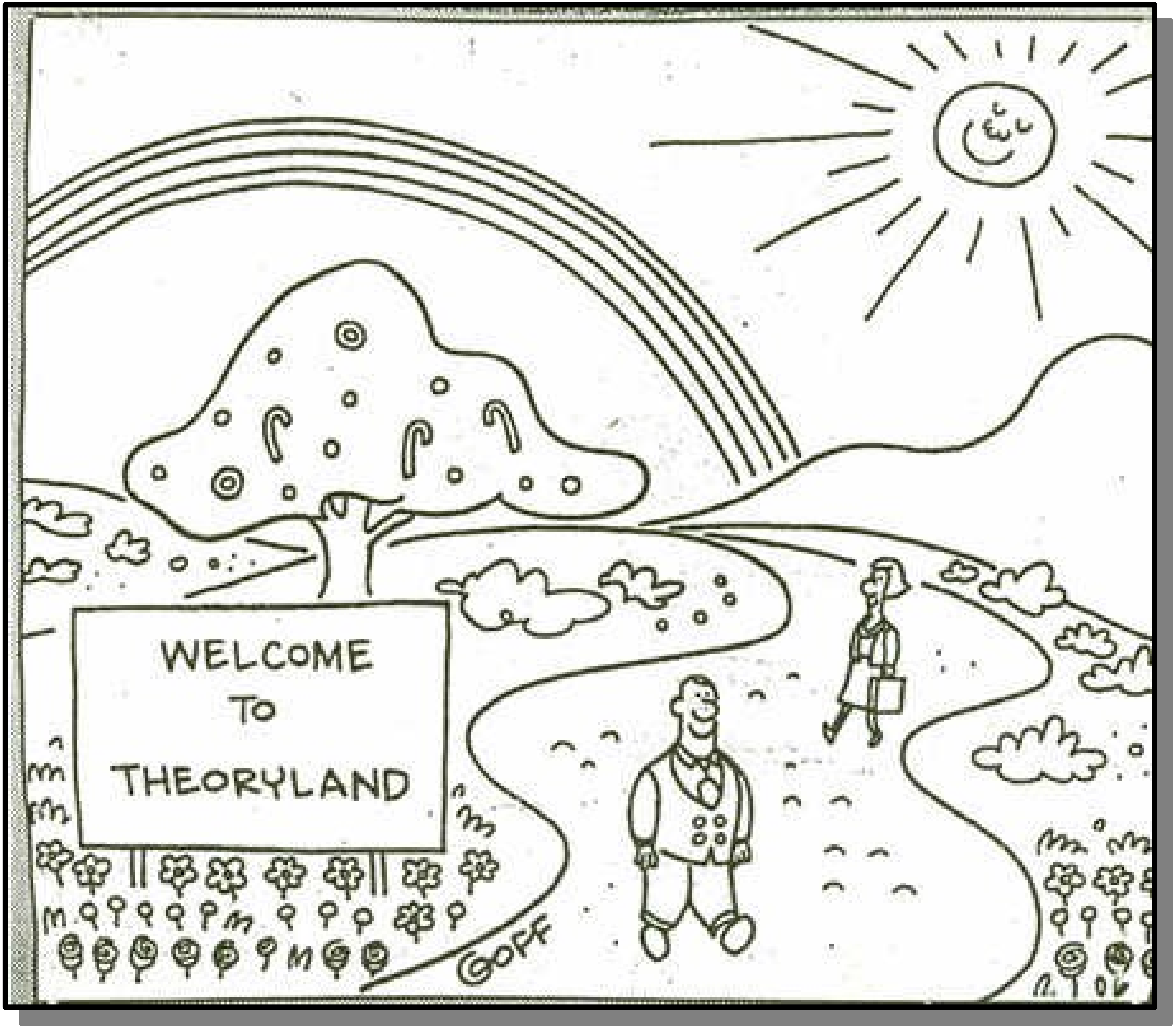
Complexity Theory

Part One

It may be that since one is customarily concerned with existence, […] finiteness, and so forth, one is not inclined to take seriously the question of the existence of a *better-than-finite* algorithm.

- Jack Edmonds, "Paths, Trees, and Flowers"


WELCOME
TO
THEORYLAND
GOFF

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A Decidable Problem

- ***Presburger arithmetic*** is a logical system for reasoning about arithmetic.
  - $\forall x.\ x + 1 \neq 0$
  - $\forall x.\ \forall y.\ (x + 1 = y + 1 \rightarrow x = y)$
  - $\forall x.\ x + 0 = x$
  - $\forall x.\ \forall y.\ (x + y) + 1 = x + (y + 1)$
  - $(P(0) \land \forall y.\ (P(y) \rightarrow P(y + 1))) \rightarrow \forall x.\ P(x)$
- Given a statement, it is decidable whether that statement can be proven from the laws of Presburger arithmetic.
- Any Turing machine that decides whether a statement in Presburger arithmetic is true or false has to move its tape head at least $2^{2^{cn}}$ times on some inputs of length n (for some fixed constant $c \geq 1$).

For Reference

- Assume $c = 1$.

The Limits of Decidability

- The fact that a problem is decidable does not mean that it is *feasibly* decidable.
- In ***computability theory***, we ask the question

  What problems can be solved by a computer?

- In ***complexity theory***, we ask the question

  What problems can be solved ***efficiently*** by a computer?

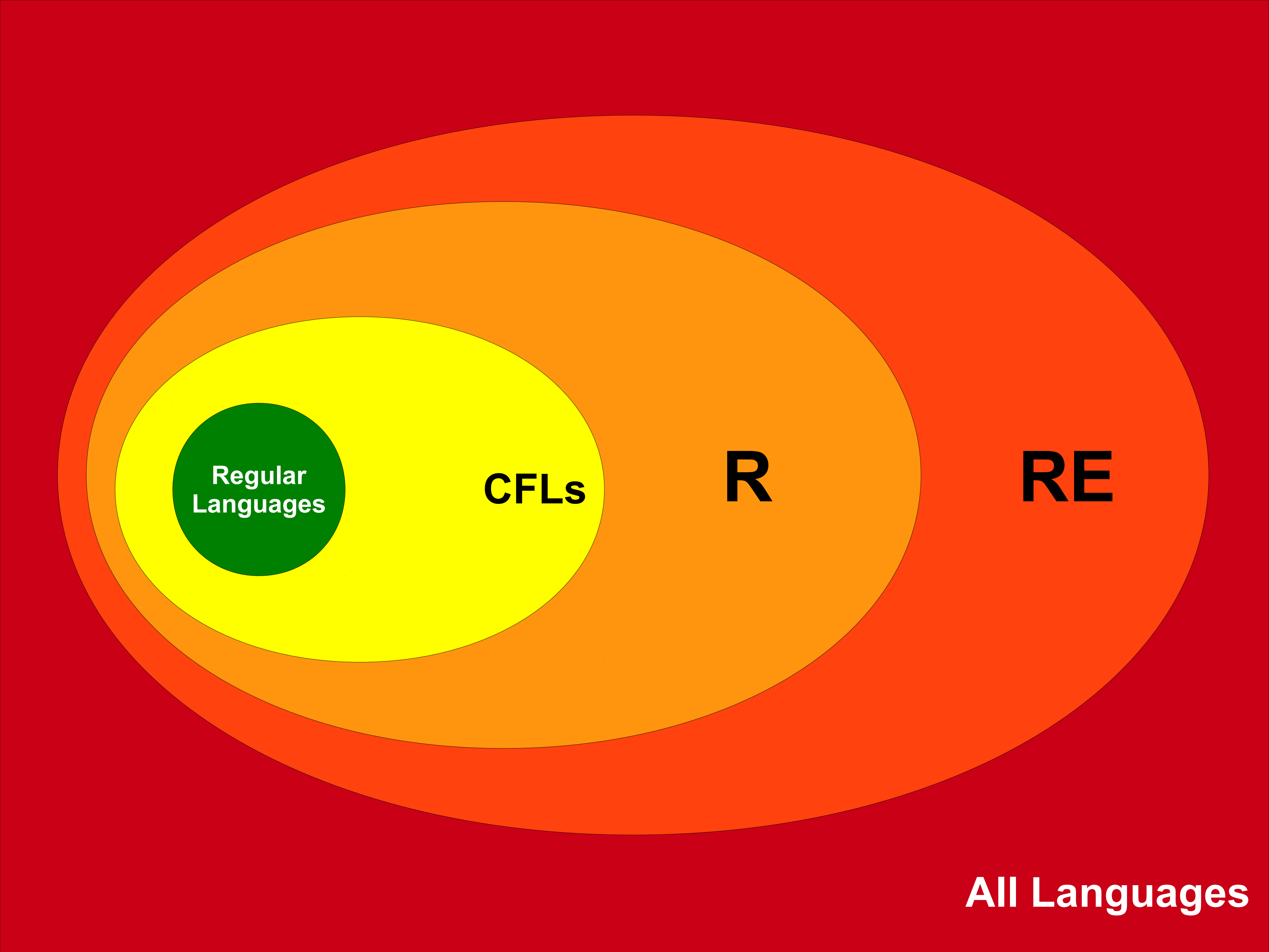
- In the remainder of this course, we will explore this question in more detail.

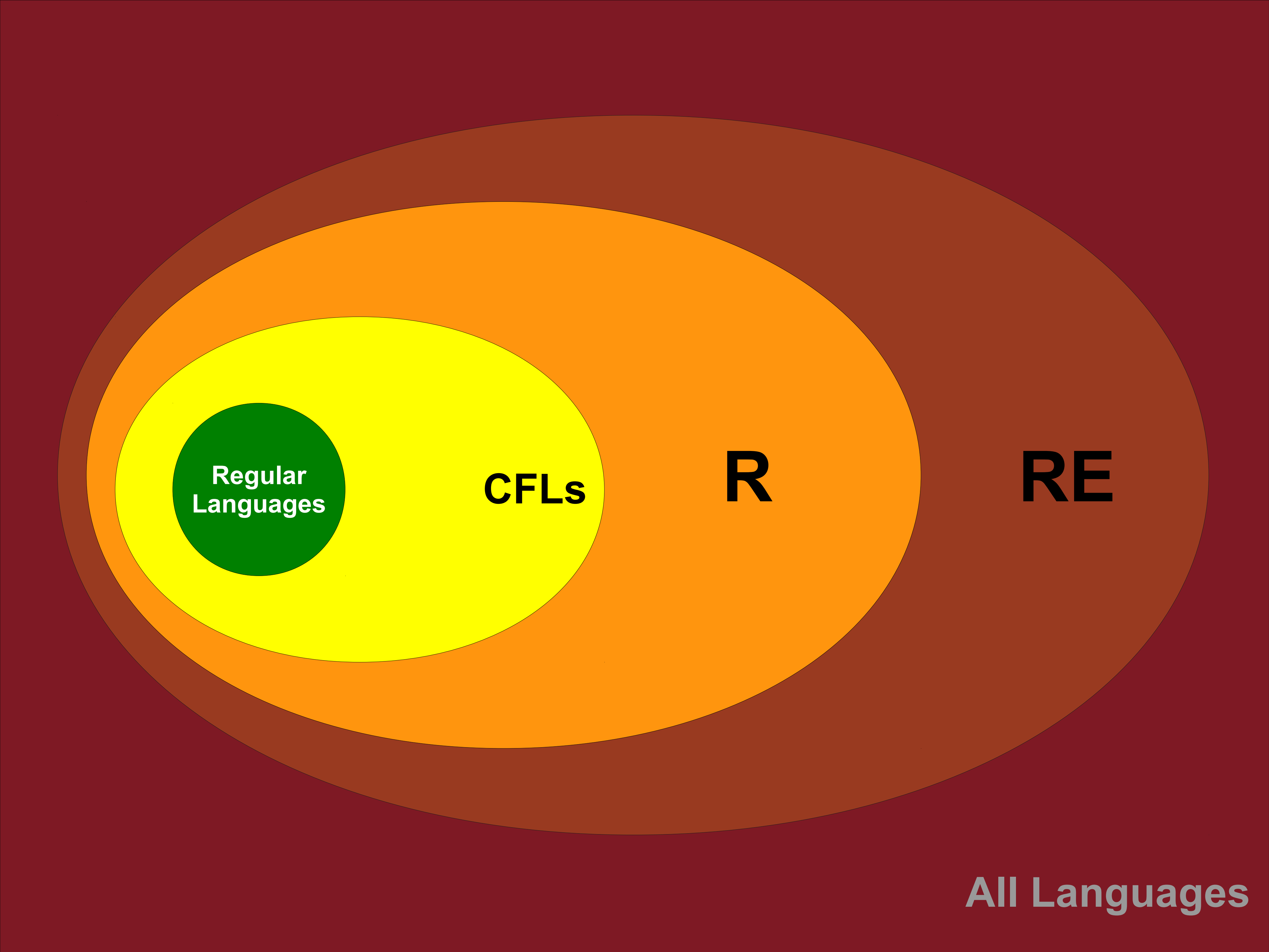
Where We've Been

- The class **R** represents problems that can be solved by a computer.
- The class **RE** represents problems where "yes" answers can be verified by a computer.

Where We're Going

- The class **P** represents problems that can be solved *efficiently* by a computer.
- The class **NP** represents problems where “yes” answers can be verified *efficiently* by a computer.


Regular Languages
CFLs
R
RE
All Languages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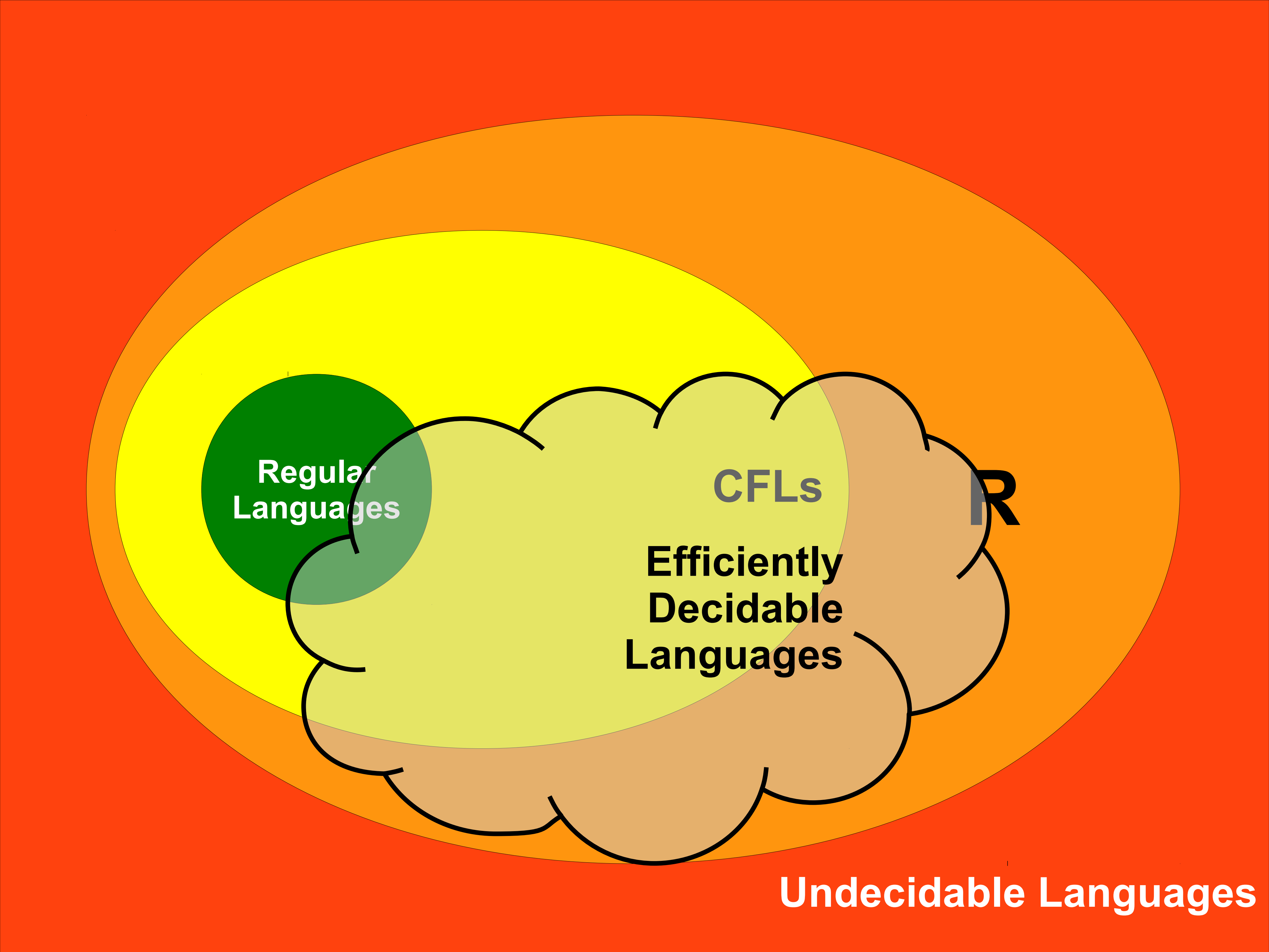
Regular
Languages
CFLs
R
Efficiently
Decidable
Languages
Undecidable Languages

The Setup

- In order to study computability, we needed to answer these questions:
  - What is "computation?"
  - What is a "problem?"
  - What does it mean to "solve" a problem?
- To study complexity, we need to answer these questions:
  - What does "complexity" even mean?
  - What is an "efficient" solution to a problem?

Measuring Complexity

- Suppose that we have a decider D for some language L.
- How might we measure the complexity of D?

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  - Size of tape alphabet.
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  - Amount of tape required.
  - Amount of time required.
  - Number of times a given state is entered.
  - Number of times a given symbol is printed.
  - Number of times a given transition is taken.
  - (Plus a whole lot more…)

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What is an efficient algorithm?

Searching Finite Spaces

- Many decidable problems can be solved by searching over a large but finite space of possible options.
- Searching this space might take a staggeringly long time, but only finite time.
- From a decidability perspective, this is totally fine.
- From a complexity perspective, this may be totally unacceptable.

