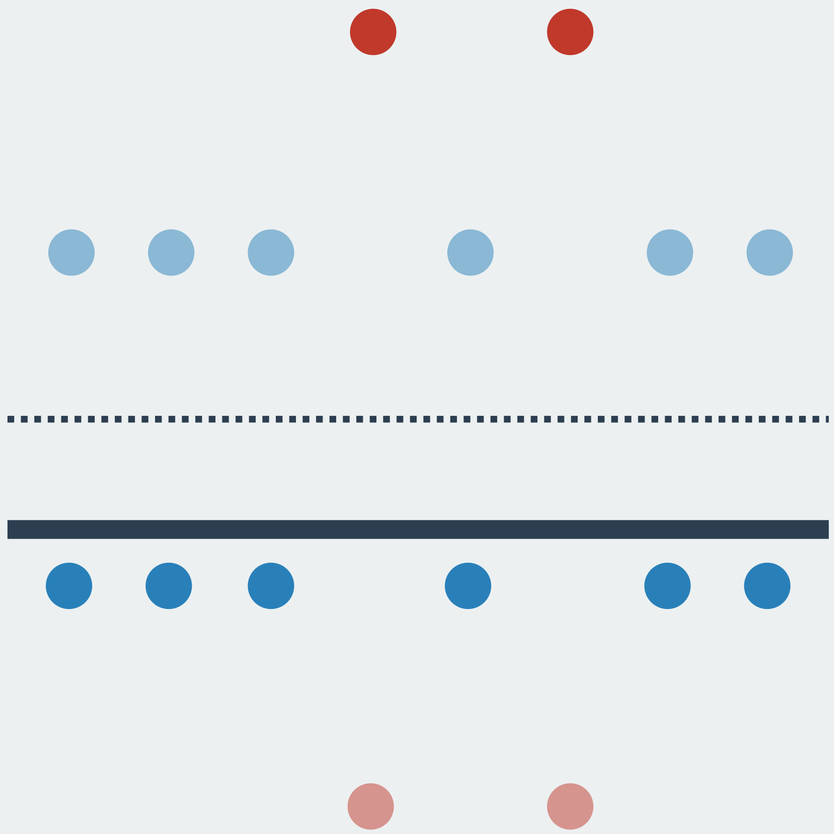

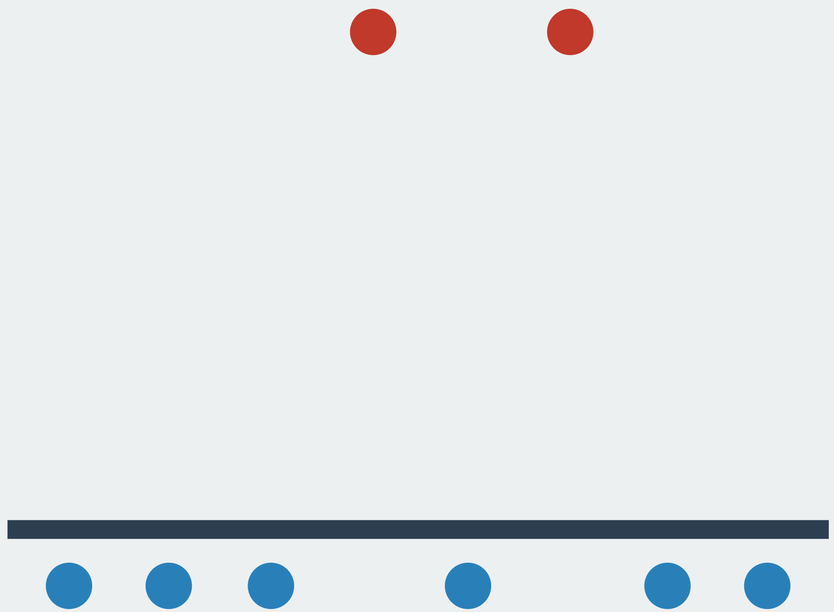

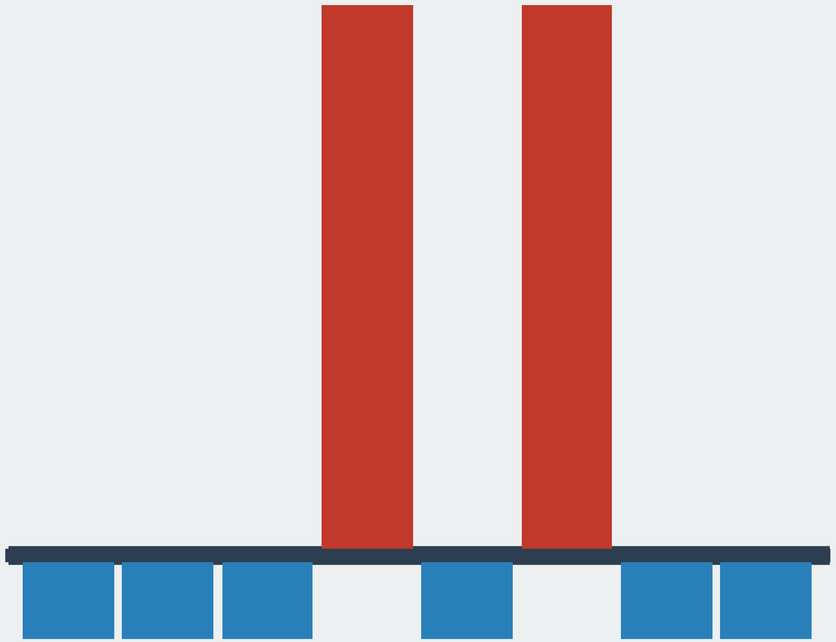

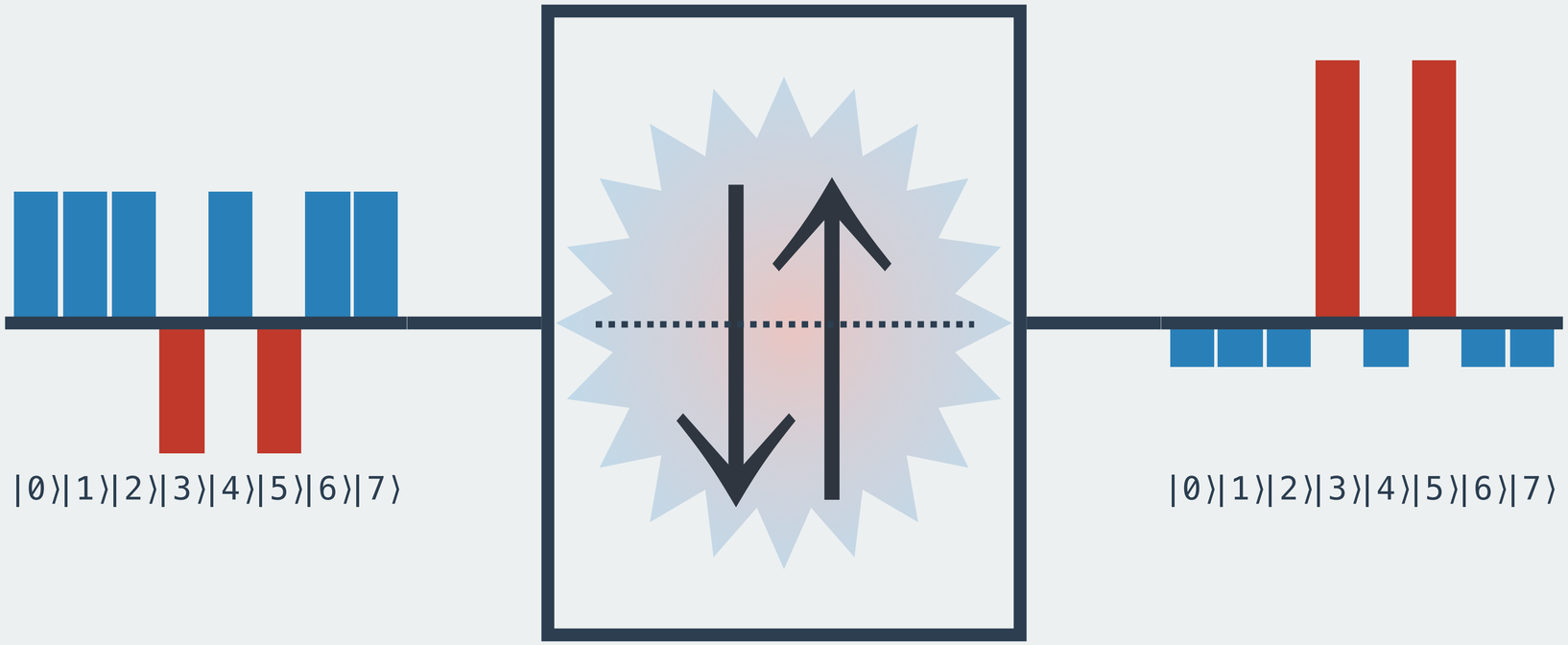
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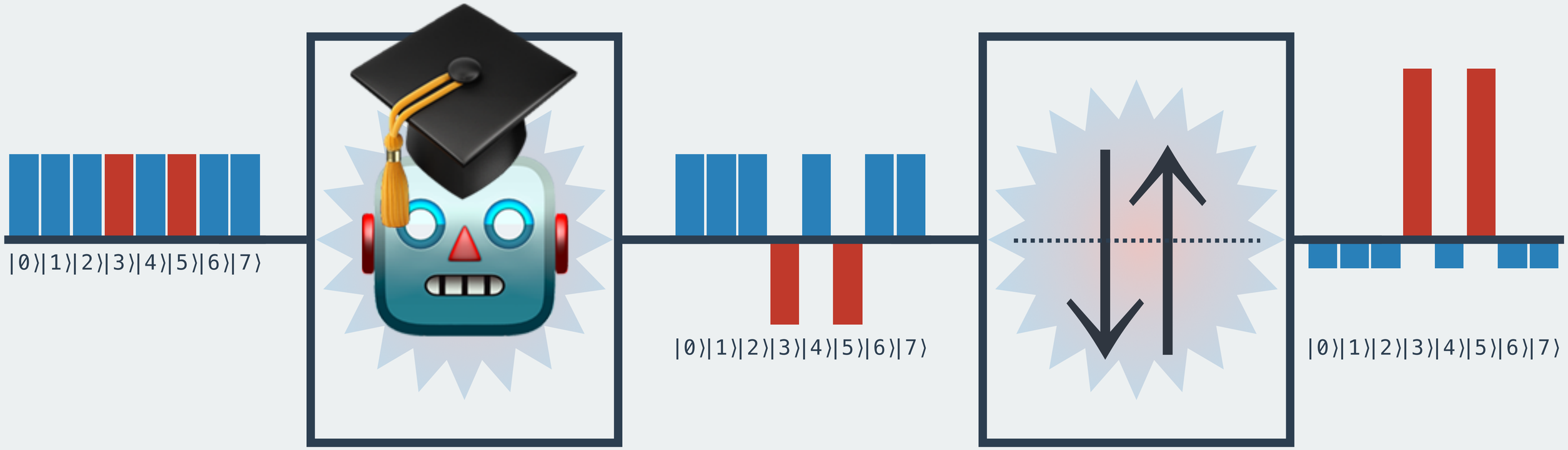
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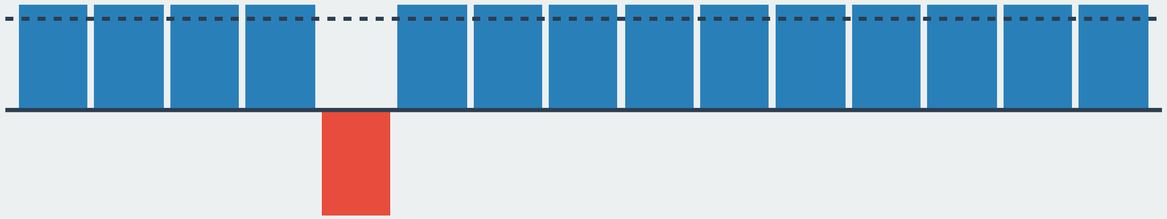
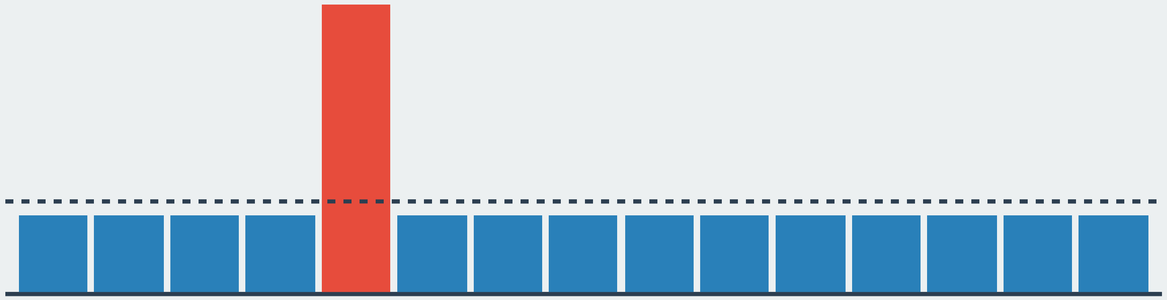
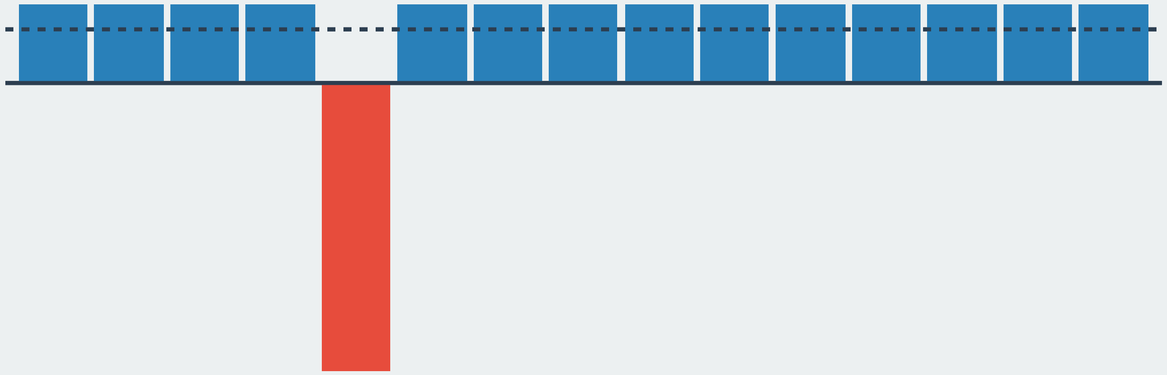
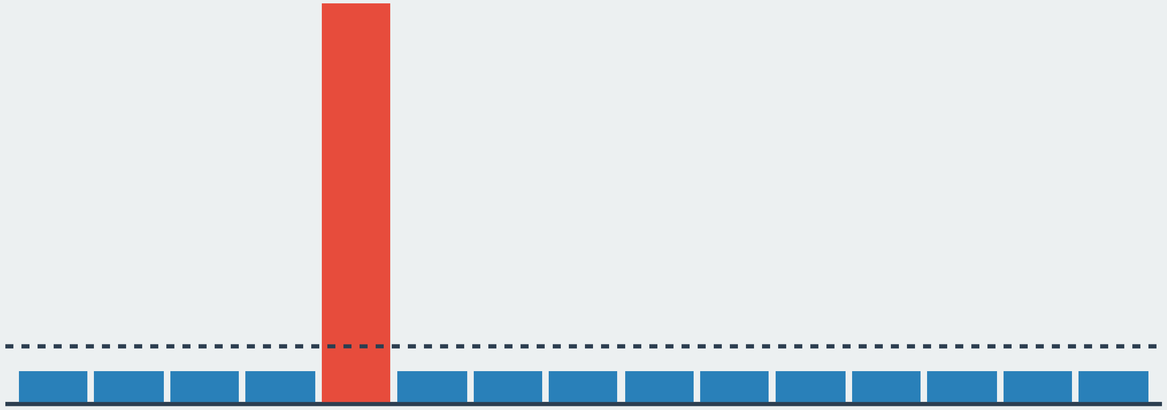
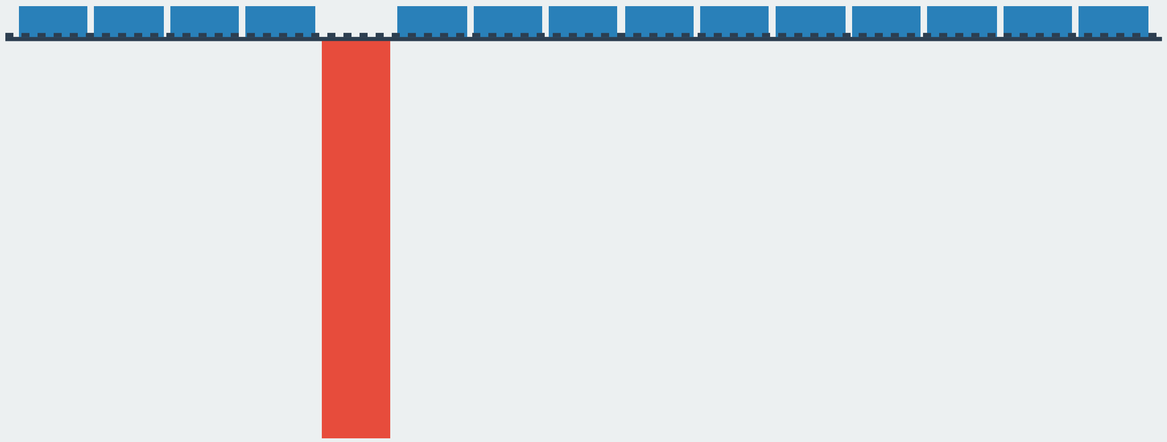
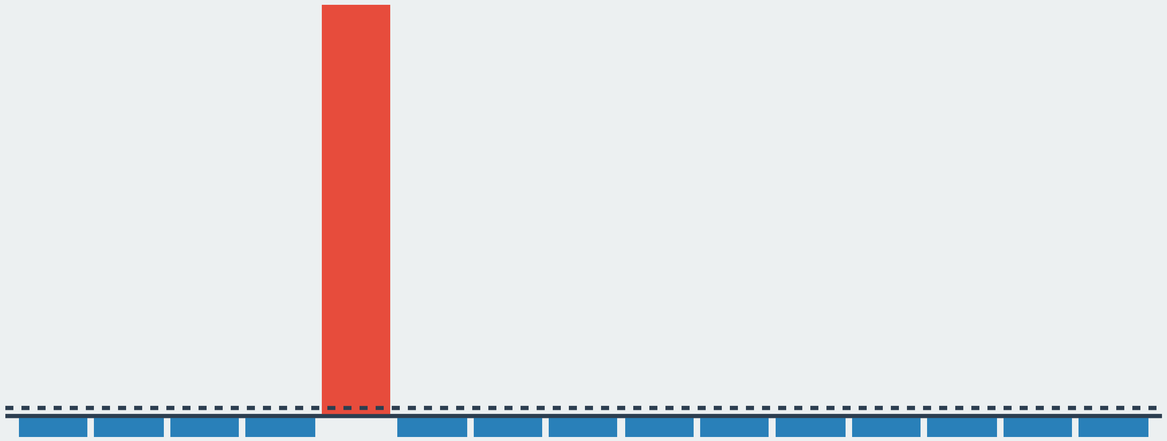