A Sample Problem

4	3	11	9	7	13	5	6	1	12	2	8	0	10

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Goal: Find the length of the longest increasing subsequence of this sequence.

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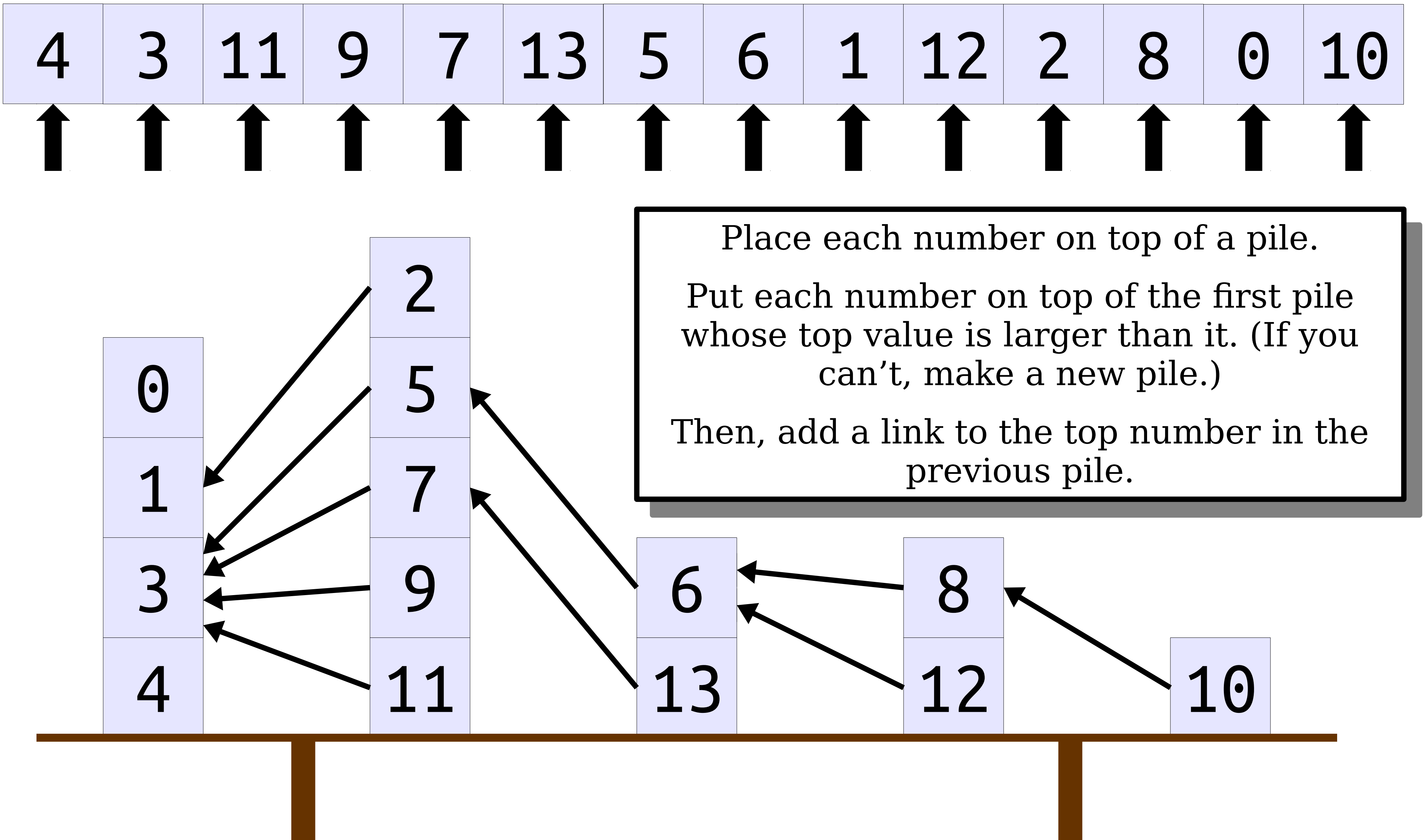
Longest Increasing Subsequences

- ***One possible algorithm:*** try all subsequences, find the longest one that's increasing, and return that.
- There are 2^n subsequences of an array of length n.
  - (Each subset of the elements gives back a subsequence.)
- Checking all of them to find the longest increasing subsequence will take time $O(n \cdot 2^n)$.
- Nifty fact: the age of the universe is about 4.3×10^{26} nanoseconds old. That's about 2^{85} nanoseconds.
- Practically speaking, this algorithm doesn't terminate if you give it an input of size 100 or more.

A Different Approach

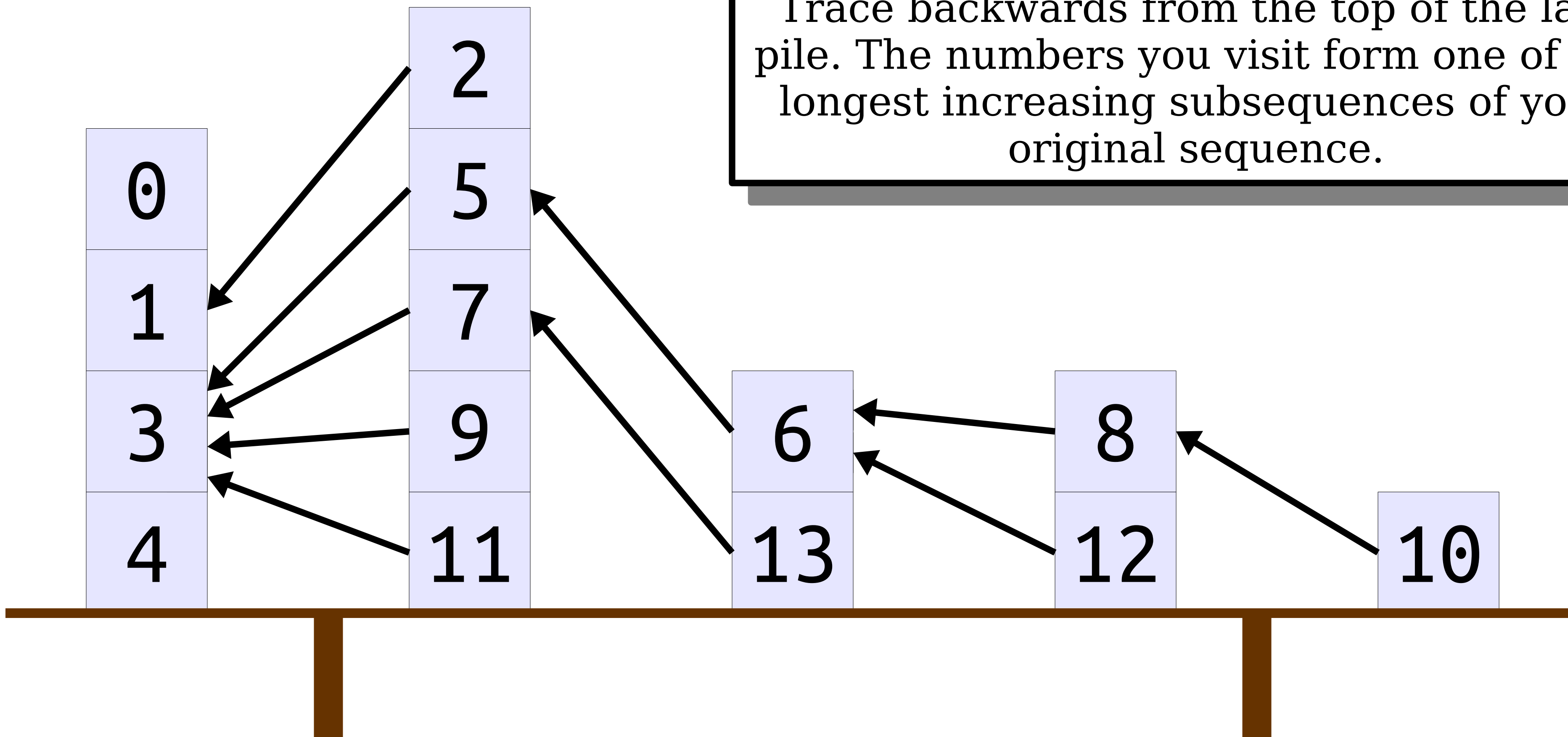
Patience Sorting



Patience Sorting

4	3	11	9	7	13	5	6	1	12	2	8	0	10

Trace backwards from the top of the last pile. The numbers you visit form one of the longest increasing subsequences of your original sequence.



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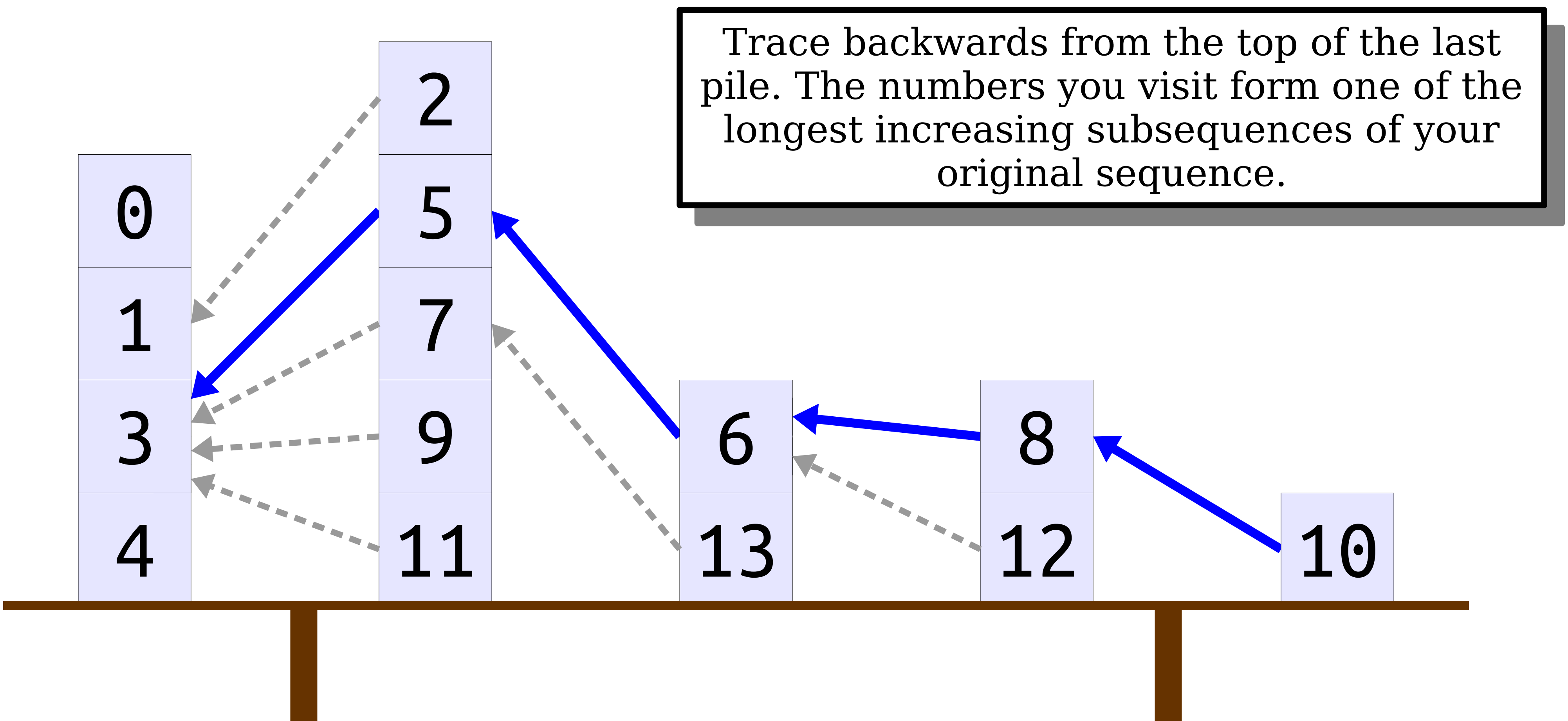

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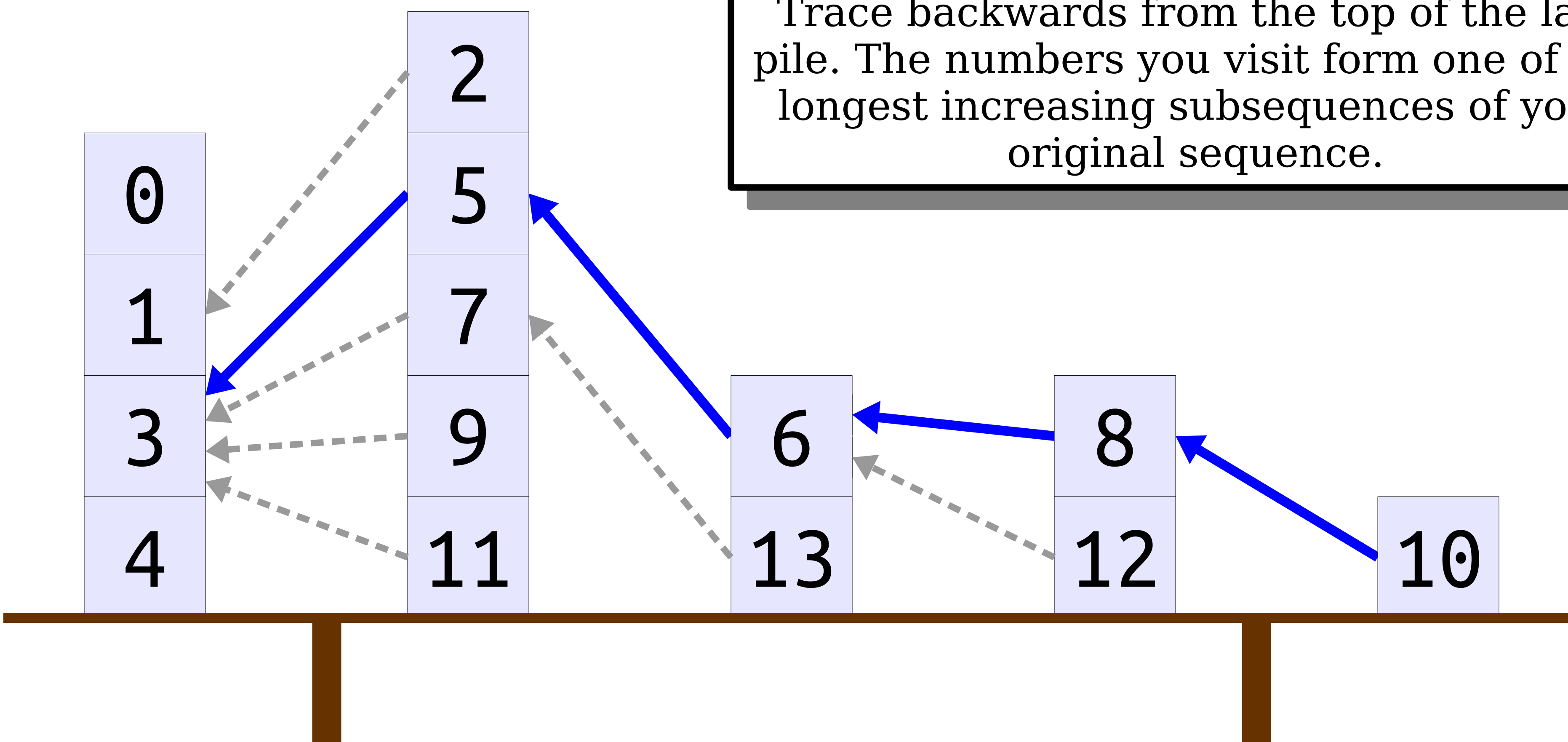
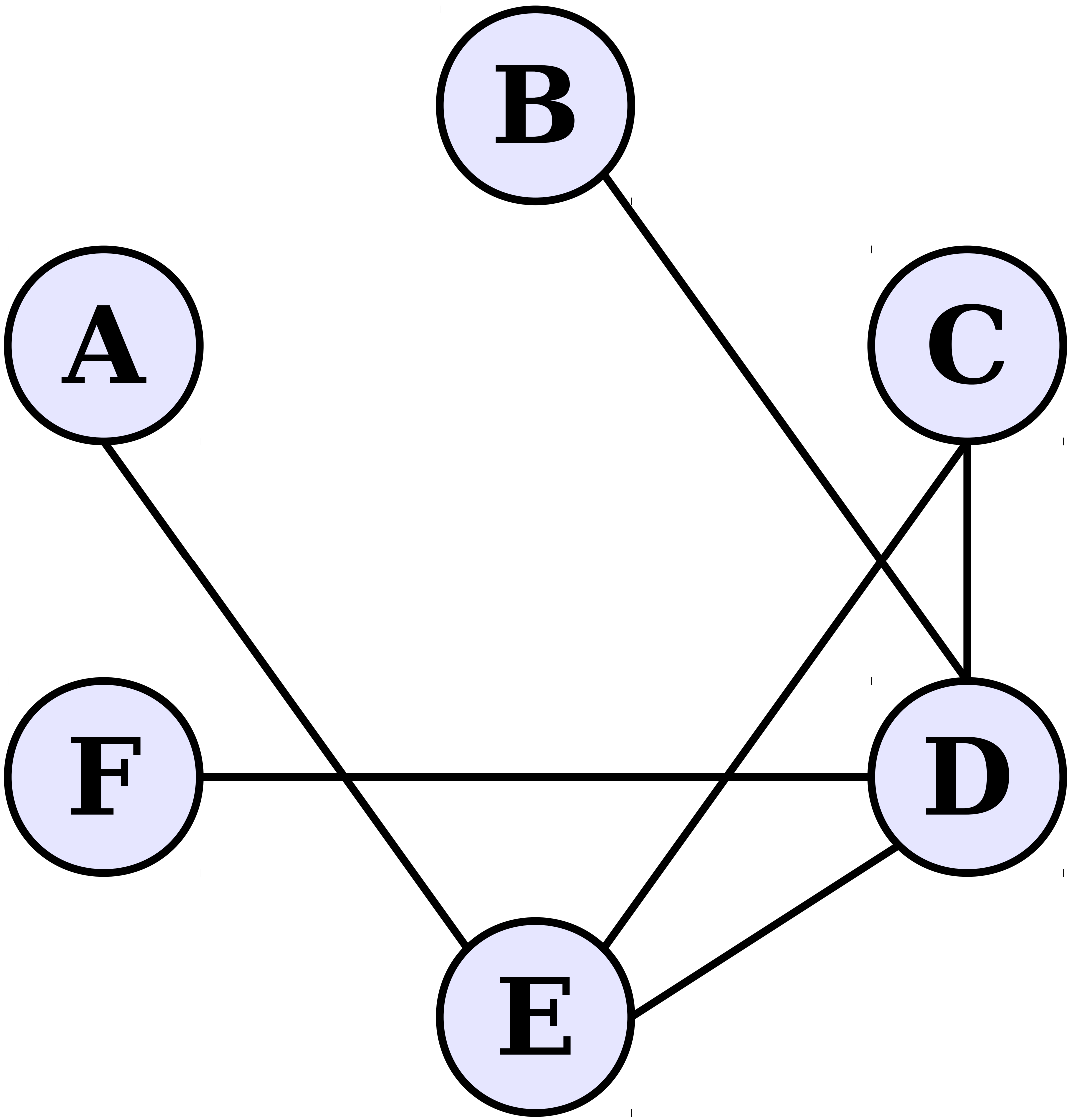


Longest Increasing Subsequences

- ***Theorem:*** There is an algorithm that can find the longest increasing subsequence of an array in time $O(n^2)$.
  - It's the previous ***patience sorting*** algorithm, with some clever implementation tricks.
- This algorithm works by exploiting particular aspects of how longest increasing subsequences are constructed. It's not immediately obvious that it works correctly.
- ***Phenomenal Exercise 1:*** Prove that this procedure always works!
- ***Phenomenal Exercise 2:*** Show that you can actually implement this same algorithm in time $O(n \log n)$.

Another Problem



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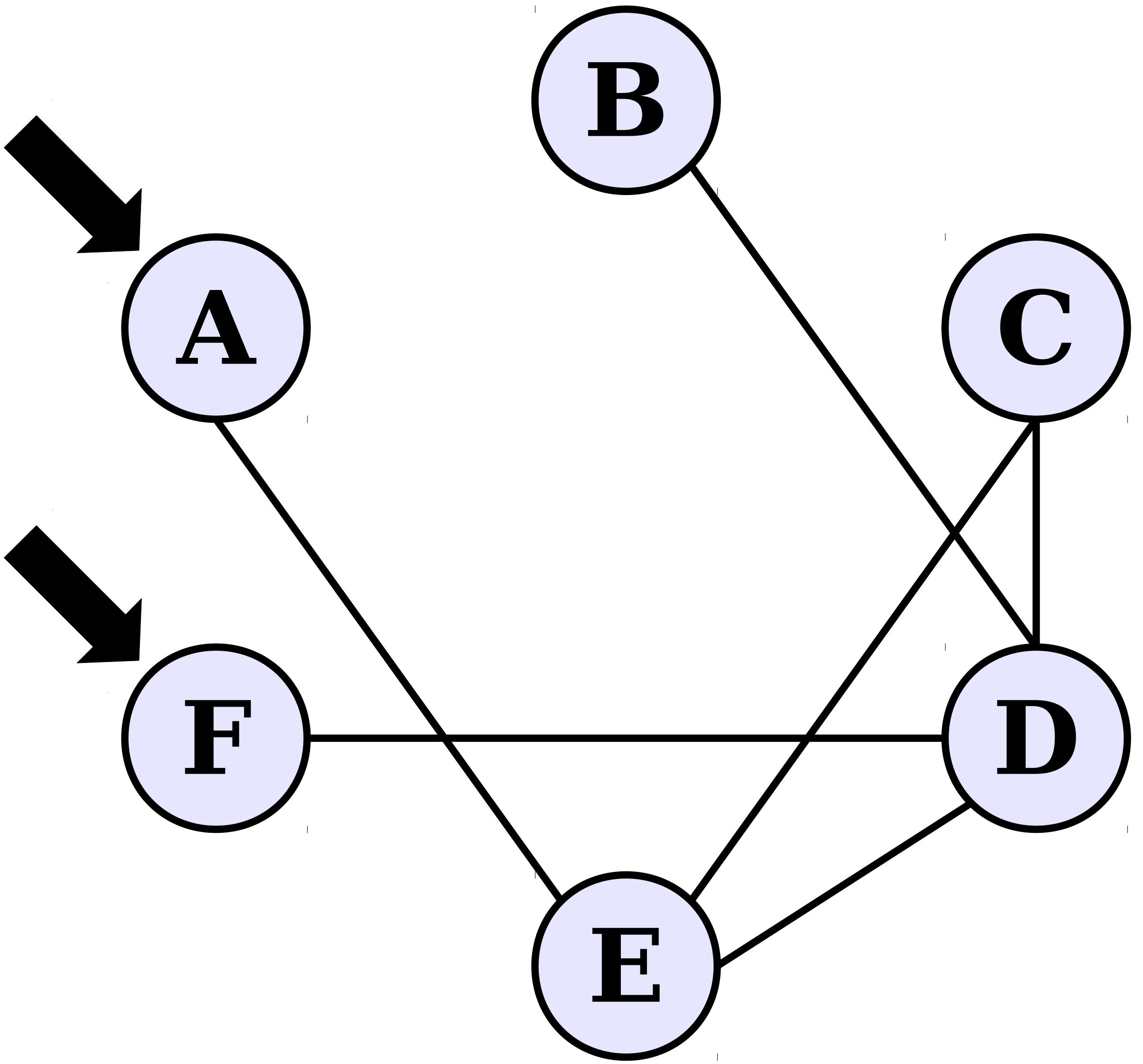

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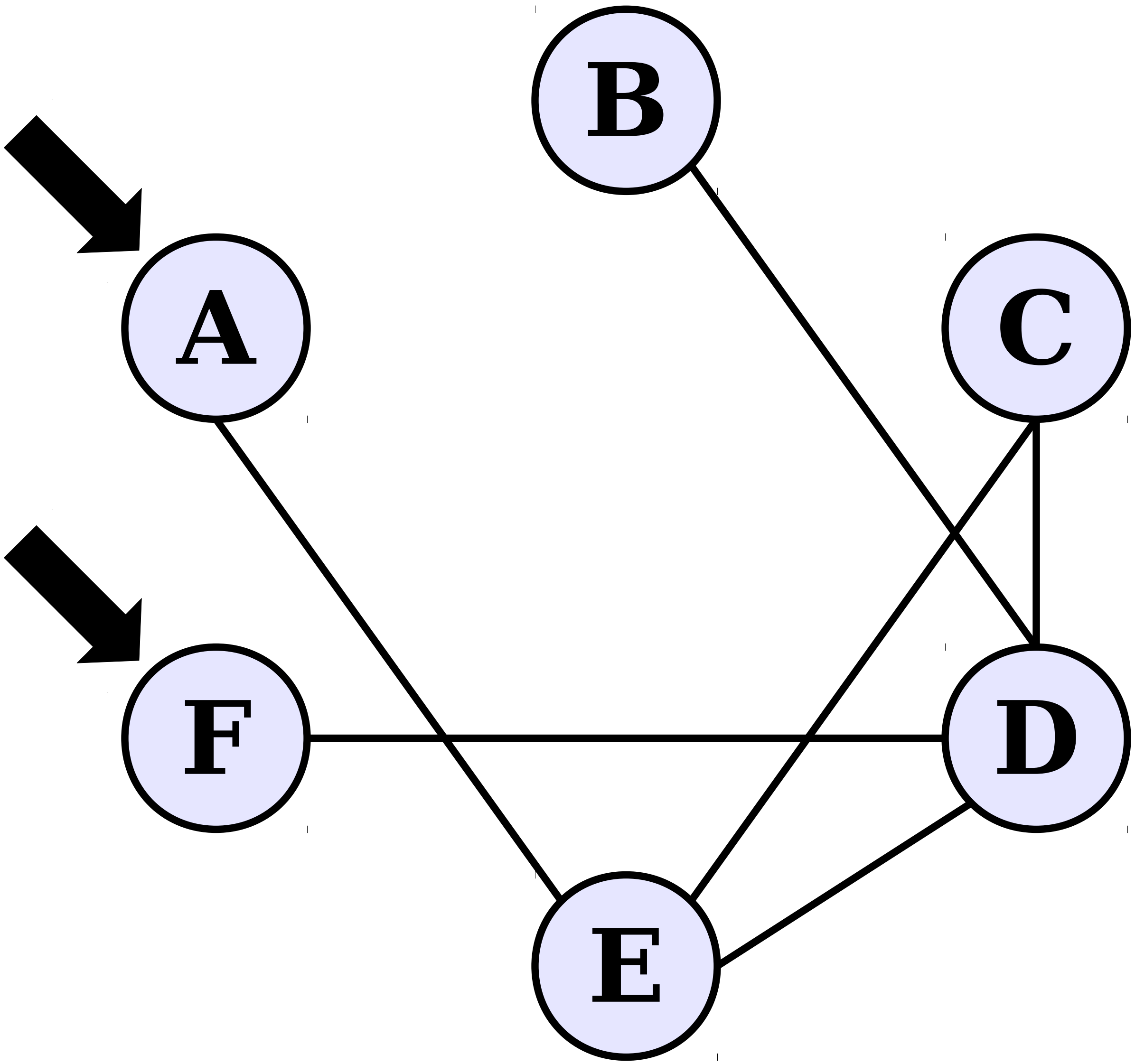


Goal: Determine the length of the shortest path from **A** to **F** in this graph.

Shortest Paths

- It is possible to find the shortest path in a graph by listing off all sequences of nodes in the graph in ascending order of length and finding the first that's a path.
- This takes time $O(n \cdot n!)$ in an n-node graph.
- For reference: 29! nanoseconds is longer than the lifetime of the universe.

Shortest Paths

- ***Theorem:*** It's possible to find the shortest path between two nodes in an n-node, m-edge graph in time $O(m + n)$.
- ***Proof idea:*** Use breadth-first search!
- The algorithm is a bit nuanced. It uses some specific properties of shortest paths and the proof of correctness is nontrivial.

For Comparison

- ***Longest increasing subsequence:***
  - Naive: $O(n \cdot 2^n)$
  - Fast: $O(n^2)$
- ***Shortest path problem:***
  - Naive: $O(n \cdot n!)$
  - Fast: $O(n + m)$.

Defining Efficiency

- When dealing with problems that search for the “best” object of some sort, there are often at least exponentially many possible options.
- Brute-force solutions tend to take at least exponential time to complete.
- Clever algorithms often run in time O(n), or O(n^2), or O(n^3), etc.

Polynomials and Exponentials

- An algorithm runs in ***polynomial time*** if its runtime is some polynomial in n.
  - That is, time $O(n^k)$ for some constant k.
- Polynomial functions "scale well."
  - Small changes to the size of the input do not typically induce enormous changes to the overall runtime.
- Exponential functions scale terribly.
  - Small changes to the size of the input induce huge changes in the overall runtime.

The Cobham-Edmonds Thesis

A language L can be ***decided efficiently*** if there is a TM that decides it in polynomial time.

Equivalently, L can be decided efficiently if it can be decided in time $O(n^k)$ for some $k \in \mathbb{N}$.

Like the Church-Turing thesis, this is ***not*** a theorem!

It's an assumption about the nature of efficient computation, and it is somewhat controversial.

The Cobham-Edmonds Thesis

- Efficient runtimes:
  - $4n + 13$
  - $n^3 – 2n^2 + 4n$
  - $n \log \log n$
- "Efficient" runtimes:
  - $n^{1,000,000,000,000}$
  - 10^{500}
- Inefficient runtimes:
  - 2^n
  - $n!$
  - n^n
- "Inefficient" runtimes:
  - $n^{0.0001 \log n}$
  - 1.000000001^n

Why Polynomials?

- Polynomial time *somewhat* captures efficient computation, but has a few edge cases.
- However, polynomials have very nice mathematical properties:
  - The sum of two polynomials is a polynomial. (Running one efficient algorithm, then another, gives an efficient algorithm.)
  - The product of two polynomials is a polynomial. (Running one efficient algorithm a “reasonable” number of times gives an efficient algorithm.)
  - The *composition* of two polynomials is a polynomial. (Using the output of one efficient algorithm as the input to another efficient algorithm gives an efficient algorithm.)

The Complexity Class **P**

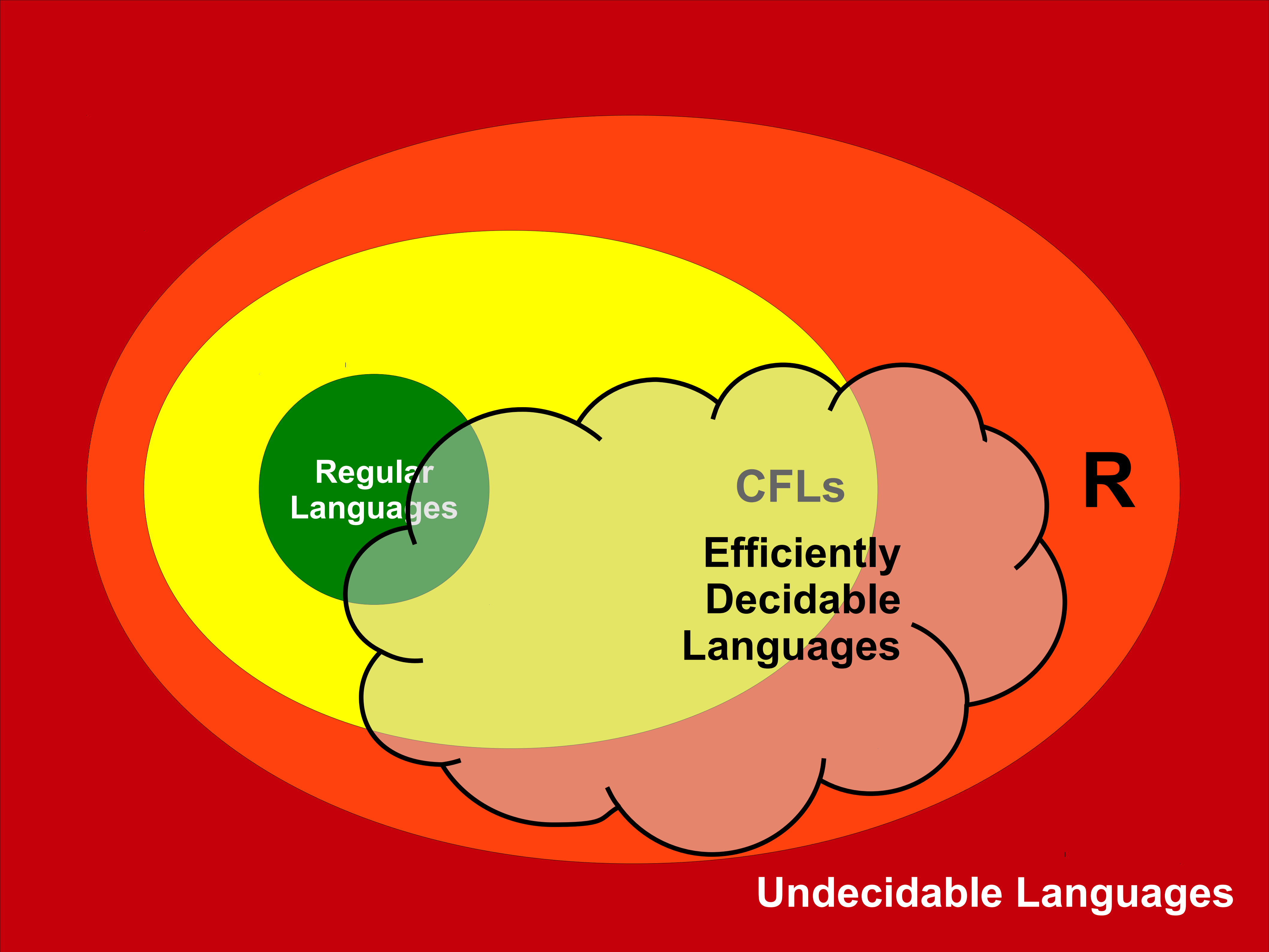
- The ***complexity class*** **P** (for ***p***olynomial time) contains all problems that can be solved in polynomial time.
- Formally:

  $$\mathbf{P} = \{\ L \mid \text{There is a polynomial-time decider for } L\ \}$$

- Assuming the Cobham-Edmonds thesis, a language is in **P** if it can be decided efficiently.