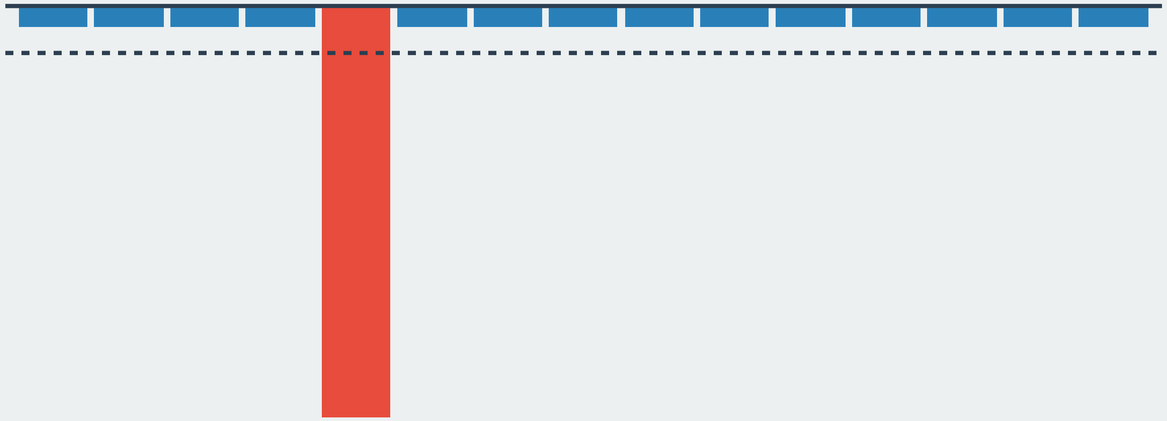


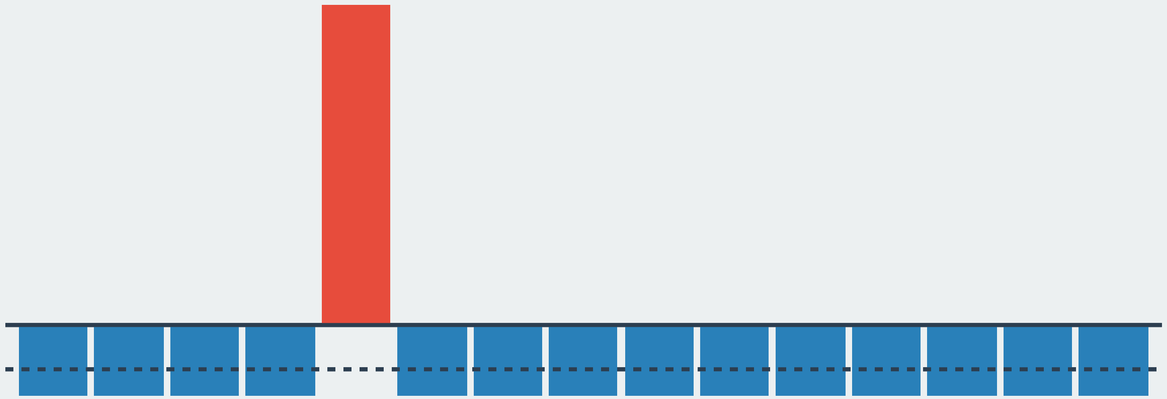


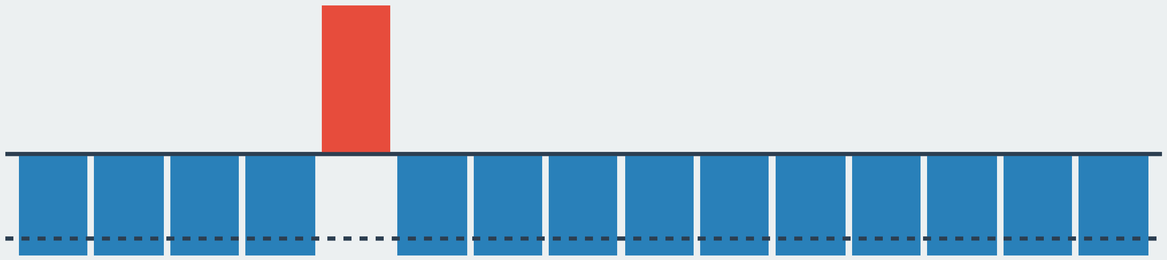


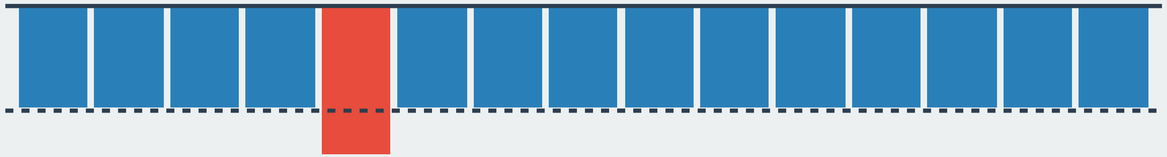


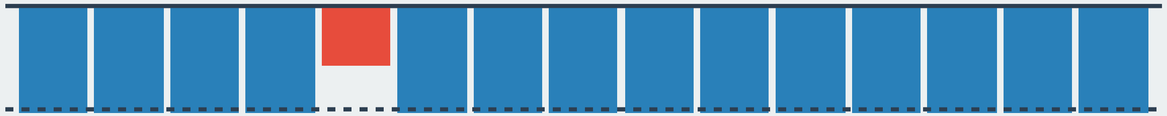




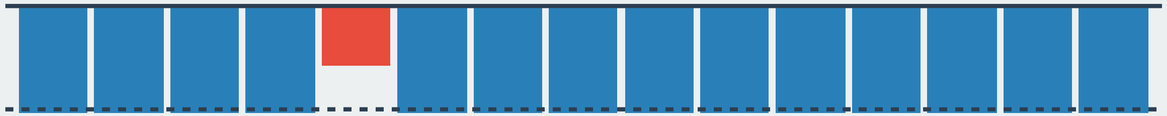








$$\approx \frac{\pi}{4}\sqrt{N/p}$$



naivno iskanje	Groverjev algoritem

naivno iskanje	Groverjev algoritem
N/p	

naivno iskanje	Groverjev algoritem
N/p	$\approx \frac{\pi}{4}\sqrt{N/p}$

naivno iskanje	Groverjev algoritem
N/p	$\approx \frac{\pi}{4}\sqrt{N/p}$
1 000 000	

naivno iskanje	Groverjev algoritem
N/p	$\approx \frac{\pi}{4}\sqrt{N/p}$
1 000 000	785

naivno iskanje	Groverjev algoritem
N/p	$\approx \frac{\pi}{4}\sqrt{N/p}$
1 000 000	785
1 000 000 000 000	

naivno iskanje	Groverjev algoritem
N/p	$\approx \frac{\pi}{4}\sqrt{N/p}$
1 000 000	785
1 000 000 000 000	785 000

naivno iskanje	Groverjev algoritem
N/p	$\approx \frac{\pi}{4}\sqrt{N/p}$
1 000 000	785
1 000 000 000 000	785 000
12 dni	

naivno iskanje	Groverjev algoritem
N/p	$\approx \frac{\pi}{4}\sqrt{N/p}$
1 000 000	785
1 000 000 000 000	785 000
12 dni	1 sekunda

SHOROV
ALGORITEM

Peter Shor, 1959-

$$21 = ? \cdot ?$$

$$D(21,10) = 1$$

$$10^0 \bmod 21 = 1$$

$$10^0 \bmod 21 = 1$$
$$10^1 \bmod 21 = 10$$

$$10^0 \bmod 21 = 1$$
$$10^1 \bmod 21 = 10$$
$$10^2 \bmod 21 = 16$$

$10^{0} \bmod 21 = 1$

$10^{1} \bmod 21 = 10$

$10^{2} \bmod 21 = 16$

$10^{3} \bmod 21 = 13$

$10^{4} \bmod 21 = 4$

$10^{5} \bmod 21 = 19$

$10^{6} \bmod 21 = 1$

$10^{7} \bmod 21 = 10$

$10^{8} \bmod 21 = 16$

$10^{9} \bmod 21 = 13$

$10^{10} \bmod 21 = 4$

$10^{11} \bmod 21 = 19$

$10^{12} \bmod 21 = 1$

$10^{13} \bmod 21 = 10$

$10^{14} \bmod 21 = 16$

$10^{15} \bmod 21 = 13$

$10^{16} \bmod 21 = 4$

$10^{17} \bmod 21 = 19$

$10^{18} \bmod 21 = 1$

$10^{19} \bmod 21 = 10$

$10^{20} \bmod 21 = 16$

$10^{21} \bmod 21 = 13$

$10^{22} \bmod 21 = 4$

$10^{23} \bmod 21 = 19$

$$10^6 \bmod 21 = 1$$

$$10^6 \bmod 21 = 1$$

$$(10^6 - 1) \bmod 21 = 0$$

$$10^6 \bmod 21 = 1$$

$$(10^6 - 1) \bmod 21 = 0$$

$$(10^3 - 1)(10^3 + 1) \bmod 21 = 0$$

$$D(10^3 - 1, 21) = 3$$

$$D(10^3 - 1, 21) = 7$$

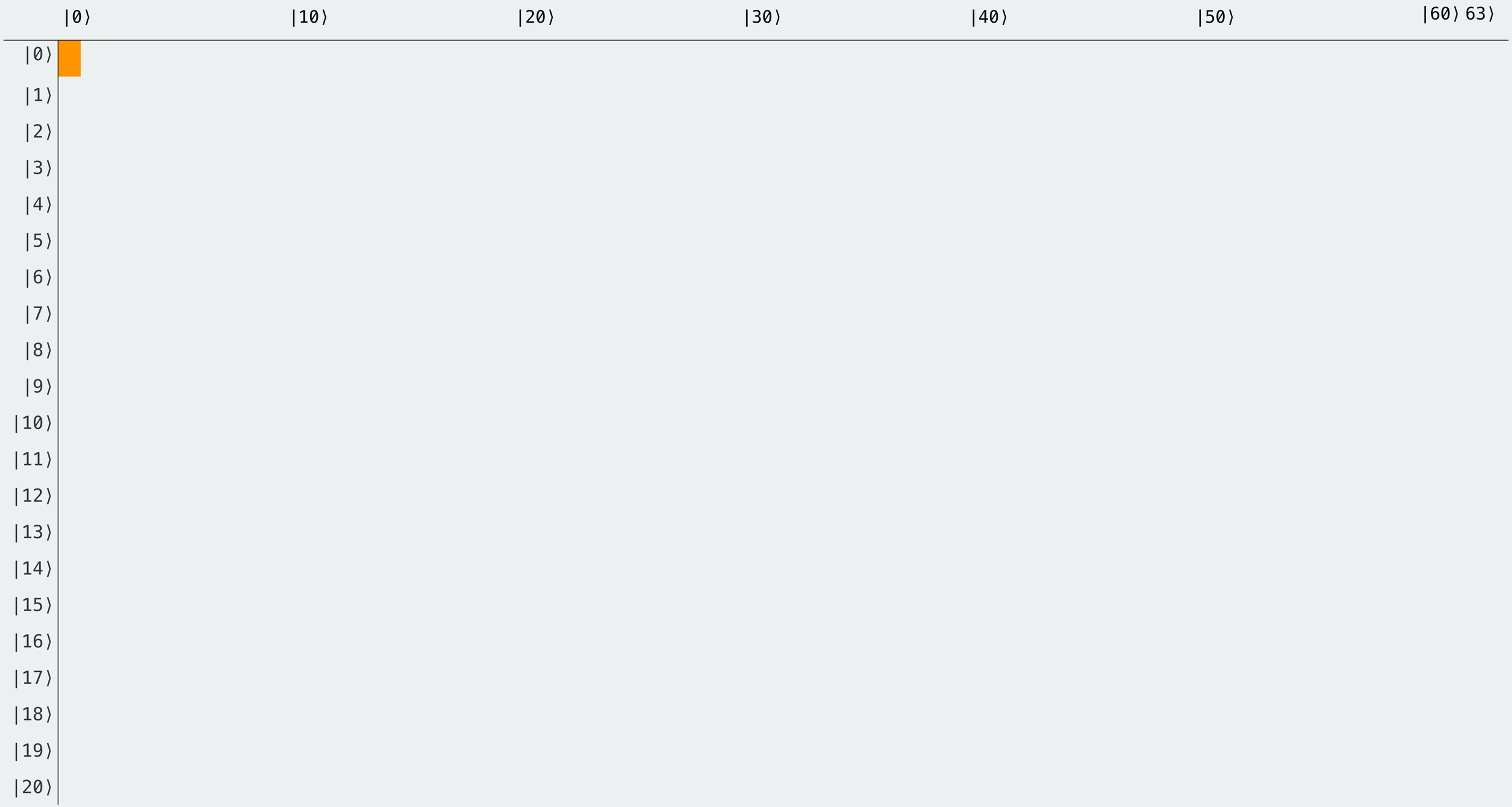
$10^2 \bmod 21 \quad \cdots \quad 10^{64} \bmod 21$