Examples of Problems in **P**

- All regular languages are in **P**.
  - All have linear-time TMs.
- All CFLs are in **P**.
  - Requires a more nuanced argument (the *CYK algorithm* or *Earley*'*s algorithm.*)
- And a *ton* of other problems are in **P** as well.
  - Curious? Take CS161!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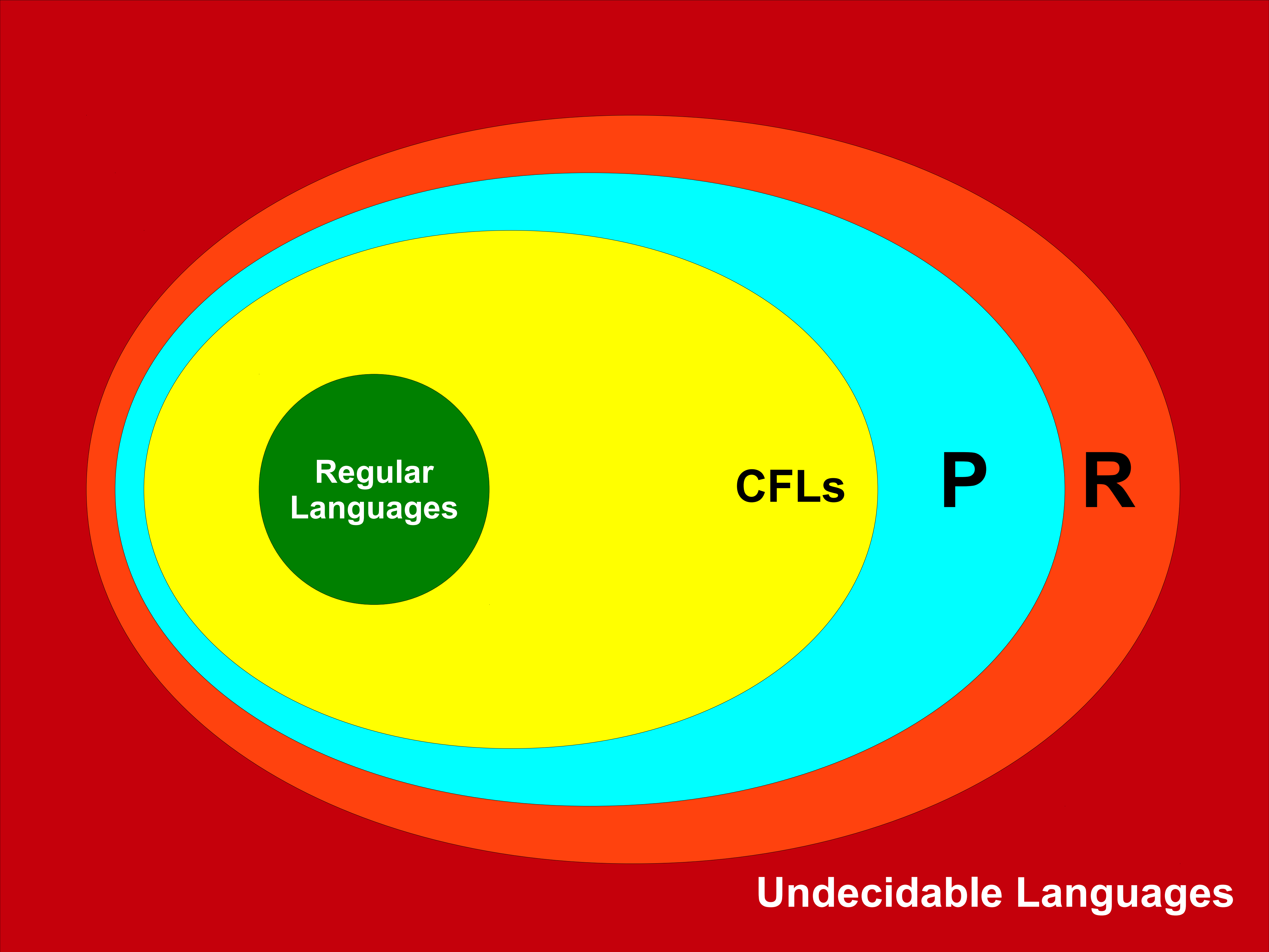
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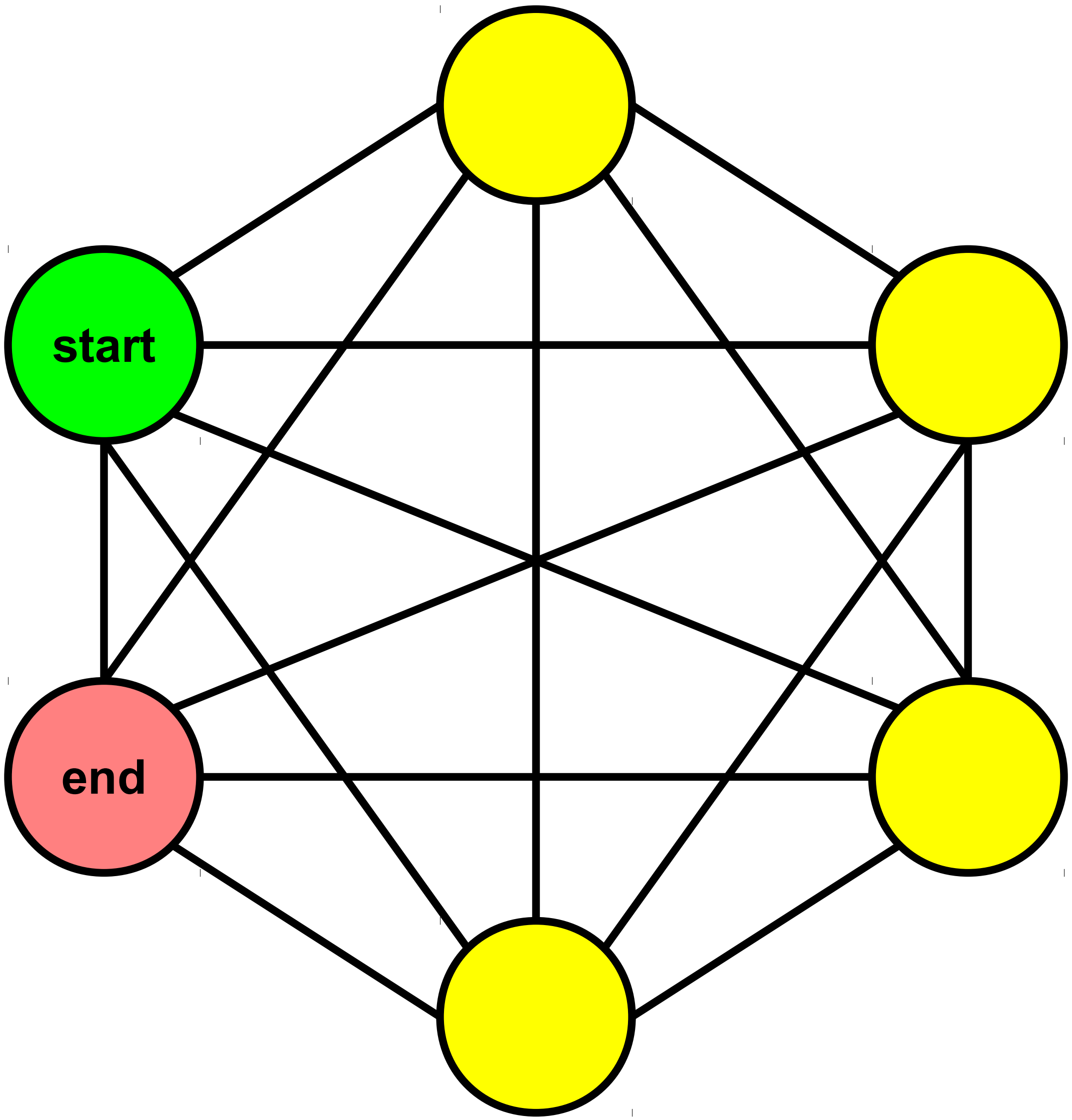
What *can't* you do in polynomial time?



How many simple paths are there from the start node to the end node?

How many subsets of this set are there?

An Interesting Observation

- There are (at least) exponentially many objects of each of the preceding types.
- However, each of those objects is not very large.
  - Each simple path has length no longer than the number of nodes in the graph.
  - Each subset of a set has no more elements than the original set.
- This brings us to our next topic…

What if you need to search a large space for a single object?

Verifiers – Again

		7		6		1		
					3		5	2
3			1		5	9		7
6		5		3		8		9
	1						2	
8		2		1		5		4
1		3	2		7			8
5	7		4					
		4		8		7		

Does this Sudoku problem have a solution?

Verifiers – Again

2	5	7	9	6	4	1	8	3
4	9	1	8	7	3	6	5	2
3	8	6	1	2	5	9	4	7
6	4	5	7	3	2	8	1	9
7	1	9	5	4	8	3	2	6
8	3	2	6	1	9	5	7	4
1	6	3	2	5	7	4	9	8
5	7	8	4	9	6	2	3	1
9	2	4	3	8	1	7	6	5

Does this Sudoku problem
have a solution?

Verifiers – Again

9	3	11	4	2	13	5	6	1	12	7	8	0	10

Is there an ascending subsequence of length at least 7?

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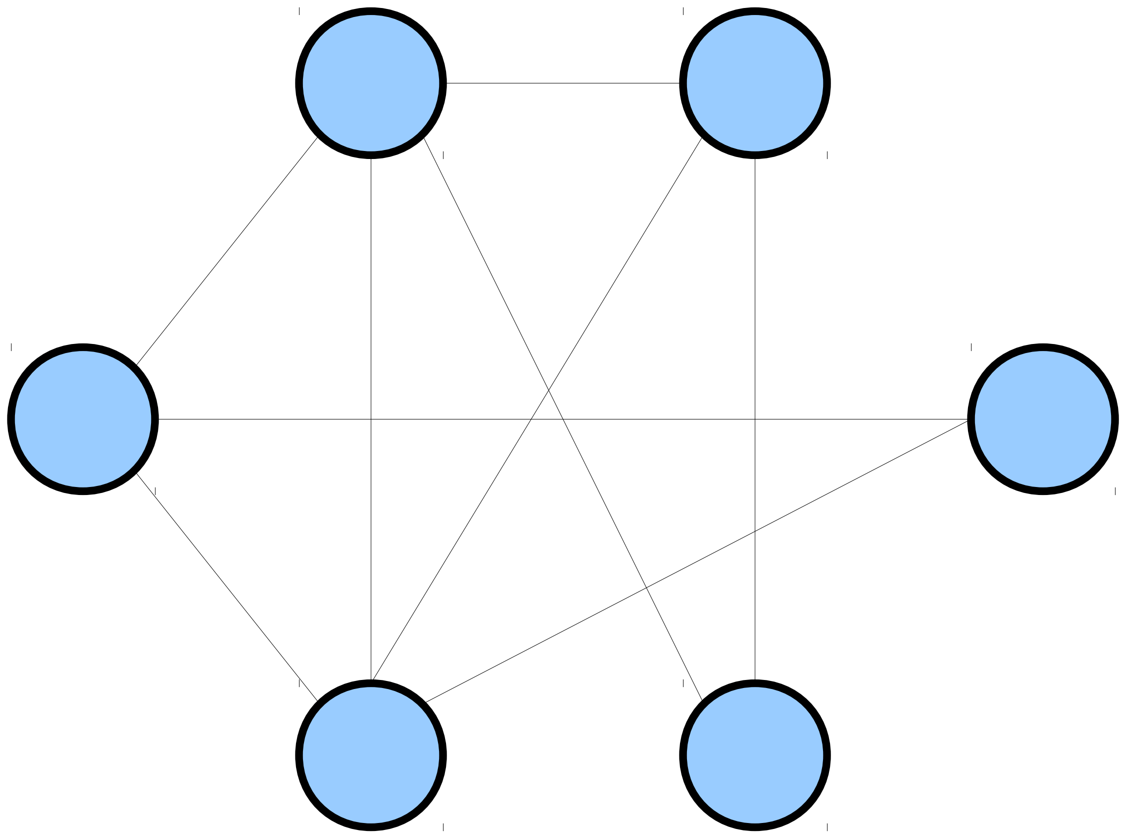
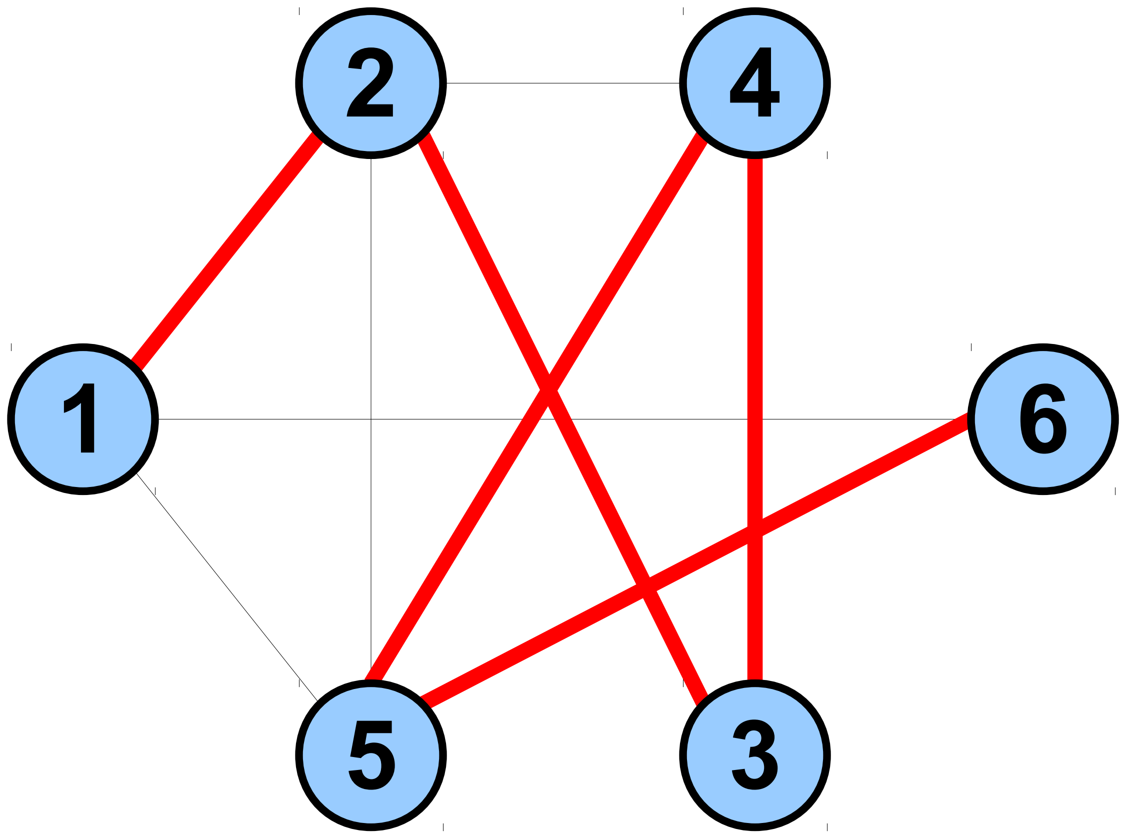


Is there a simple path that goes through every node exactly once?

Verifiers – Again



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Verifiers

- Recall that a ***verifier*** for L is a TM V such that
  - V halts on all inputs.
  - $w \in L \quad \text{iff} \quad \exists c \in \Sigma^*.\ V$ accepts $\langle w, c \rangle$.

Polynomial-Time Verifiers

- A ***polynomial-time verifier*** for L is a TM V such that
  - V halts on all inputs.
  - $w \in L \quad \text{iff} \quad \exists c \in \Sigma^*. V$ accepts $\langle w, c \rangle$.
  - V's runtime is a polynomial in $|w|$ (that is, V's runtime is $O(|w|^k)$ for some integer k)

The Complexity Class **NP**

- The complexity class **NP** (***nondeterministic polynomial time***) contains all problems that can be verified in polynomial time.
- Formally:

NP = { *L* | There is a polynomial-time verifier for *L* }

- The name **NP** comes from another way of characterizing **NP**. If you introduce *nondeterministic Turing machines* and appropriately define "polynomial time," then **NP** is the set of problems that an NTM can solve in polynomial time.
- ***Useful fact:*** **NP** $\subsetneq$ **R**. Come talk to me after class if you're curious why!

$$\mathbf{P} = \{ L \mid \text{there is a polynomial-time decider for } L \}$$

$$\mathbf{NP} = \{ L \mid \text{there is a polynomial-time verifier for } L \}$$

R = { *L* | there is a ~~polynomial-time~~ decider for *L* }

RE = { *L* | there is a ~~polynomial-time~~ verifier for *L* }

We know that $\mathbf{R} \neq \mathbf{RE}$.

So does that mean $\mathbf{P} \neq \mathbf{NP}$?

Time-Out for Announcements!

Problem Sets

- Problem Set Six was due today at 3:00PM.
- Problem Set Seven is due next **Wednesday** at 3:00PM.
  - As a reminder, ***no late submissions will be accepted***. Please budget enough time to get your submission in!
  - ***Very smart idea:*** submit at least two hours early.
- As always, feel free to ask questions in office hours or online via Piazza.
  - Note: Updated OH schedule for next Tuesday and Wednesday.

Final Exam Logistics

- Our final exam is Friday, August 16th from 7PM – 10PM in ***Bishop Auditorium***.
- The exam is cumulative. You’re responsible for topics from PS0 – PS7 and all of the lectures up through and including Unsolvable Problems.
- The exam is closed-book, closed-computer, and limited-note. You can bring one double-sided sheet of 8.5” × 11” notes with you to the exam, decorated any way you’d like.
- Students with OAE accommodations: if we don’t yet have your OAE letter, please send it to us ASAP.

Preparing for the Exam

- We've posted two practice final exams, with solutions, to the course website. They're on the *Extra Practice* page under *Resources*.
  - The practice exam we'll be using during the practice final will be released on Wednesday.
- ***Review Session*** on Monday, August 12th here during class, led by your lovely TAs!
- ***Practice Final*** on Wednesday, August 14th from 5:30-8:30 PM upstairs in Gates 104.

Back to CS103!