$10^2 \bmod 21 \quad \cdots \quad 10^{64} \bmod 21$

$21 \bmod 2 \quad \cdots \quad 21 \bmod 20$

$10^2 \bmod 21 \quad \cdots \quad 10^{64} \bmod 21$

$21 \bmod 2 \quad \cdots \quad 21 \bmod 20$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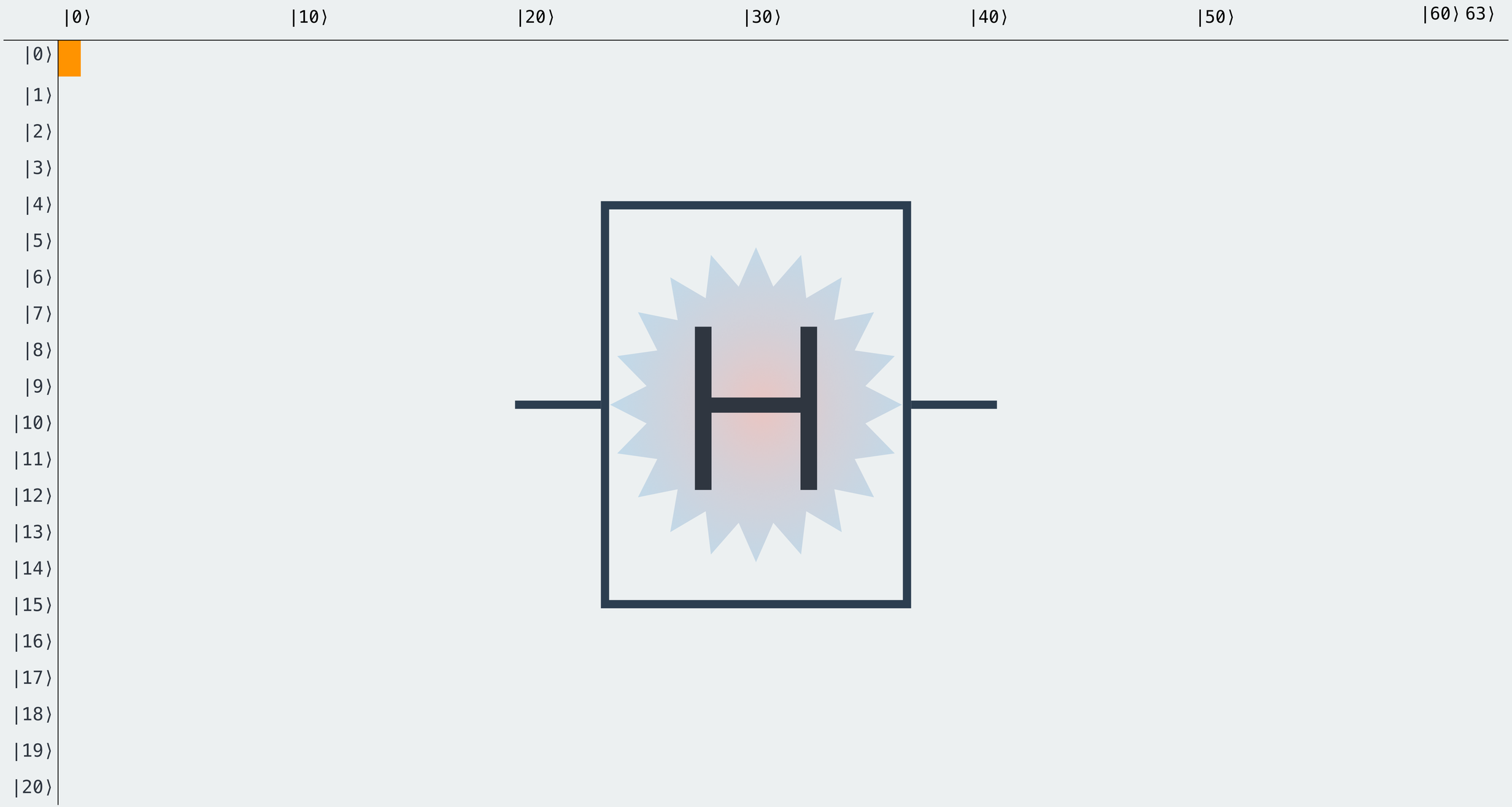
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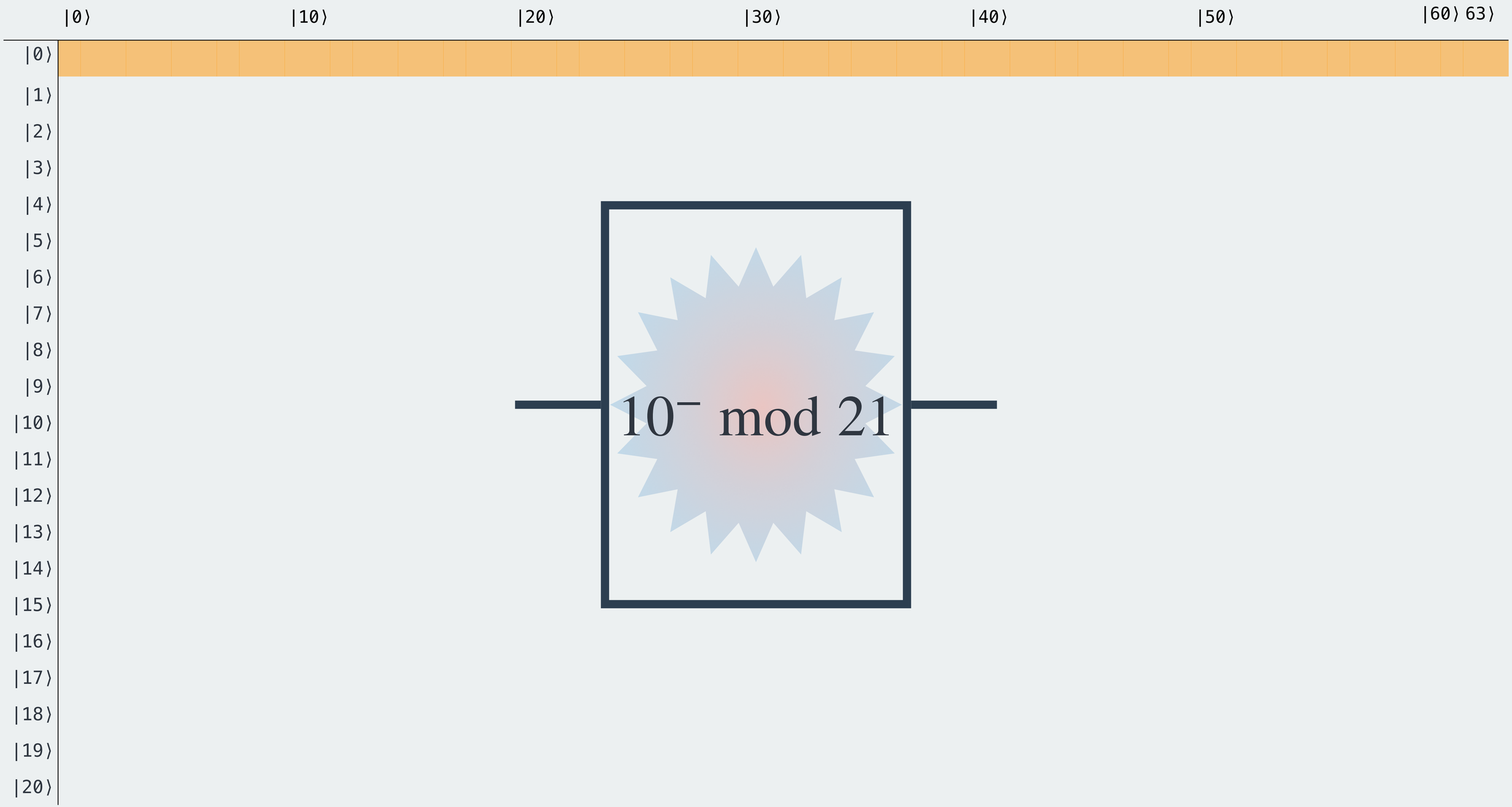
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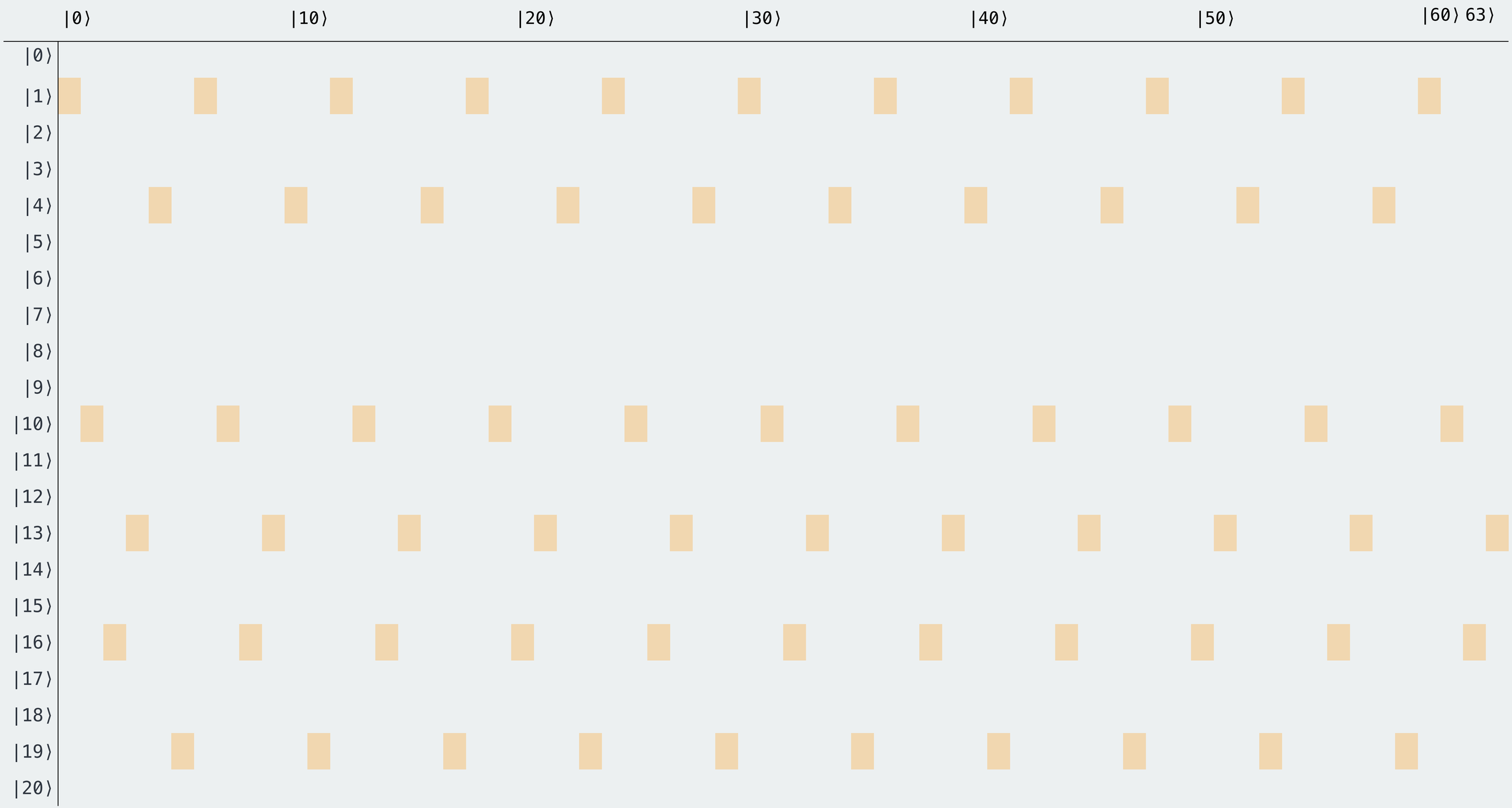
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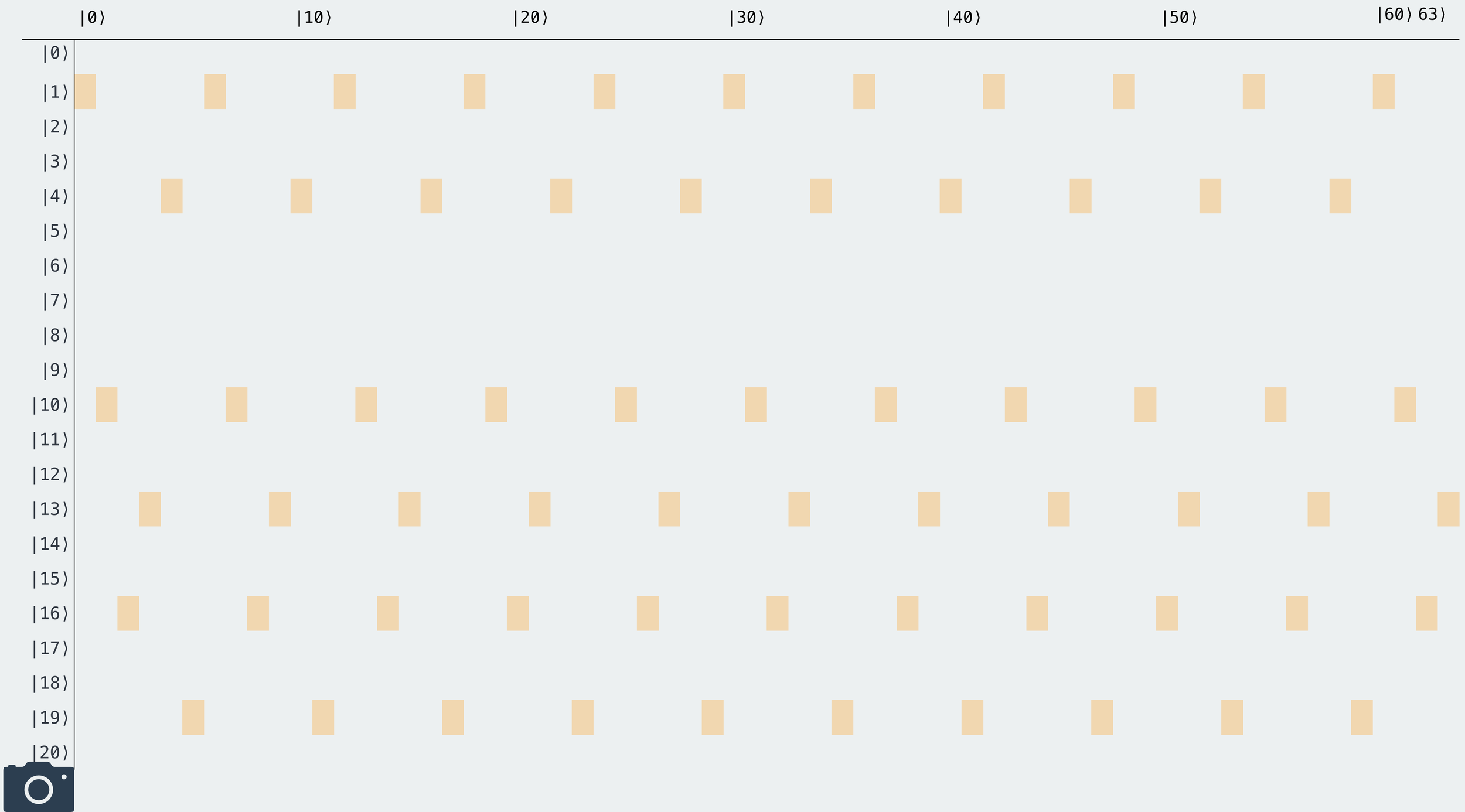
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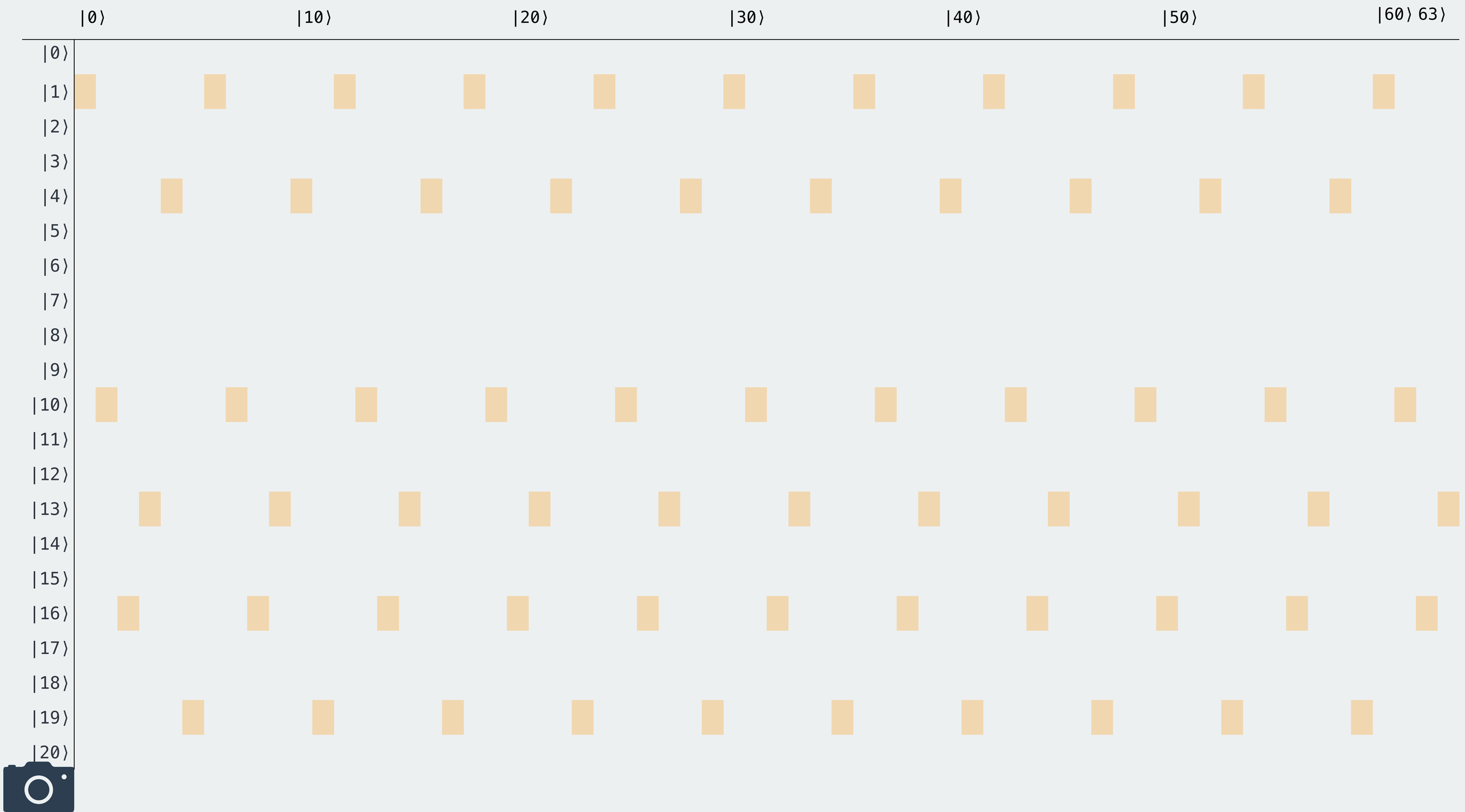
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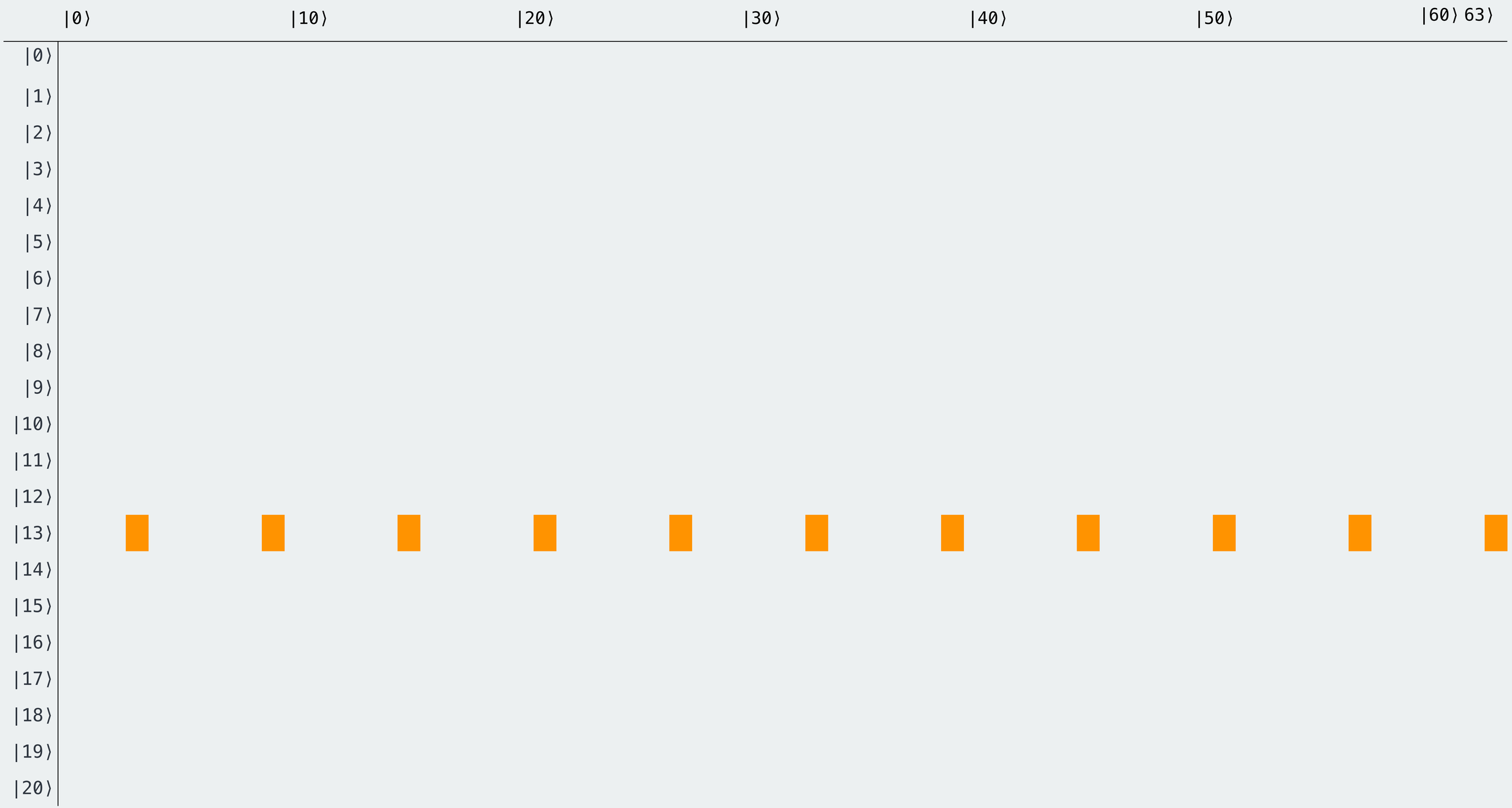
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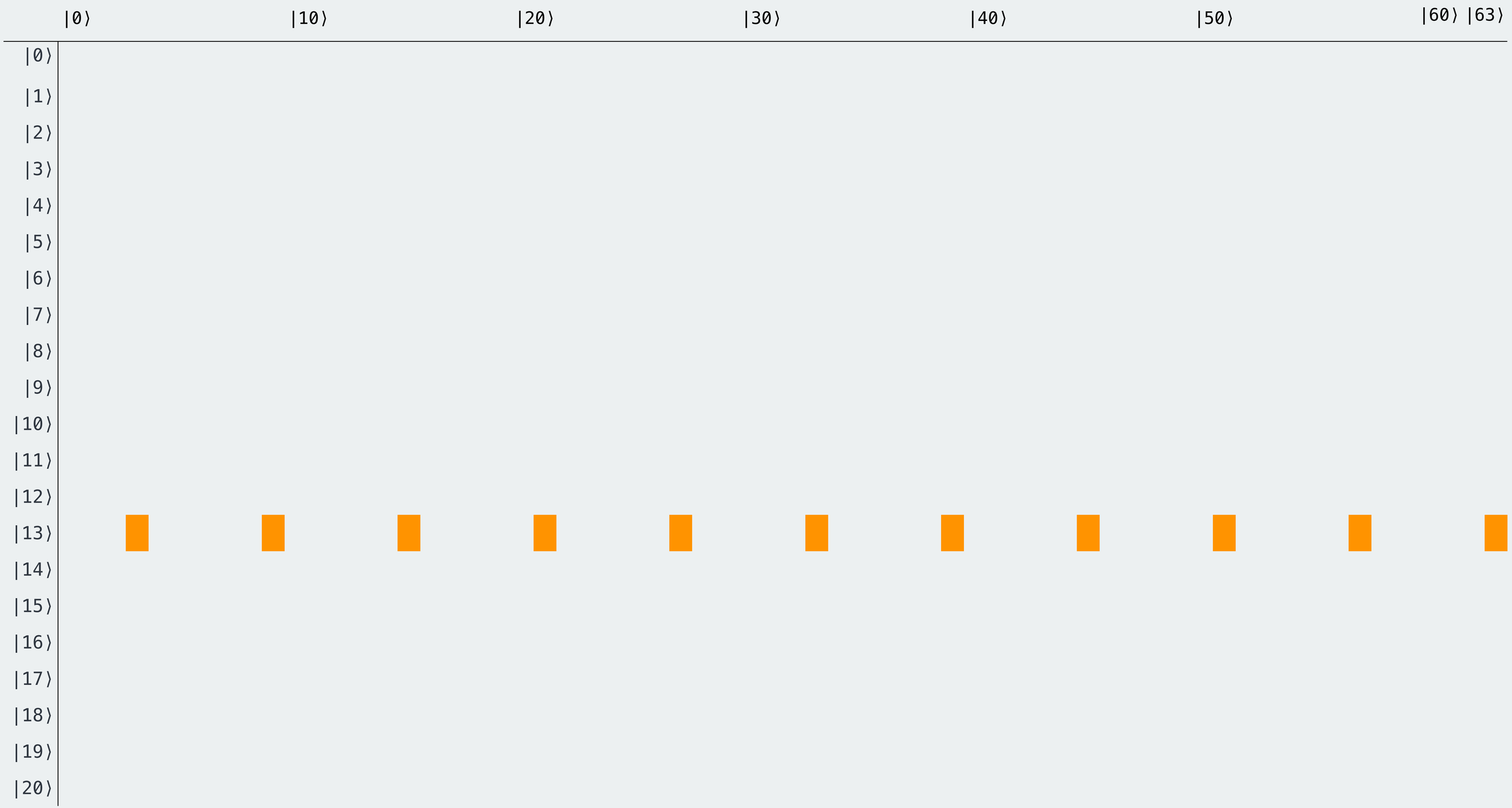
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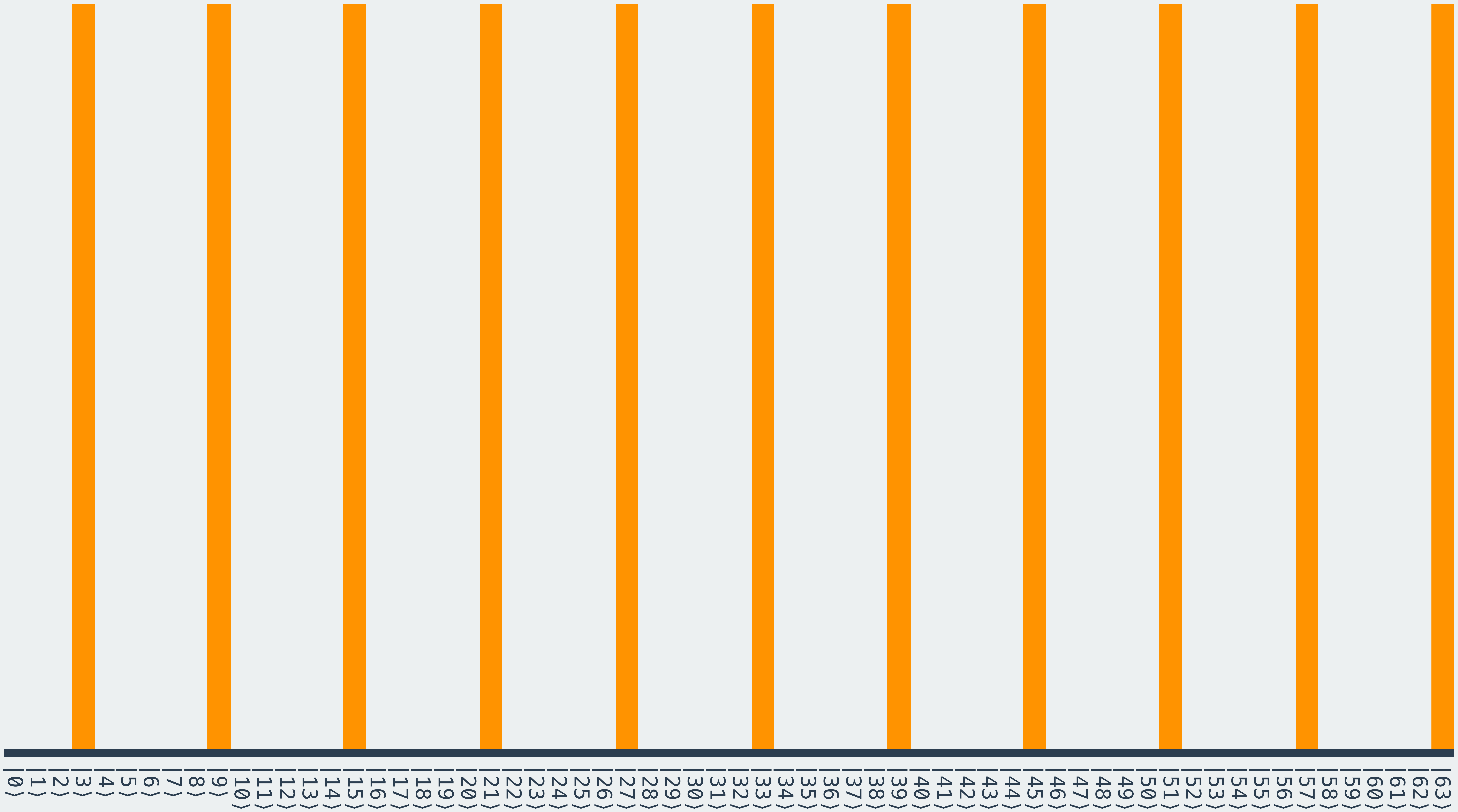
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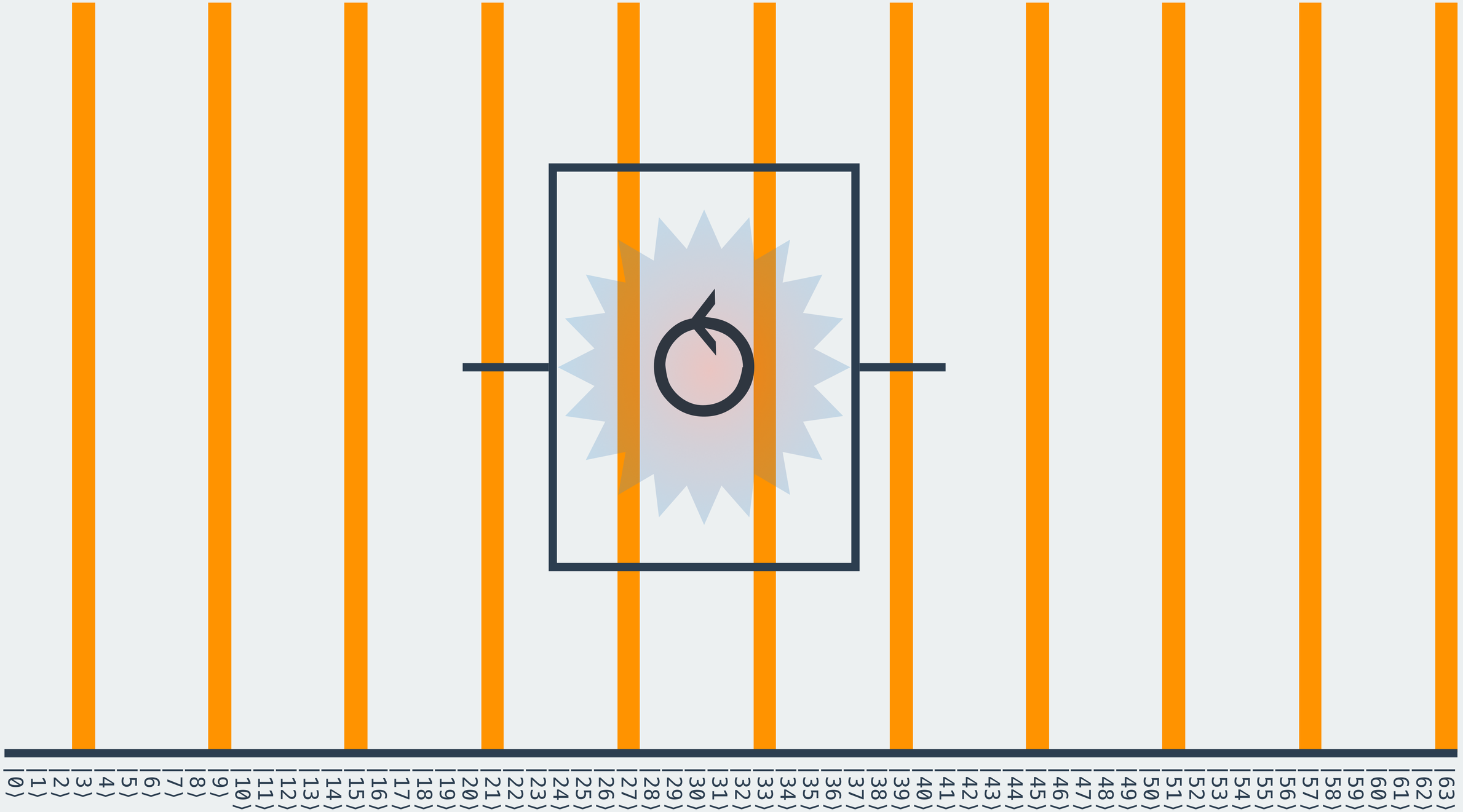
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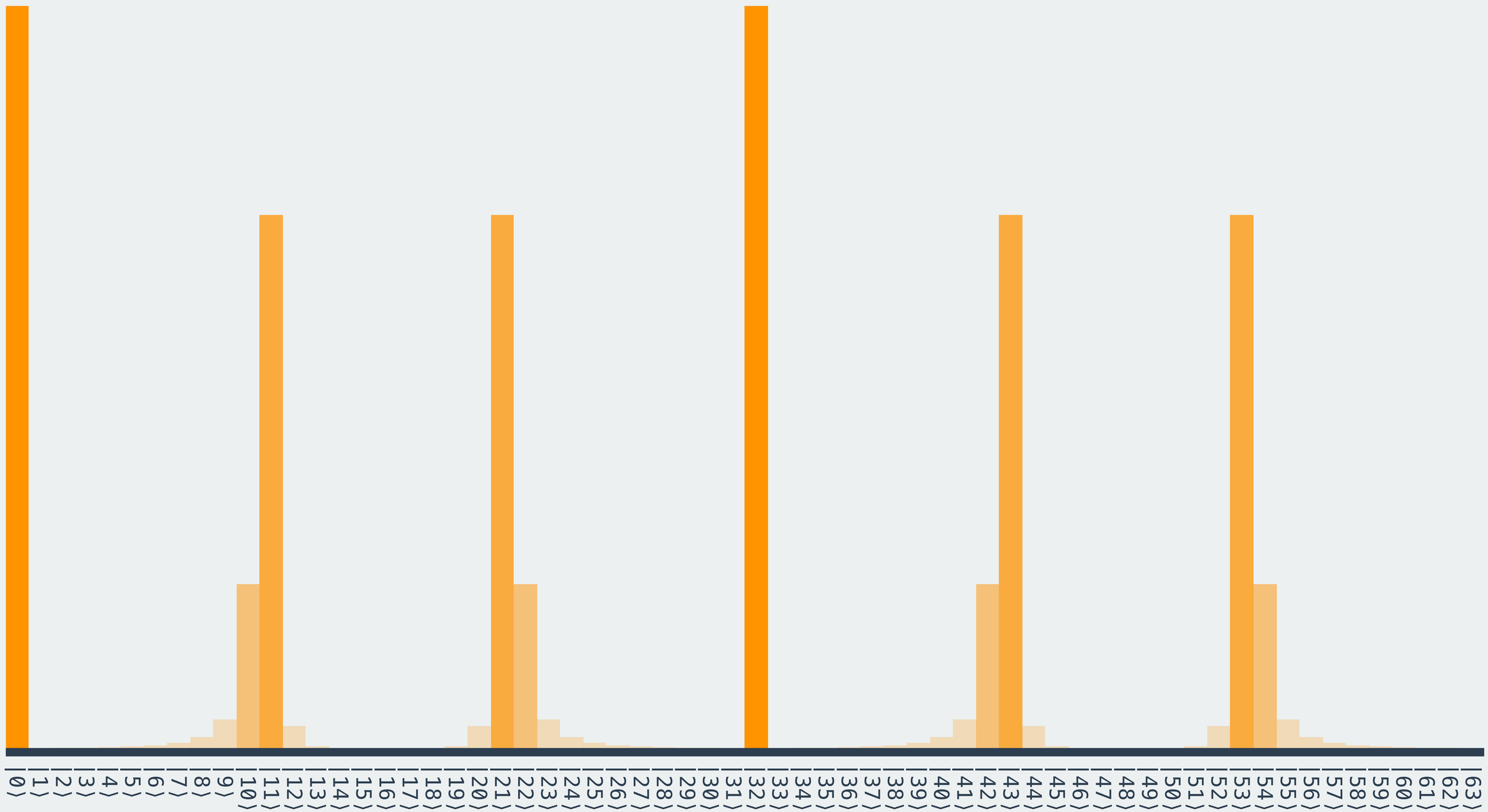
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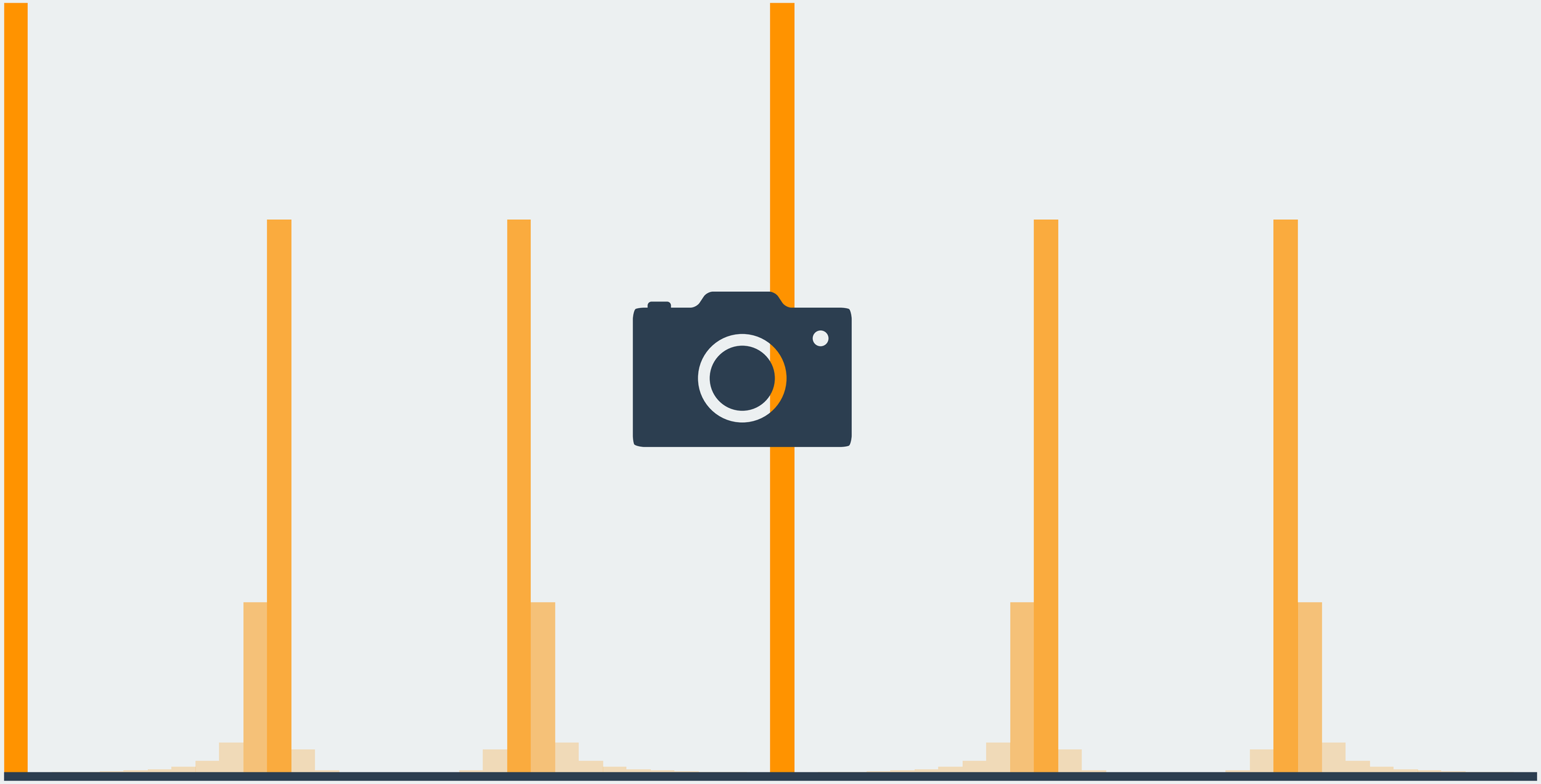
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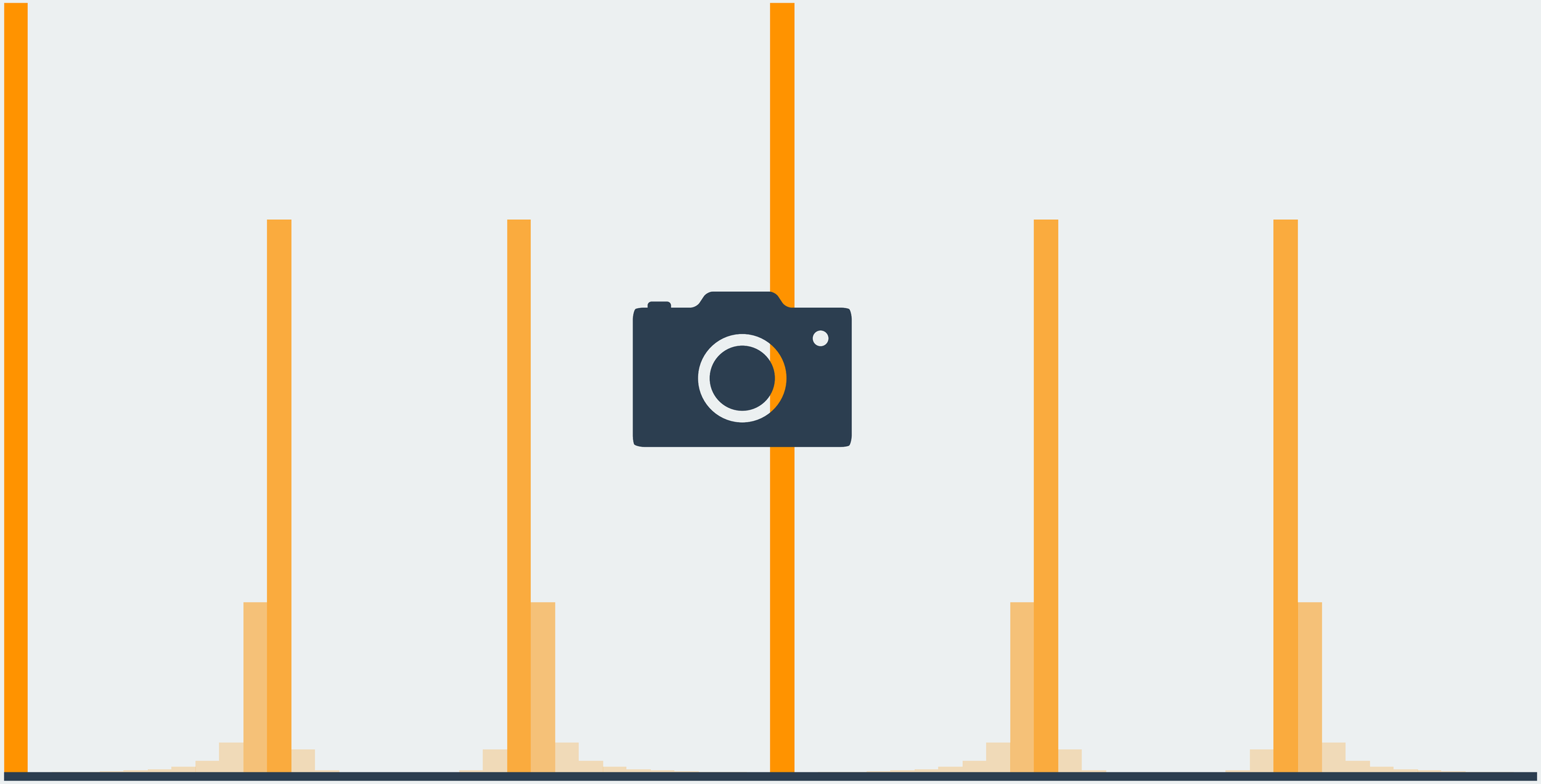
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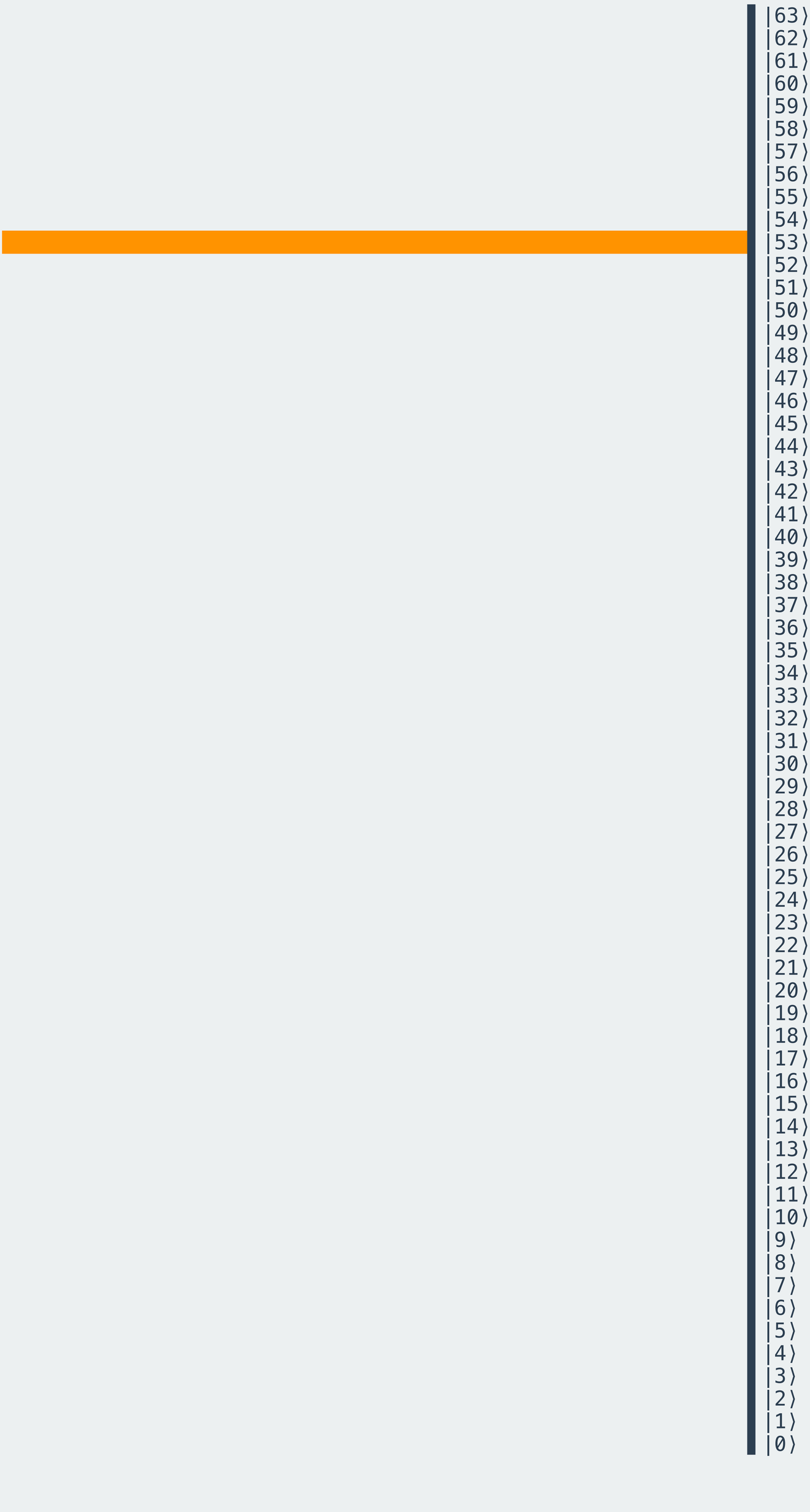
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$$\frac{53}{64} = \frac{1}{1 + \frac{11}{53}}$$