And now…

The

Biggest Question

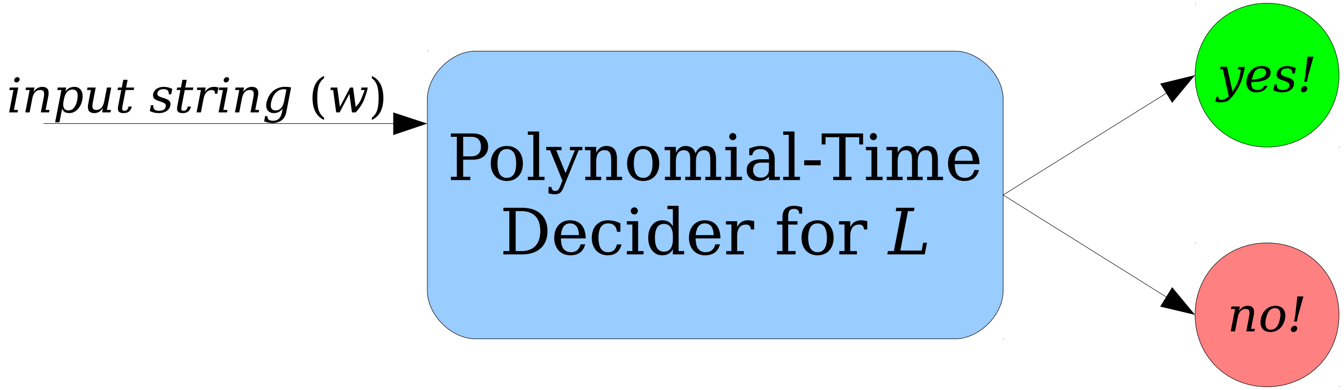
in

Theoretical Computer Science

$$\mathbf{P} \stackrel{?}{=} \mathbf{NP}$$

P = { L | There is a polynomial-time decider for L }

NP = { L | There is a polynomial-time verifier for L }



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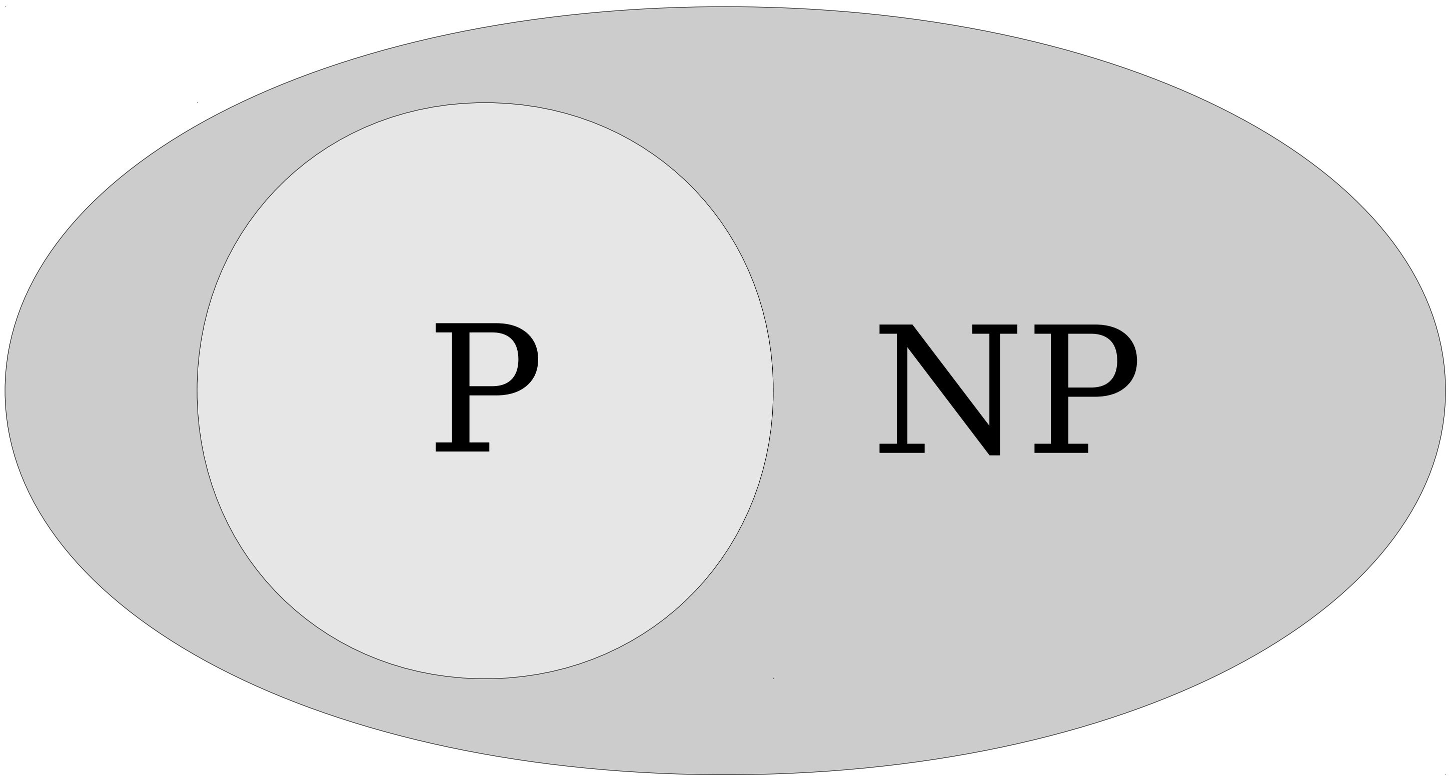
$$\mathbf{P} \subseteq \mathbf{NP}$$

Which Picture is Correct?



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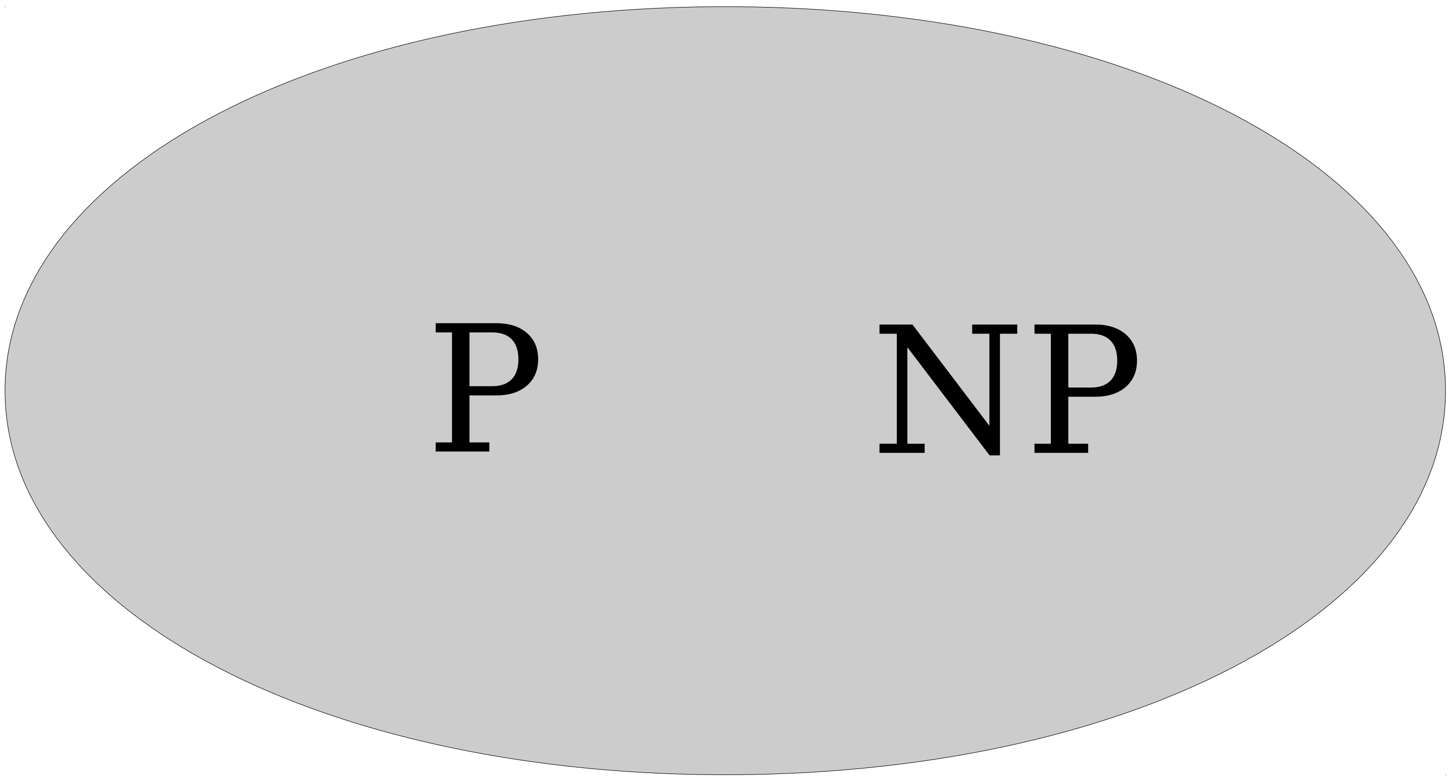

$\mathbf{P} \stackrel{?}{=} \mathbf{NP}$

- The $\mathbf{P} \stackrel{?}{=} \mathbf{NP}$ question is the most important question in theoretical computer science.
- With the verifier definition of **NP**, one way of phrasing this question is

*If a solution to a problem can be **checked** efficiently, can that problem be **solved** efficiently?*

- An answer either way will give fundamental insights into the nature of computation.

Why This Matters

- The following problems are known to be efficiently verifiable, but have no known efficient solutions:
    - Determining whether an electrical grid can be built to link up some number of houses for some price (Steiner tree problem).
    - Determining whether a simple DNA strand exists that multiple gene sequences could be a part of (shortest common supersequence).
    - Determining the best way to assign hardware resources in a compiler (optimal register allocation).
    - Determining the best way to distribute tasks to multiple workers to minimize completion time (job scheduling).
    - ***And many more***.
- If **P** = **NP**, ***all*** of these problems have efficient solutions.
- If **P** ≠ **NP**, ***none*** of these problems have efficient solutions.

Why This Matters

- If **P = NP**:
  - A huge number of seemingly difficult problems could be solved efficiently.
  - Our capacity to solve many problems will scale well with the size of the problems we want to solve.
- If **P ≠ NP**:
  - Enormous computational power would be required to solve many seemingly easy tasks.
  - Our capacity to solve problems will fail to keep up with our curiosity.

What We Know

- Resolving **P** $\stackrel{?}{=}$ **NP** has proven ***extremely difficult***.
- In the past 45 years:
  - Not a single correct proof either way has been found.
  - Many types of proofs have been shown to be insufficiently powerful to determine whether **P** $\stackrel{?}{=}$ **NP**.
  - A majority of computer scientists believe **P** ≠ **NP**, but this isn't a large majority.
- Interesting read: Interviews with leading thinkers about **P** $\stackrel{?}{=}$ **NP**:
  - http://web.ing.puc.cl/~jabaier/iic2212/poll-1.pdf

The Million-Dollar Question

The Clay Mathematics Institute has offered a ***$1,000,000 prize*** to anyone who proves or disproves **P = NP**.

“My hunch is that [$\mathbf{P} \stackrel{?}{=} \mathbf{NP}$] will be solved by a young researcher who is not encumbered by too much conventional wisdom about how to attack the problem.”

– Prof. Richard Karp

(The guy who first popularized the $\mathbf{P} \stackrel{?}{=} \mathbf{NP}$ *problem.)*

“There is something very strange about this problem, something very philosophical. It is the greatest unsolved problem in mathematics […] It is the *raison d’être* of abstract computer science, and as long as it remains unsolved, its mystery will ennoble the field.”

-Prof. Jim Owings

(Computability/Complexity theorist)

What do we know about $\mathbf{P} \stackrel{?}{=} \mathbf{NP}$?

Adapting our Techniques

$$\mathbf{P} = \{ L \mid \text{there is a polynomial-time decider for } L \}$$

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RE = { L | there is a ~~polynomial-time~~ verifier for L }

We know that **R** $\neq$ **RE**.

So does that mean **P** $\neq$ **NP**?

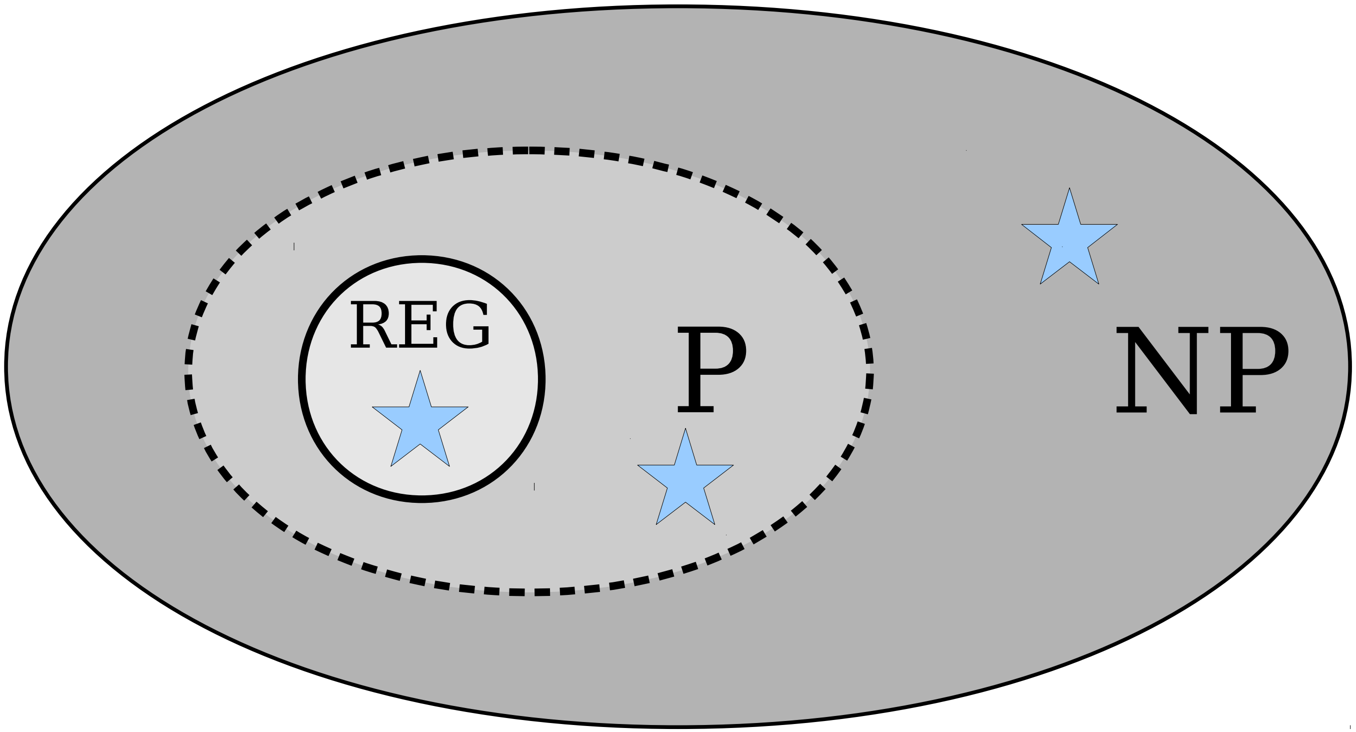
A Problem

- The **R** and **RE** languages correspond to problems that can be decided and verified, *period*, without any time bounds.
- To reason about what's in **R** and what's in **RE**, we used two key techniques:
  - ***Universality***: TMs can run other TMs as subroutines.
  - ***Self-Reference***: TMs can get their own source code.
- Why can't we just do that for **P** and **NP**?

Theorem (Baker-Gill-Solovay): Any proof that purely relies on universality and self-reference cannot resolve $\mathbf{P} \stackrel{?}{=} \mathbf{NP}$.

Proof: Take CS154!

So how *are* we going to reason about **P** and **NP**?



Problems in **NP** vary widely in their difficulty, even if **P** = **NP**.

How can we rank the relative difficulties of problems?

Reducibility

Maximum Matching

- Given an undirected graph *G*, a ***matching*** in *G* is a set of edges such that no two edges share an endpoint.
- A ***maximum matching*** is a matching with the largest number of edges.

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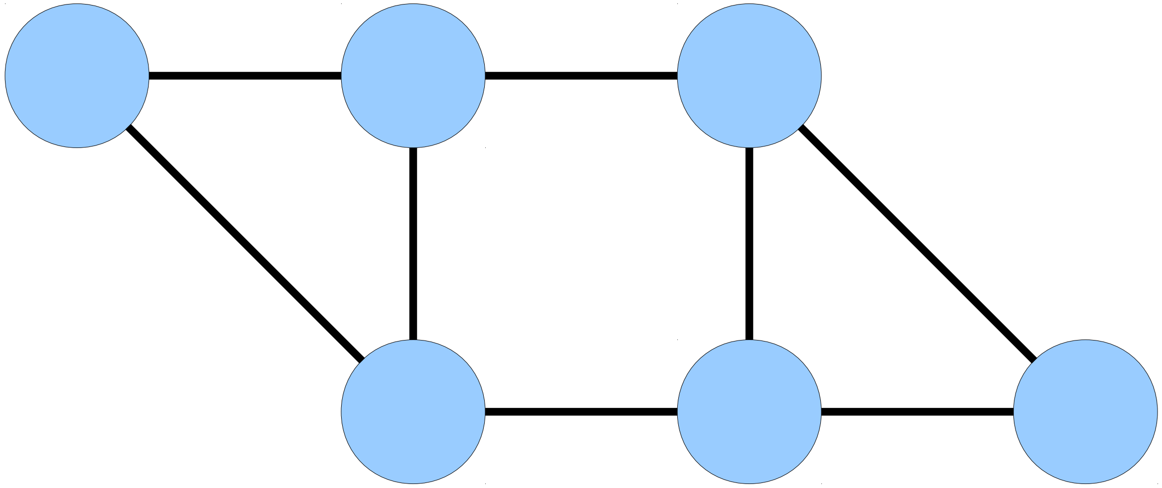

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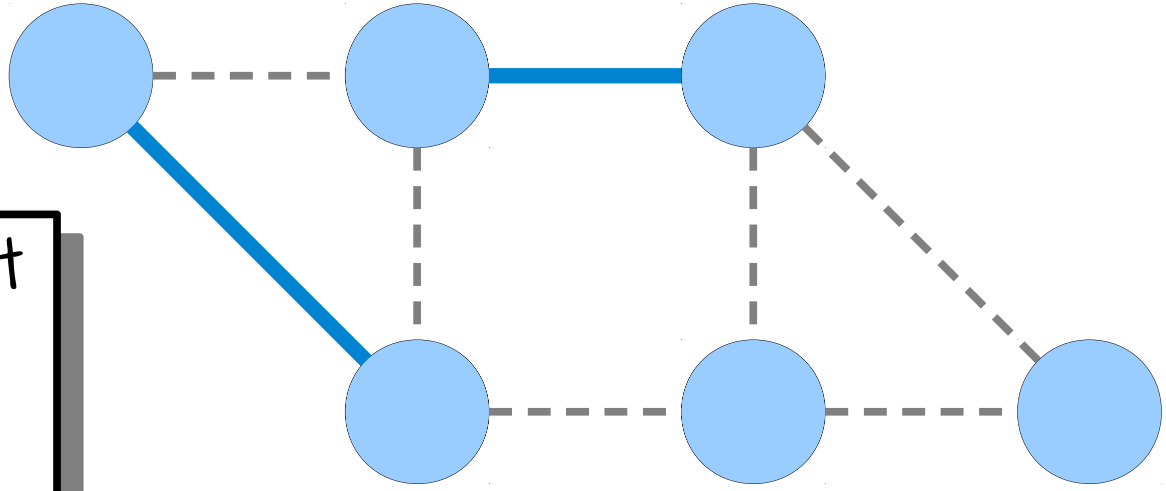

A matching, but not a maximum matching.