$$\frac{53}{64} = \frac{1}{1 + \frac{11}{53}} \approx \frac{1}{1} = 1$$

$$\frac{53}{64} = \frac{1}{1 + \frac{11}{53}} \approx \frac{1}{1} = 1$$

$$= \frac{1}{1 + \frac{1}{4 + \frac{9}{11}}}$$

$$\frac{53}{64} = \frac{1}{1 + \frac{11}{53}} \approx \frac{1}{1} = 1$$

$$= \frac{1}{1 + \frac{1}{4 + \frac{9}{11}}} \approx \frac{1}{1 + \frac{1}{4}} = \frac{4}{5}$$

$$\frac{53}{64} = \frac{1}{1 + \frac{11}{53}} \approx \frac{1}{1} = 1$$

$$= \frac{1}{1 + \frac{1}{4 + \frac{9}{11}}} \approx \frac{1}{1 + \frac{1}{4}} = \frac{4}{5}$$

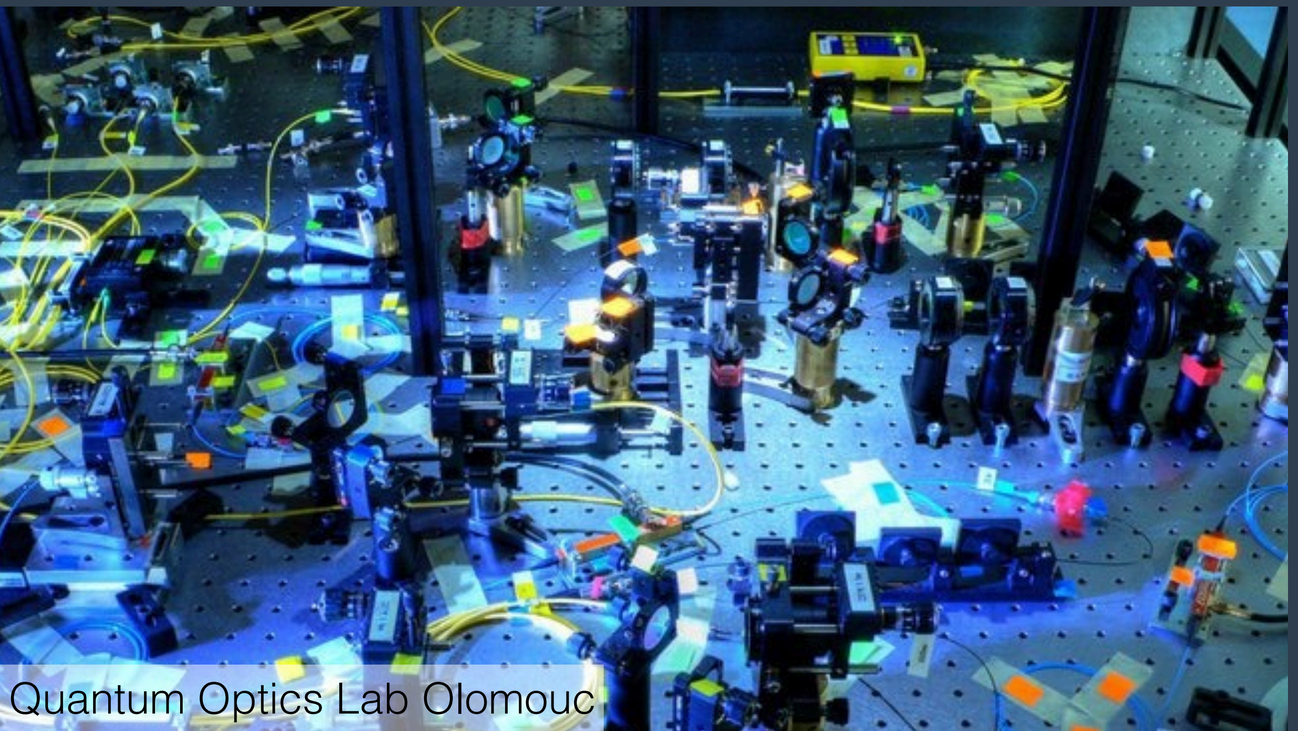
$$= \frac{1}{1 + \frac{1}{4 + \frac{1}{1 + \frac{2}{9}}}}$$

$$\frac{53}{64} = \frac{1}{1 + \frac{11}{53}} \approx \frac{1}{1} = 1$$

$$= \frac{1}{1 + \frac{1}{4 + \frac{9}{11}}} \approx \frac{1}{1 + \frac{1}{4}} = \frac{4}{5}$$

$$= \frac{1}{1 + \frac{1}{4 + \frac{1}{1 + \frac{2}{9}}}} \approx \frac{1}{1 + \frac{1}{4 + \frac{1}{1}}} = \frac{5}{6}$$

Shorov algoritem



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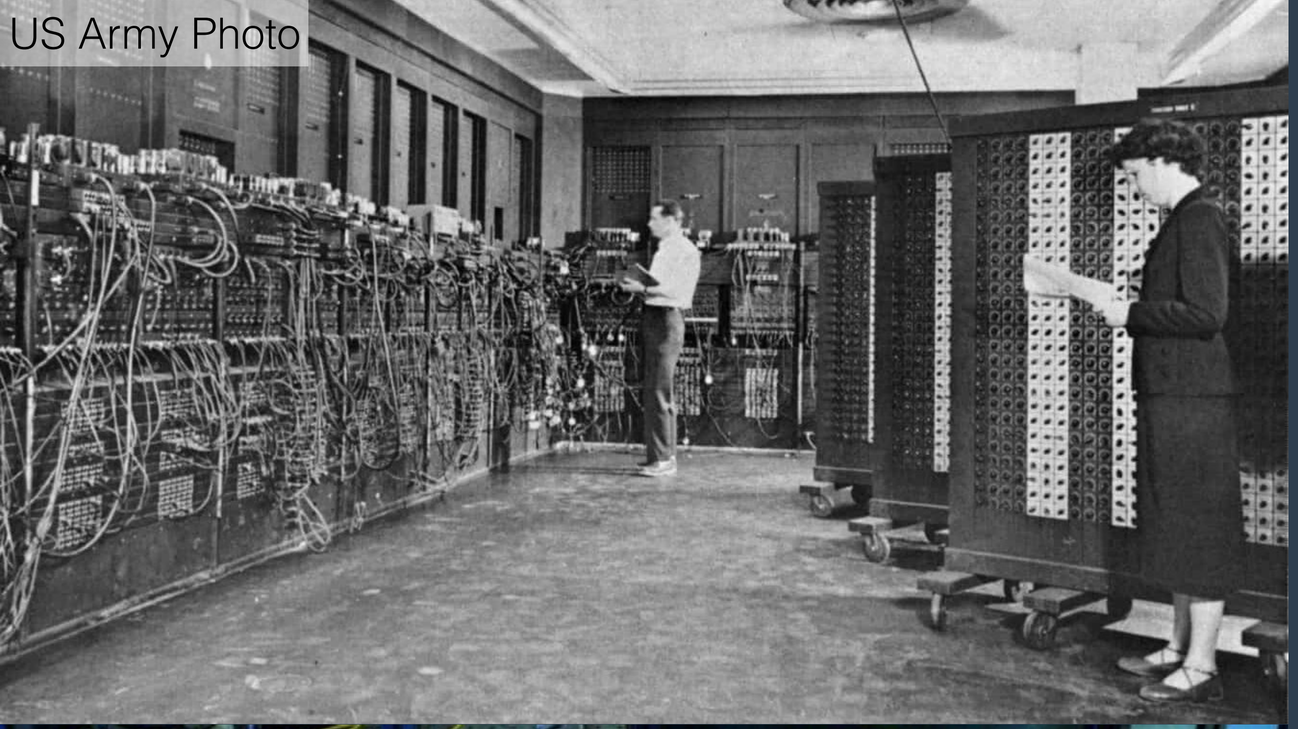

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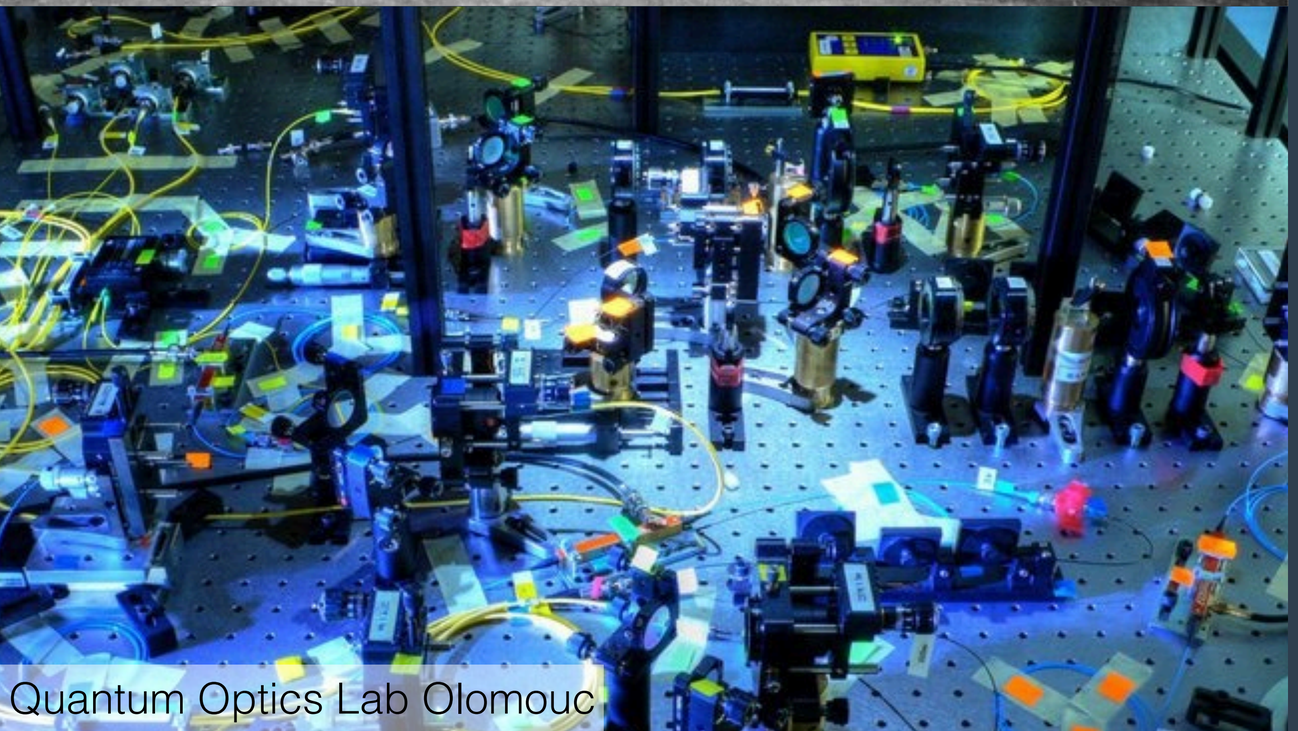

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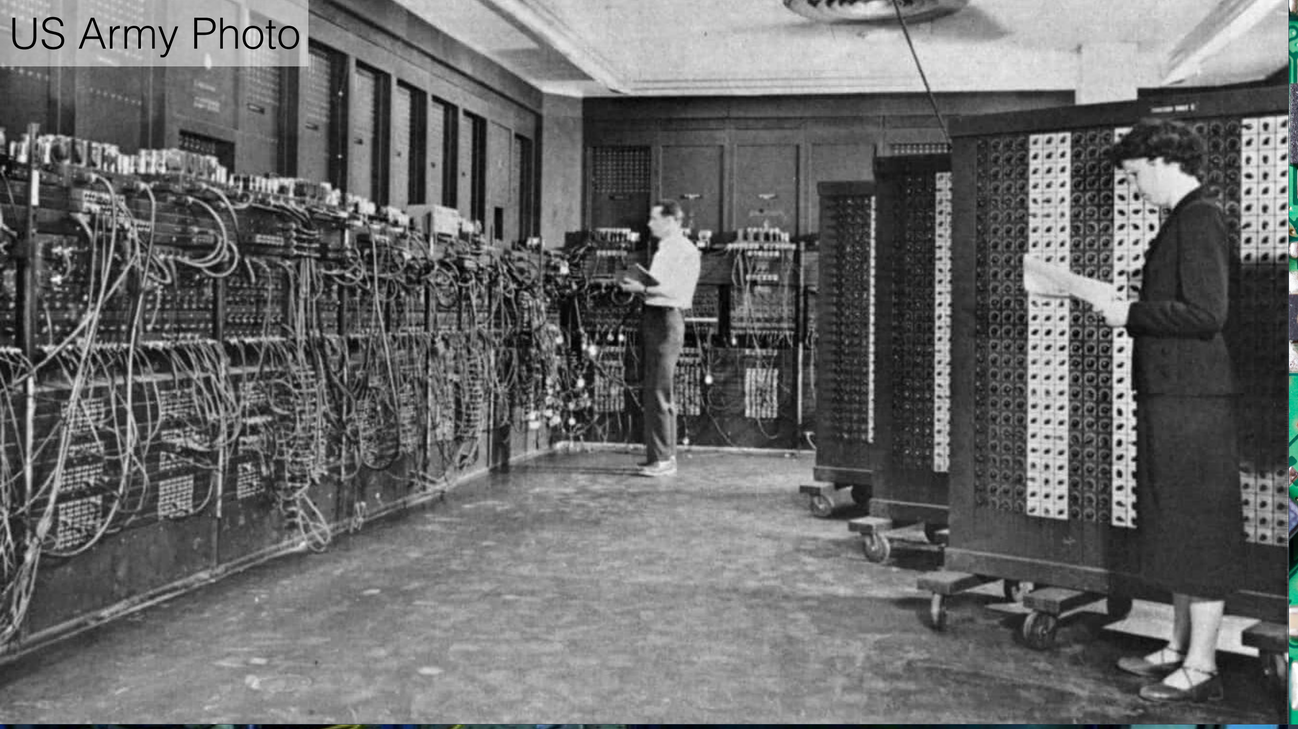

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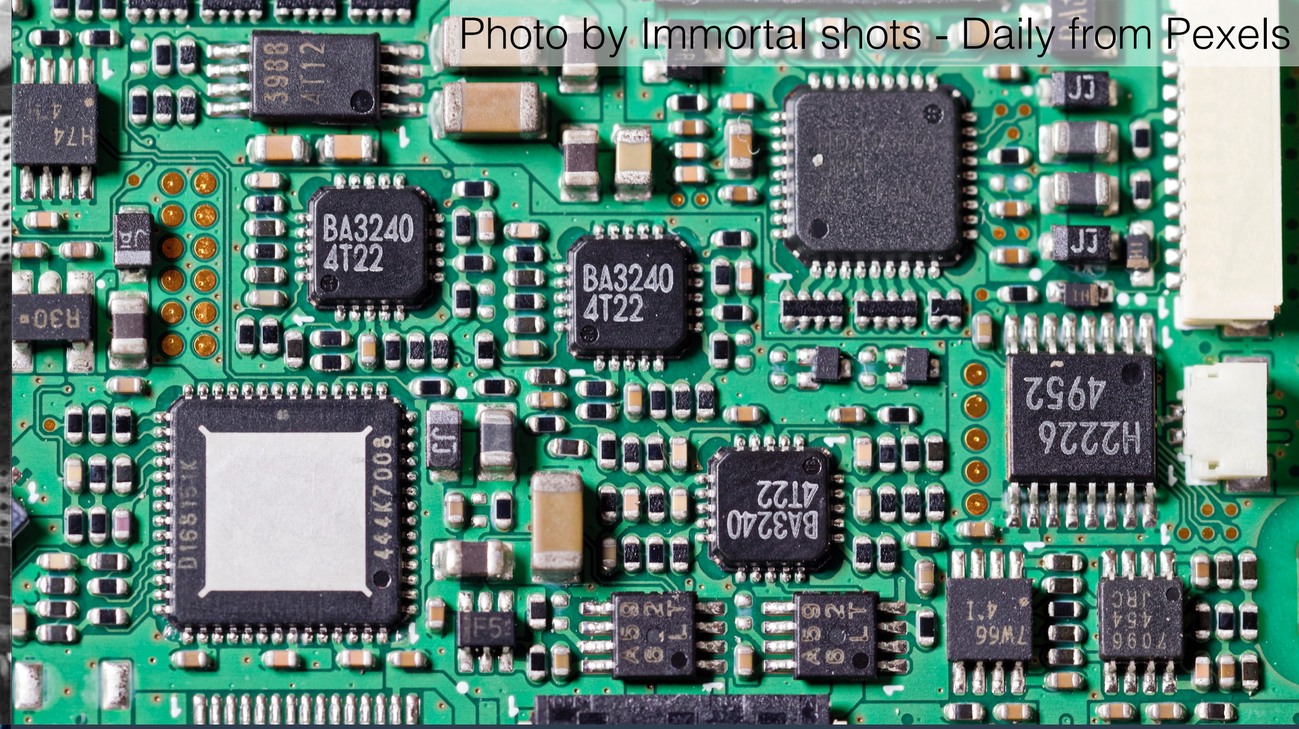