Maximum Matching

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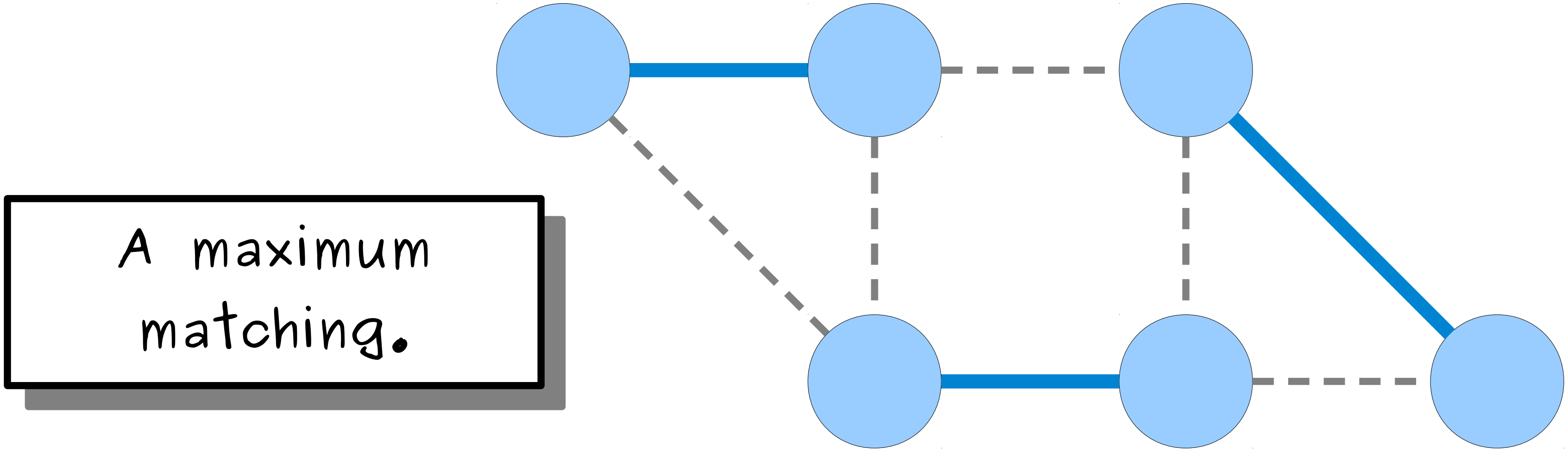

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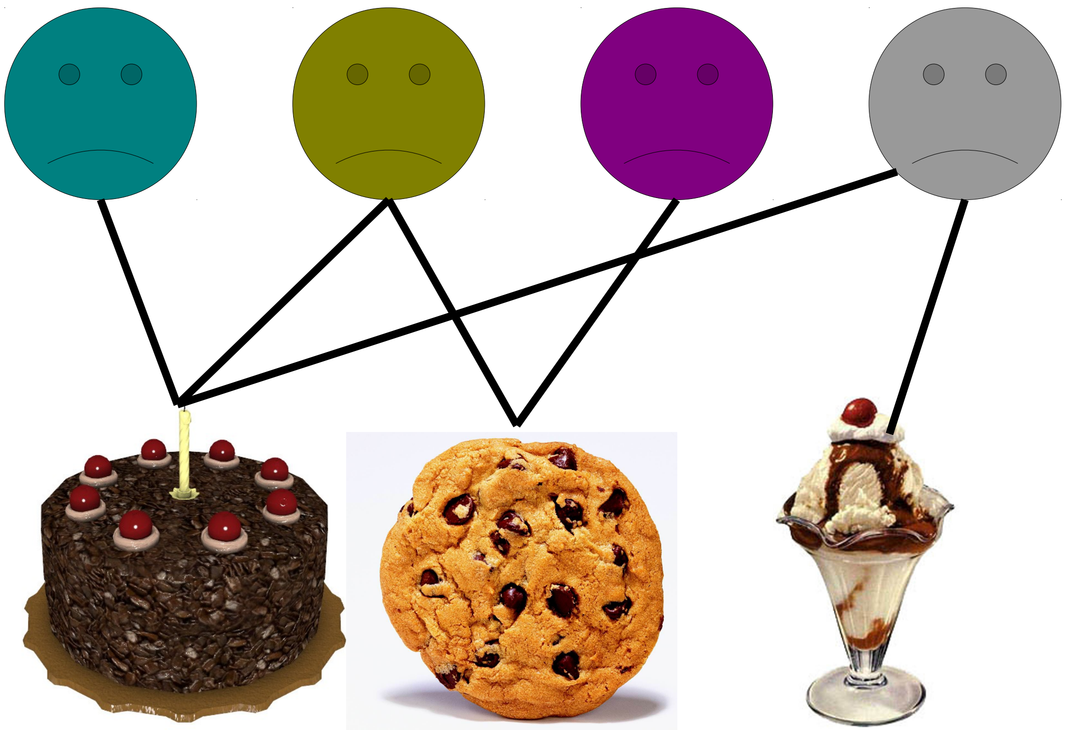

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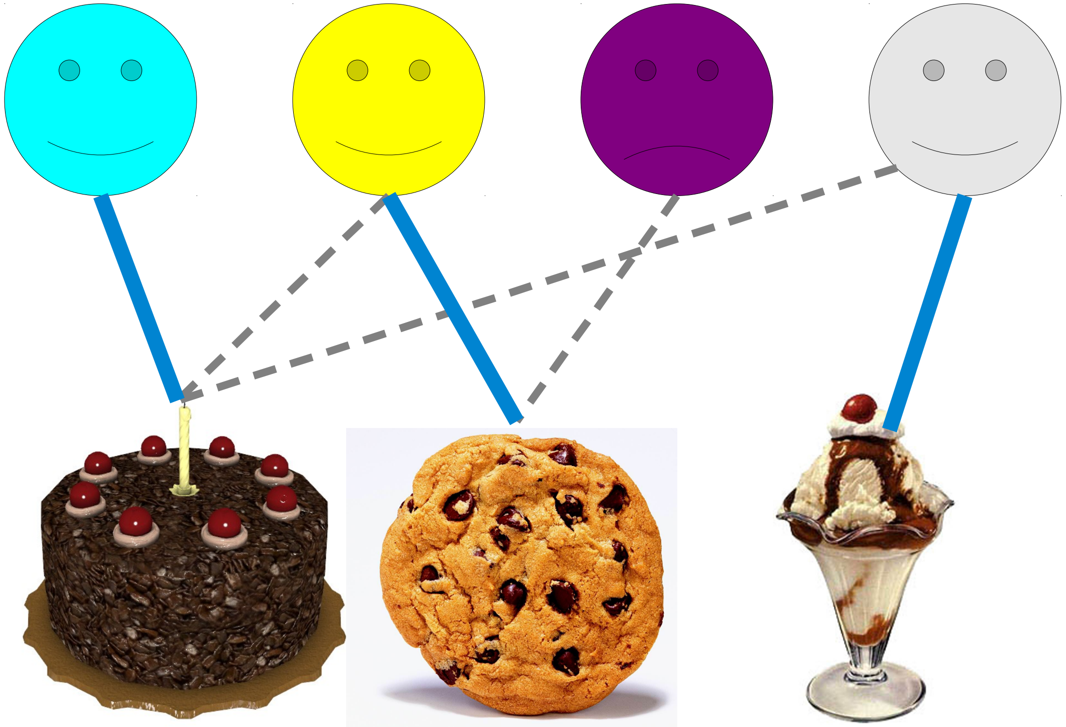
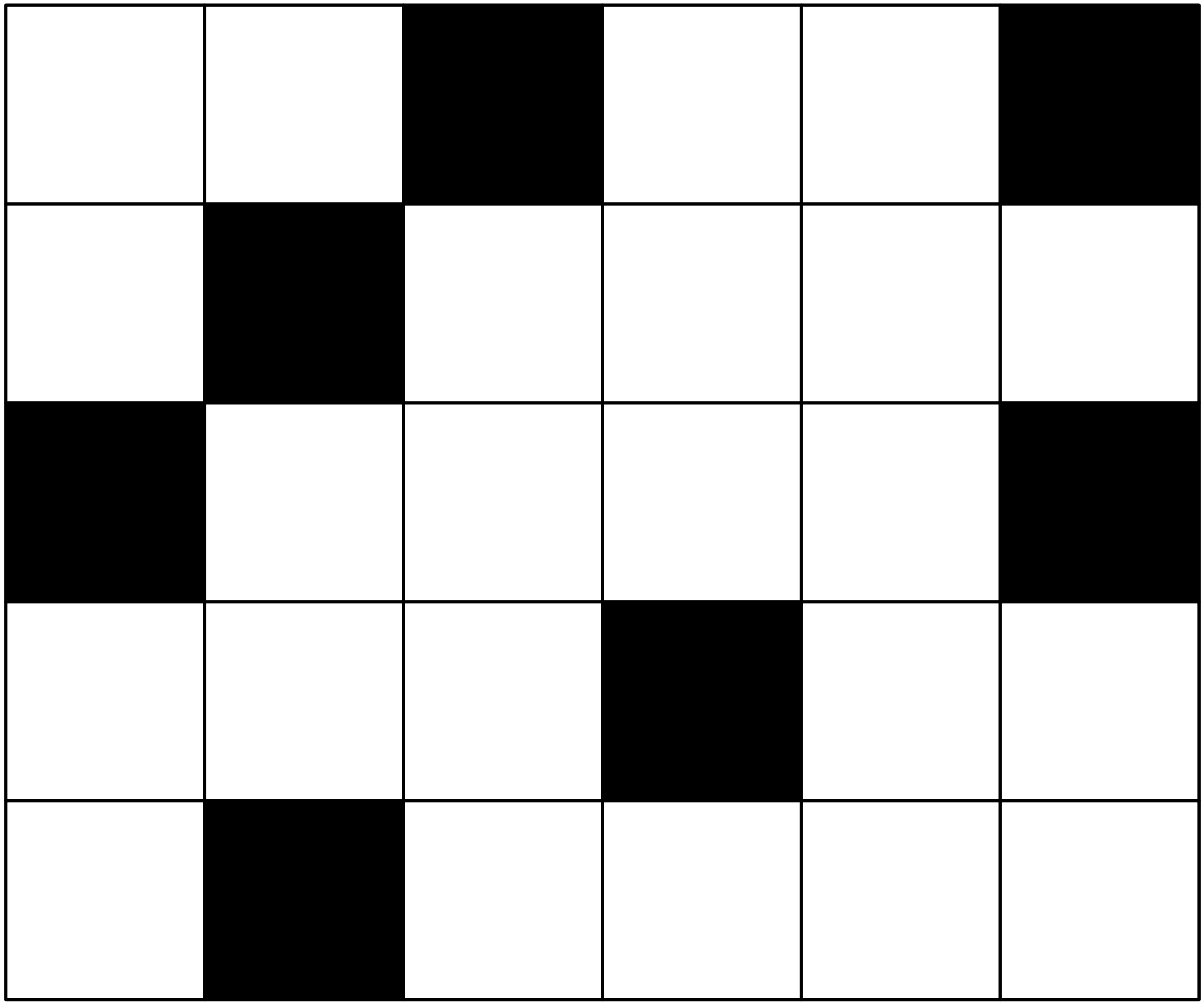


Maximum Matching

- Jack Edmonds' paper “Paths, Trees, and Flowers” gives a polynomial-time algorithm for finding maximum matchings.
  - He’s the guy with the quote about “better than decidable.”
- Using this fact, what other problems can we solve?

Domino Tiling



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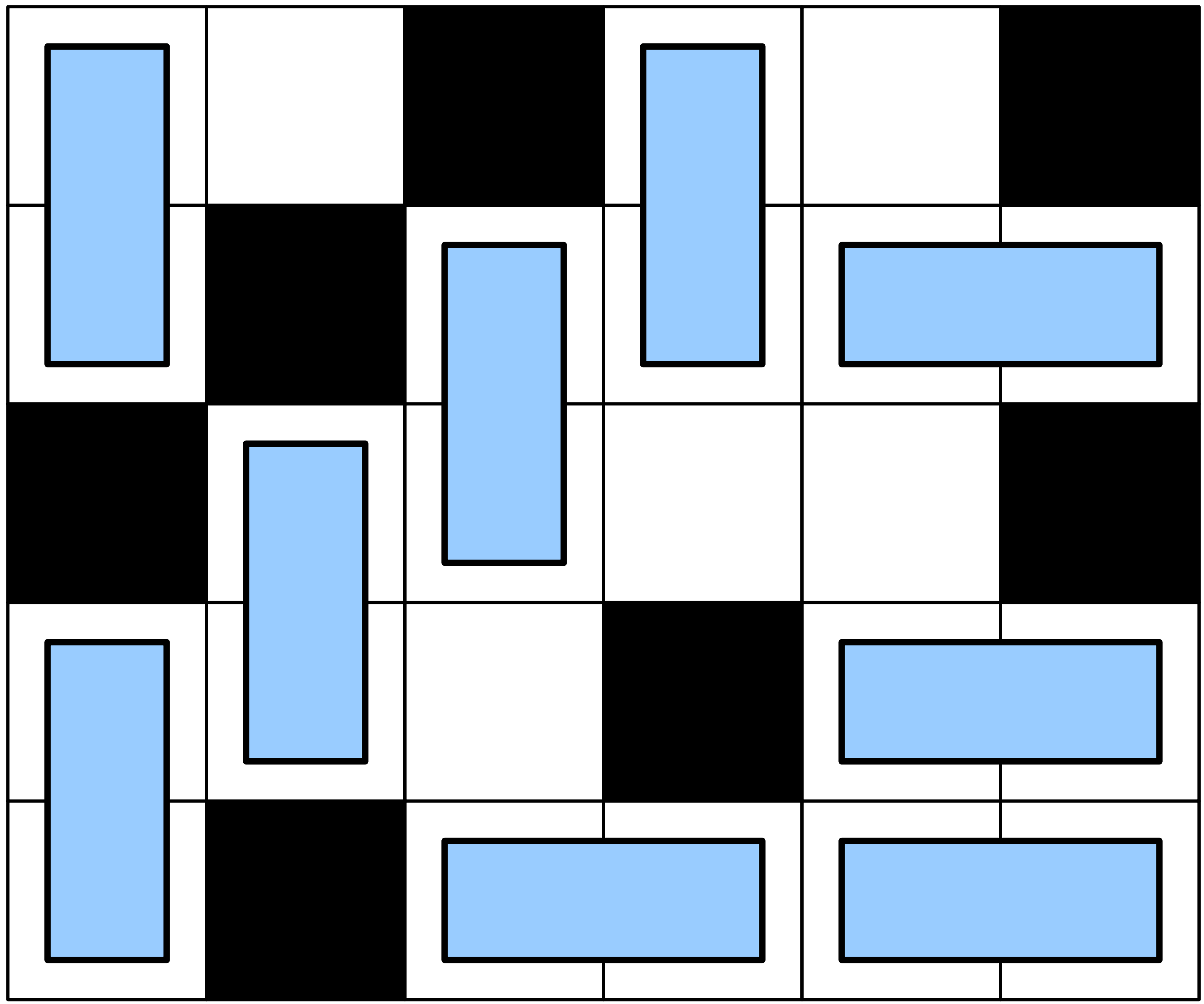