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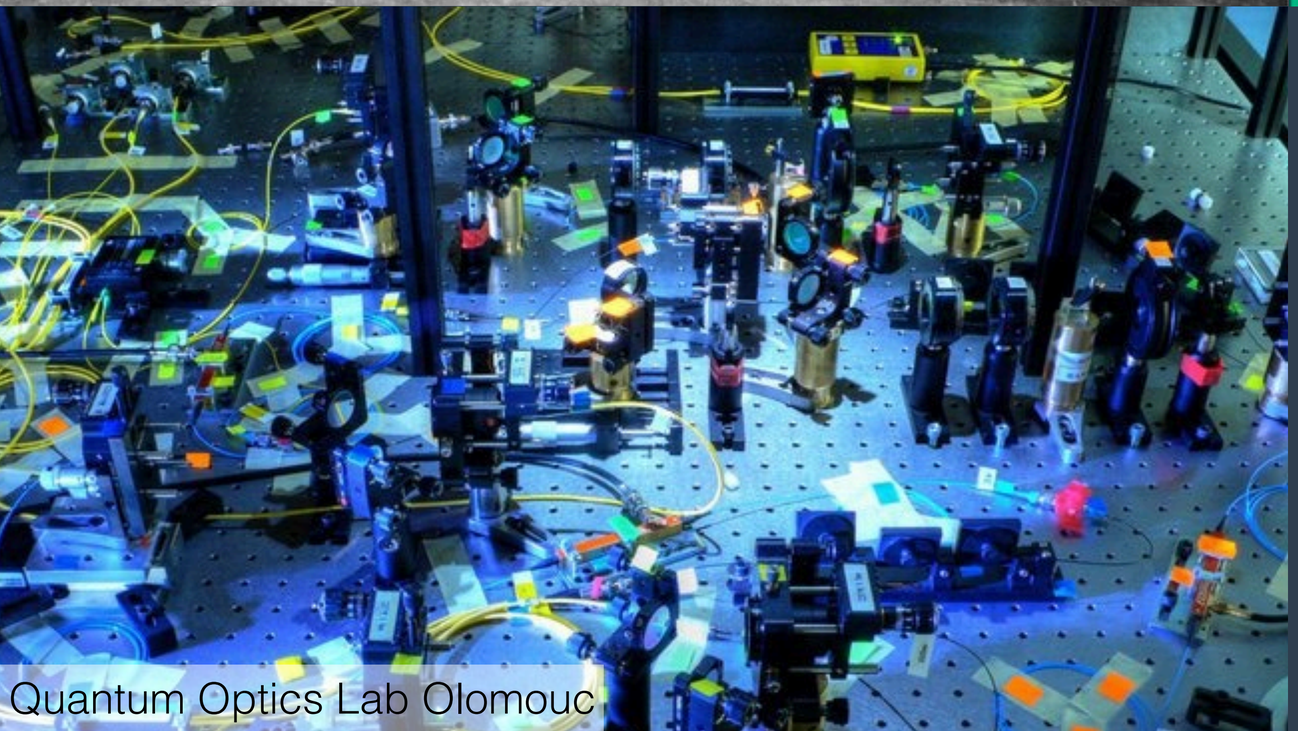

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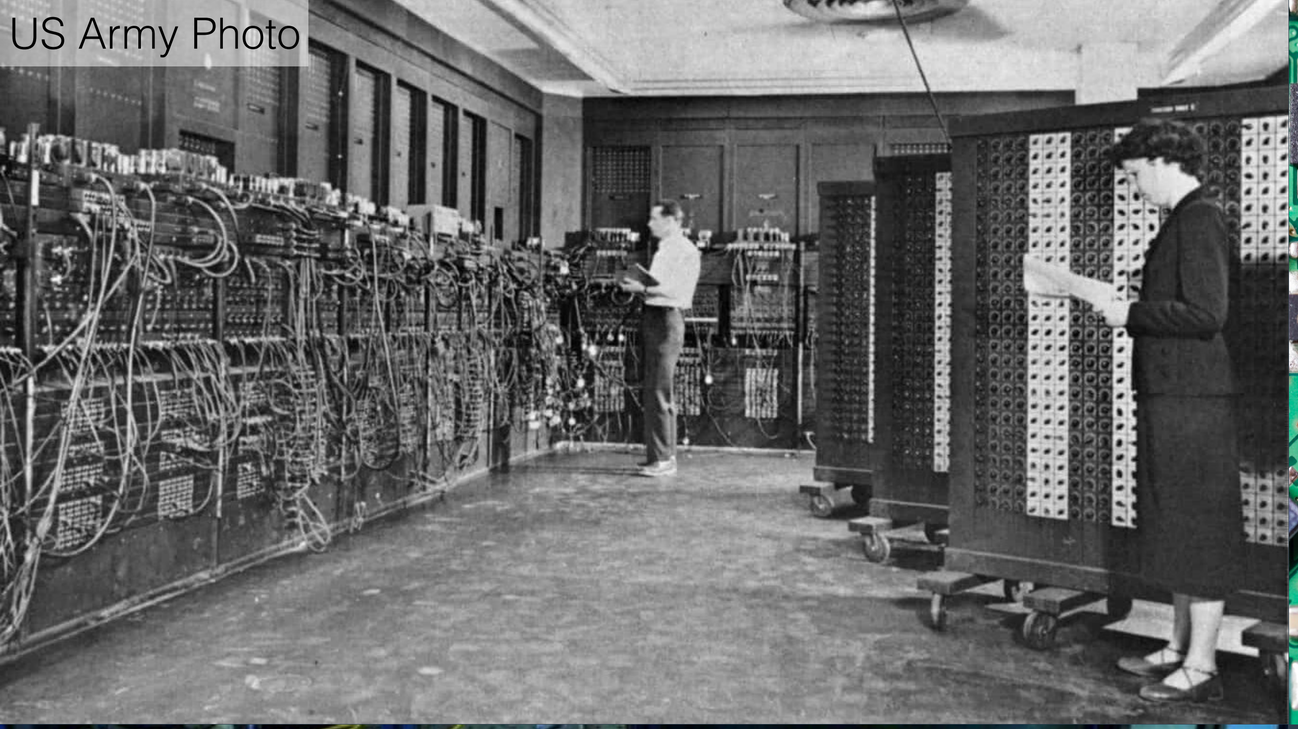

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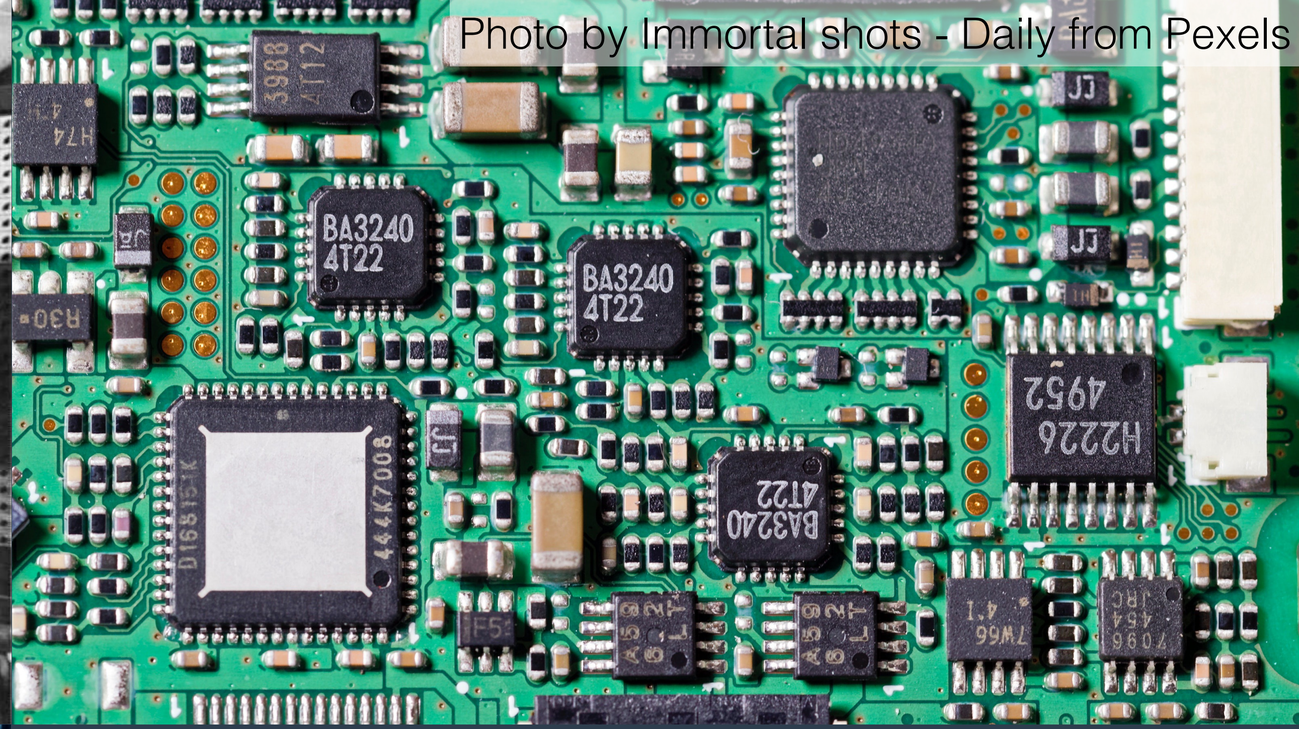

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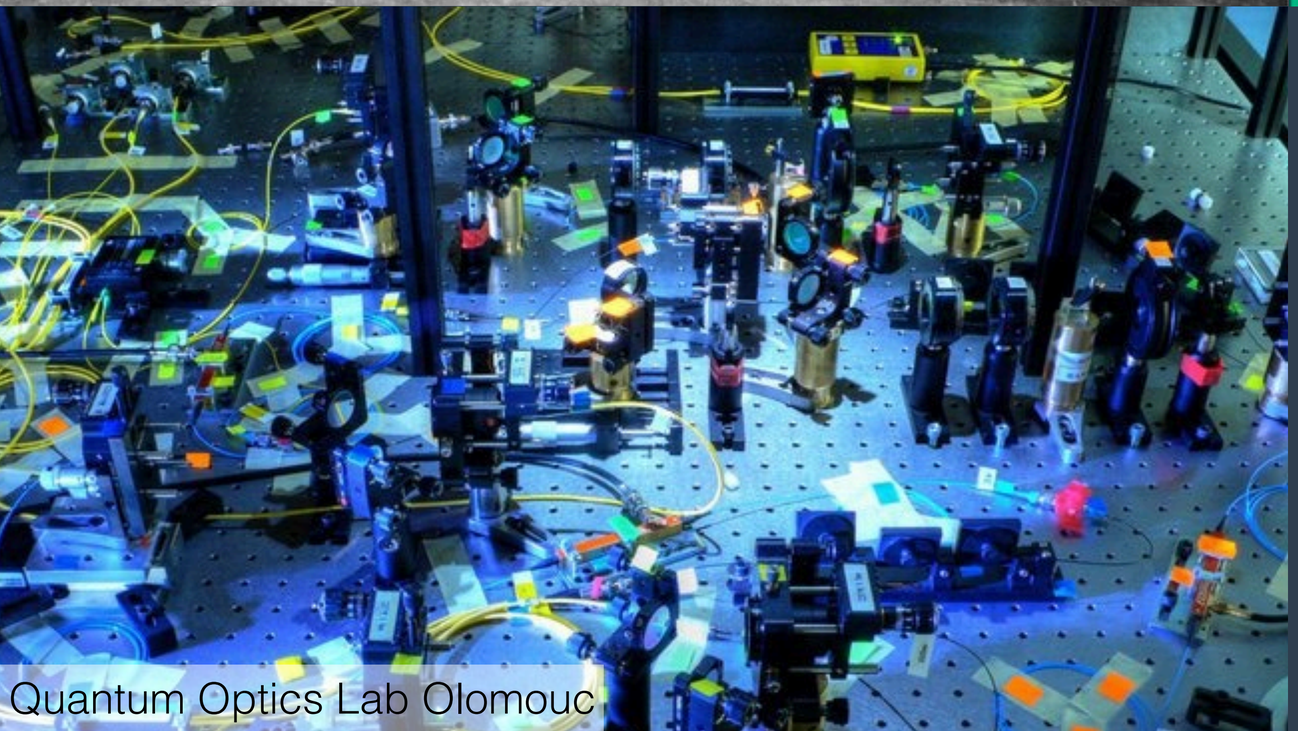

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?

OSNOVE KVANTNEGA RAČUNALNIŠTVA

MATIJA PRETNAR

Fakulteta za matematiko in fiziko
Univerza v Ljubljani

Math. Subj. Class. (2010): 68Q12, 81P68

Kvantno računalništvo skuša z izkoriščanjem kvantnih pojavov, kakršni sta superpozicija in prepletenost, učinkoviteje reševati računsko zahtevne probleme. V članku si ogledamo postulate kvantne mehanike, kvantno teleportacijo, Deutschev algoritem, ki je bil prvi kvantni algoritem, ter najznamenitejša kvantna algoritma: Groverjev algoritem za iskanje v neurejeni tabeli in Shorov algoritem za razcep na praštevila.

THE BASICS OF QUANTUM COMPUTING

Quantum computing uses quantum phenomena such as superposition and entanglement in order to efficiently solve computationally hard problems. The paper looks at the quantum mechanics postulates, quantum teleportation, Deutsch's algorithm, which was the first quantum algorithm, and at two most famous quantum algorithms: Grover's search algorithm and Shor's factorization algorithm.

Uvod

V svetu majhnih delcev ne veljajo več pravila klasične Newtonove mehanike, kot smo jih navajeni, temveč nastopijo nenavadna pravila kvantne mehanike. Po teh pravilih se delci obnašajo tako, kot bi bili na več koncih hkrati, vendar le toliko časa, dokler jim ne izmerimo položaja. Ko pa ga enkrat izmerimo, se obnašajo le v skladu z rezultatom meritve. Primer takega vedenja vidimo v poskusu z dvojno režo (slika 1), v katerem streljamo fotone proti zaslonu z dvema ozkima režama, za zaslonom pa postavimo senzor, ki meri, kam so prileteli fotoni, ki jim je uspelo priti mimo.

Če eno od rež zapremo, največ zadetkov po pričakovanjih izmerimo za drugo režo. Če odpremo obe reži, bi tako pričakovali dva vrhova, za vsako režo po enega. V resnici pa dobimo interferenčni vzorec. Lahko bi si ga poskušali razložiti s tem, da fotoni na svoji poti motijo drug drugega, vendar dobimo tako sliko tudi, če poskrbimo, da naenkrat streljamo samo en foton. Torej obe možni poti, po katerih bi lahko potoval foton, motita druga drugo. Še več: če postavimo dodaten senzor, s katerim poskušamo ugotoviti, skozi katero režo je šel foton, interferenca izgine, za zaslonom pa izmerimo vrhova, ki smo ju pričakovali prej.

Kvantno računalništvo poskuša te neobičajne kvantne pojave izkoristiti za učinkovitejše računanje. S kvantnim računalništvom je pričel znani fizik

HVALA ZA
POZORNOST!