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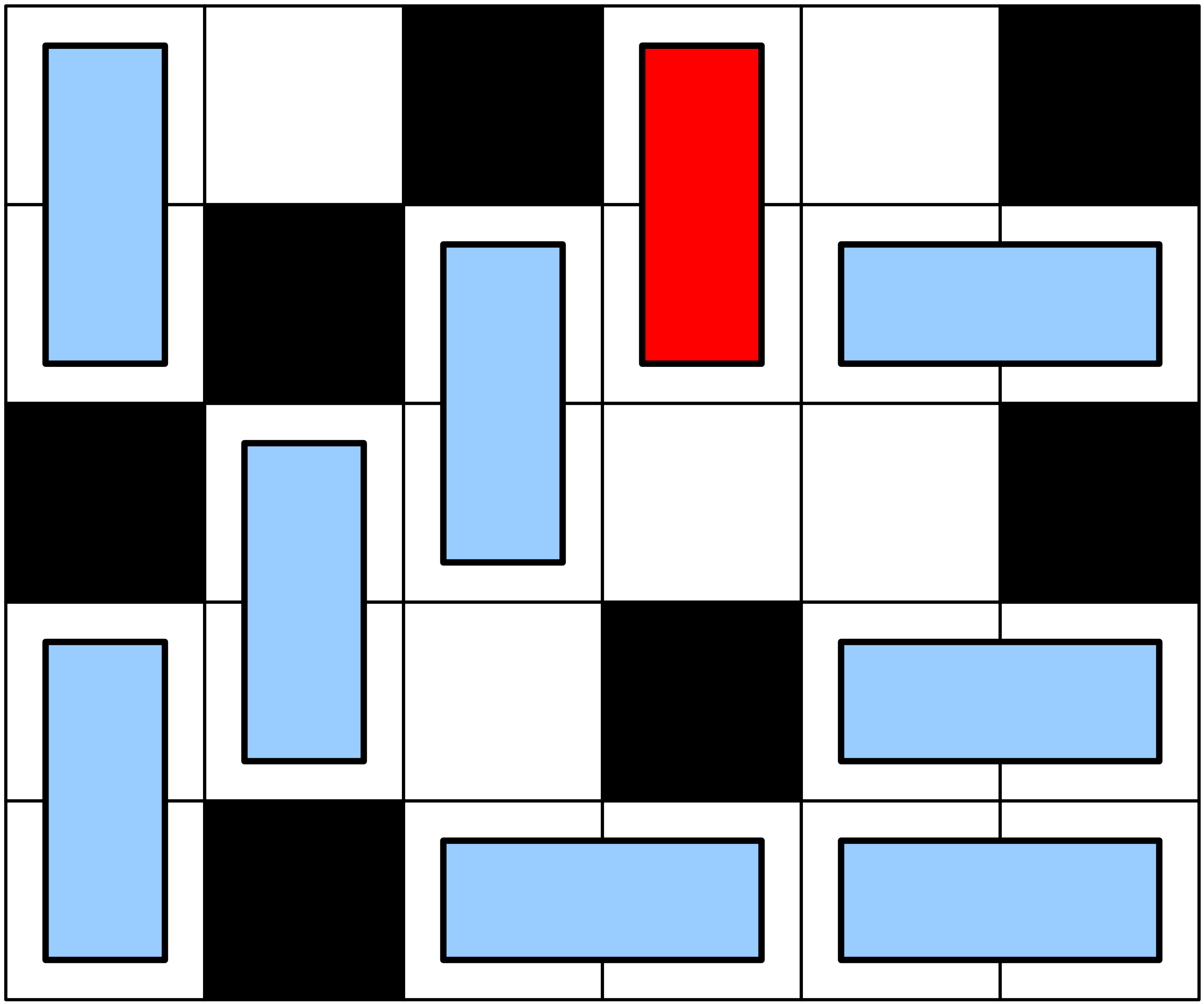

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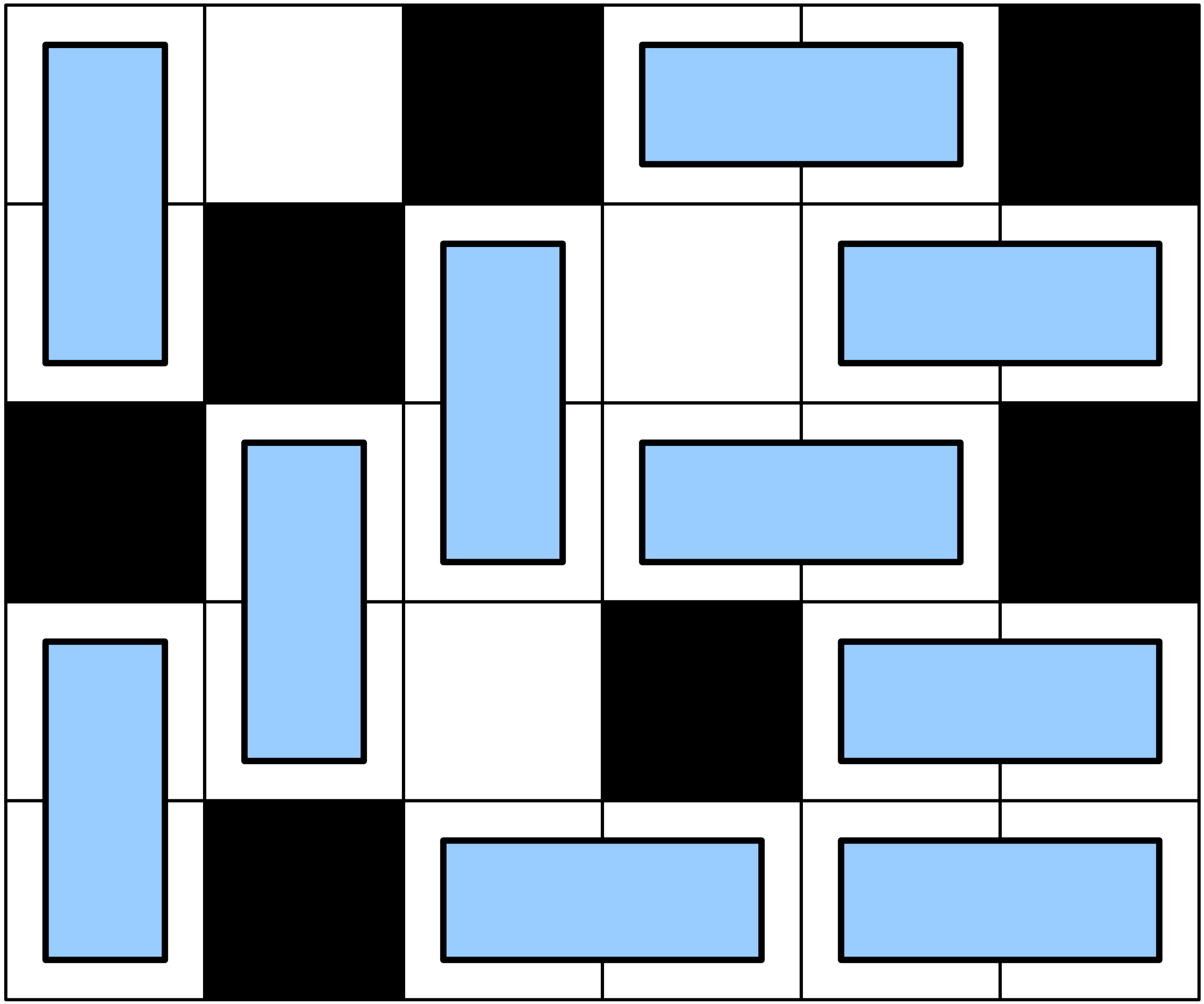

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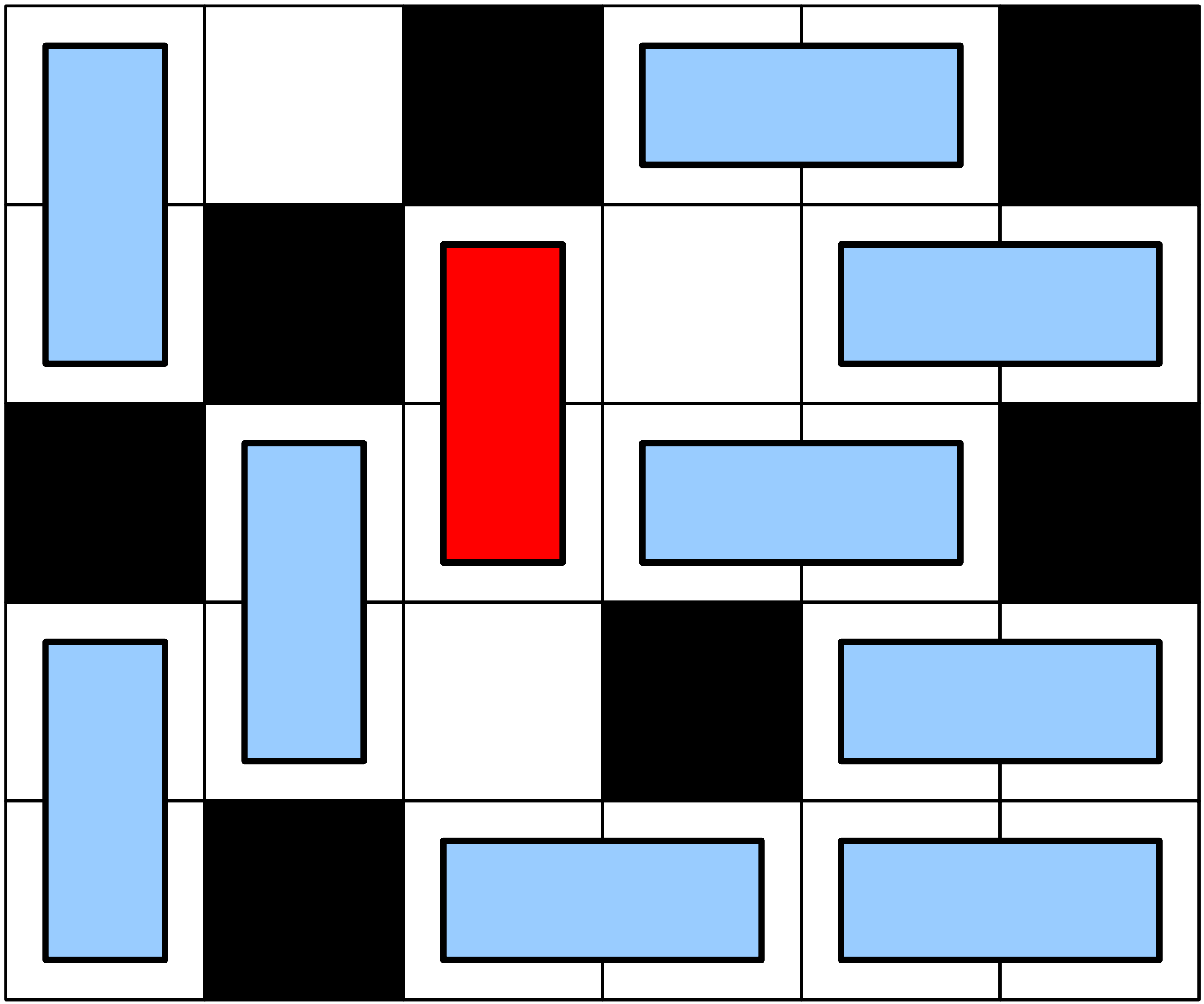

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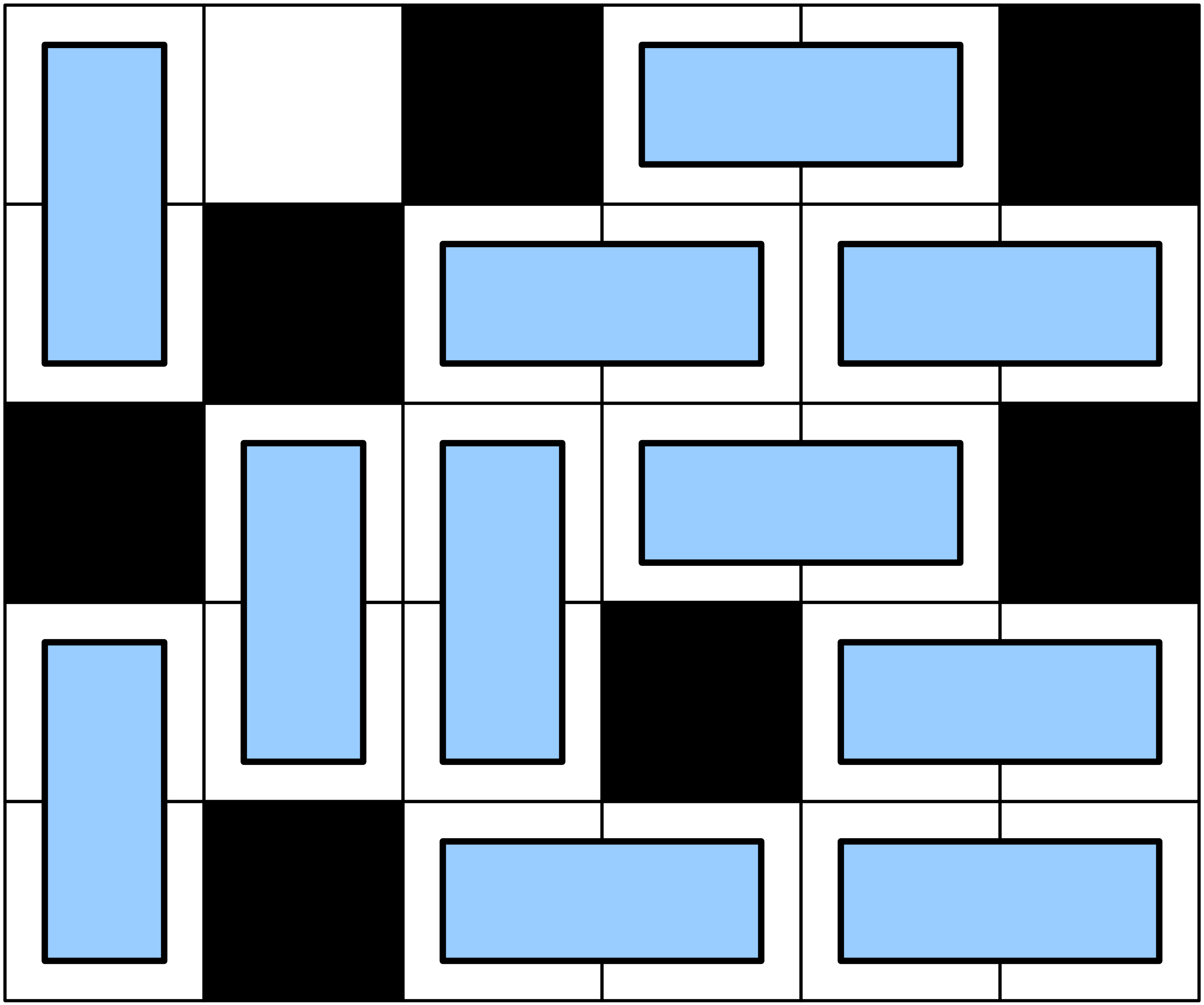
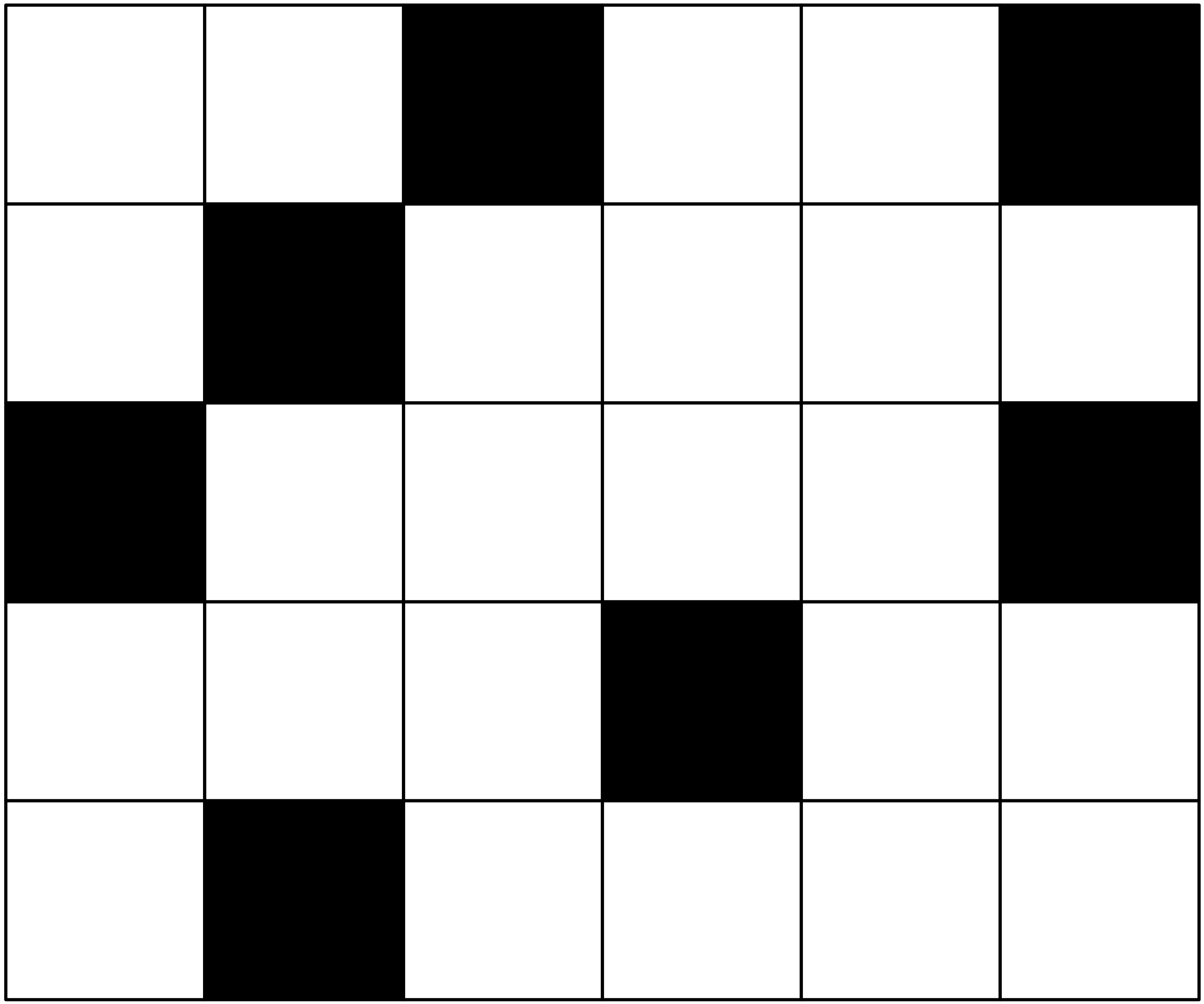


Solving Domino Tiling



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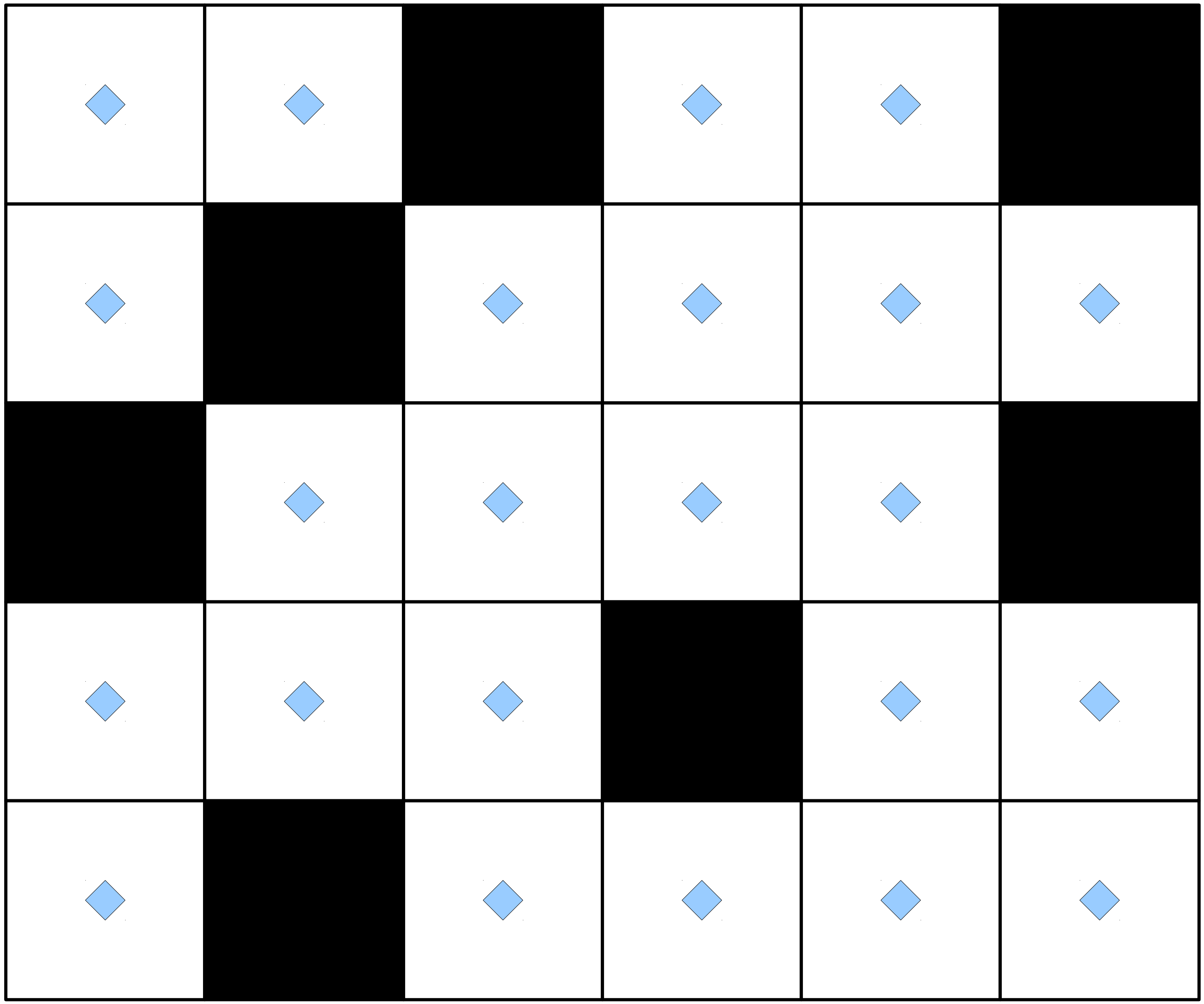

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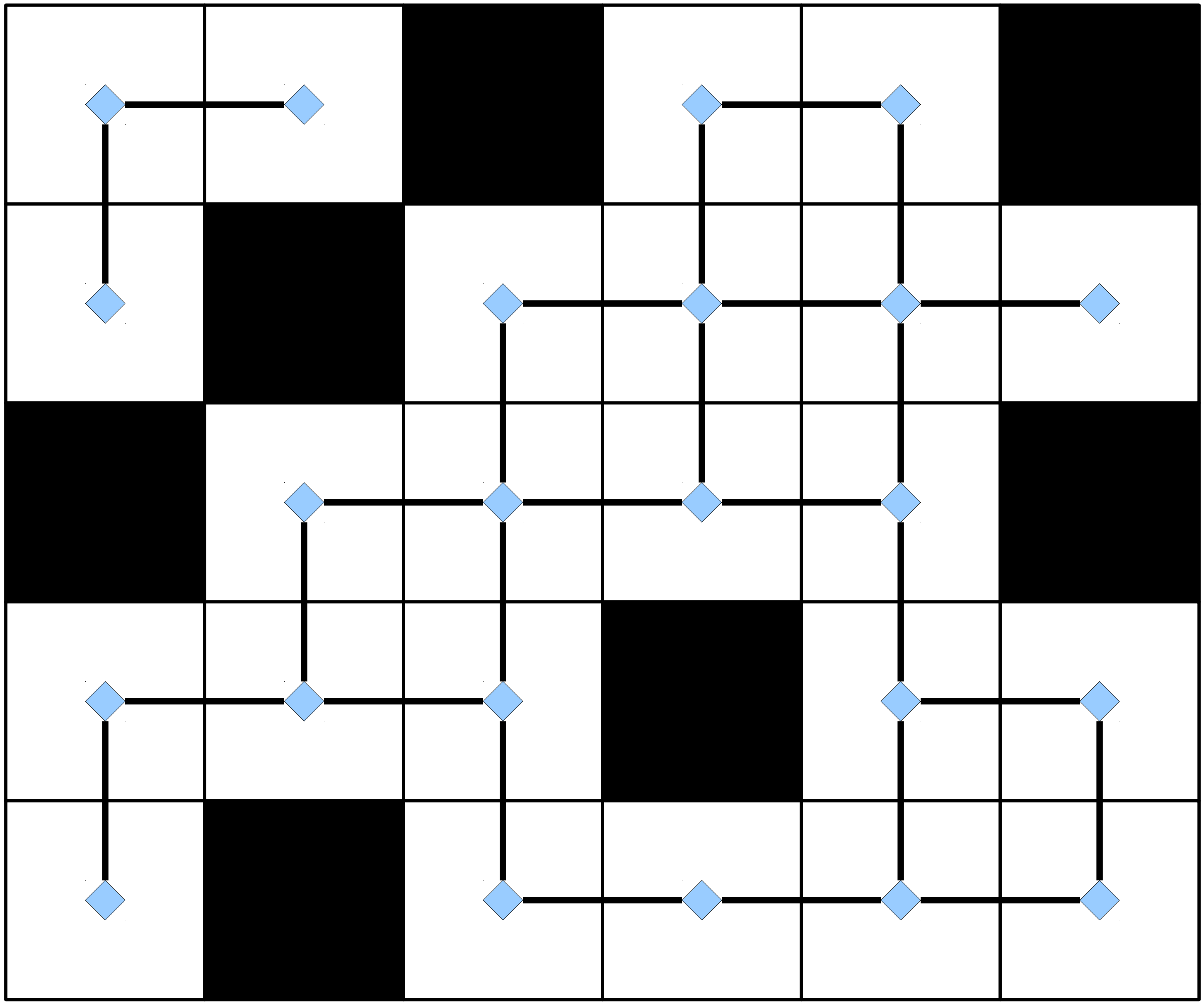

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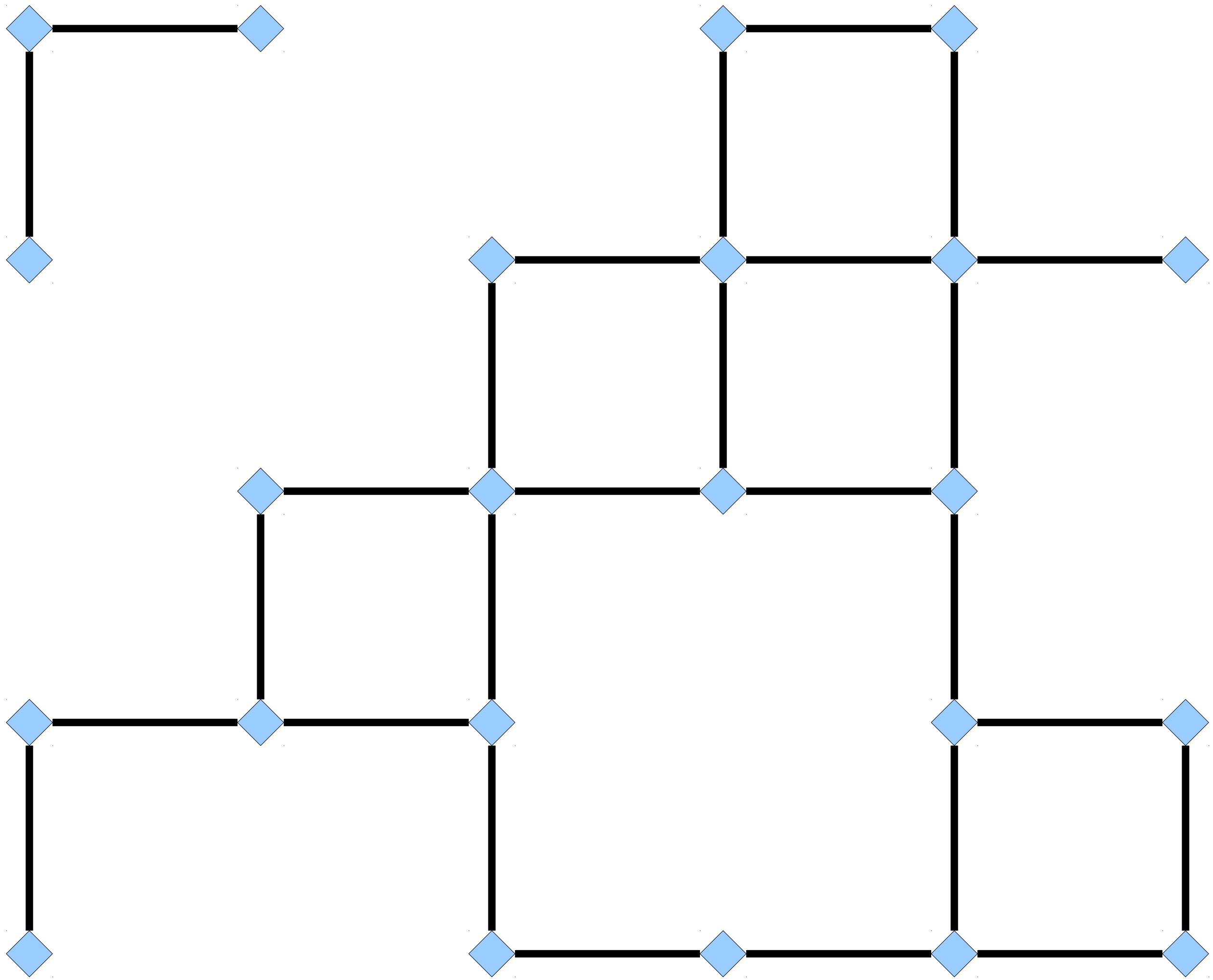

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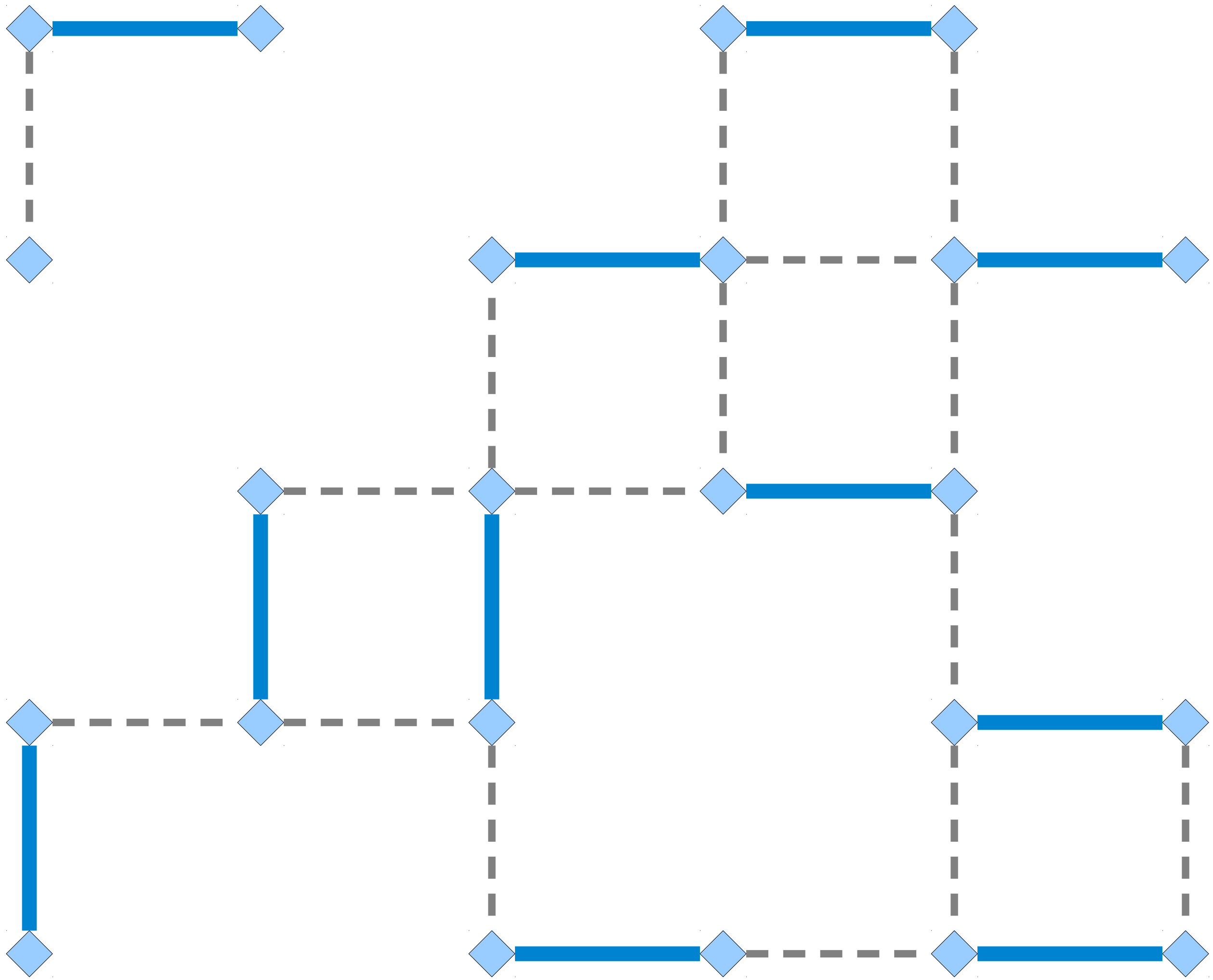

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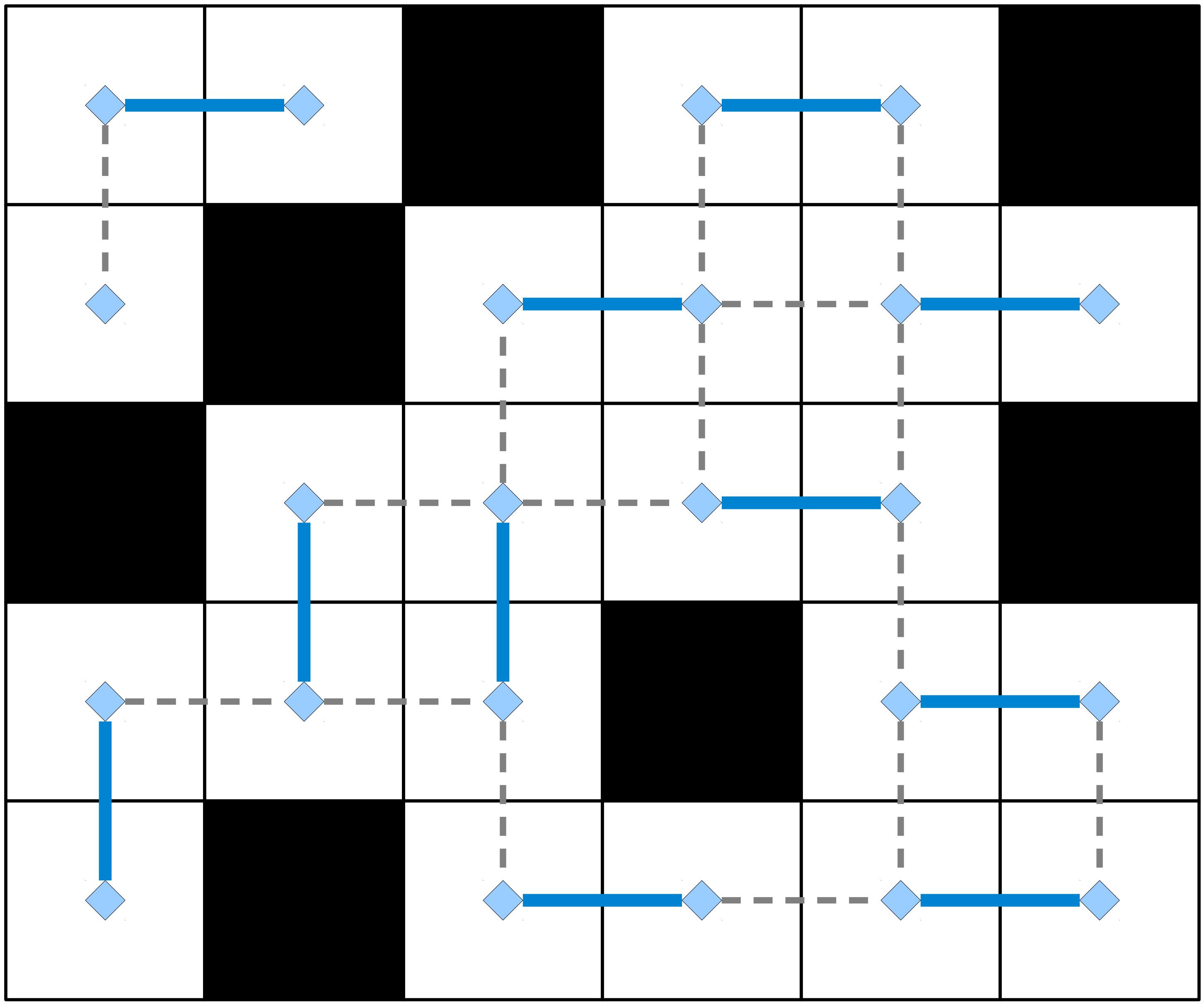

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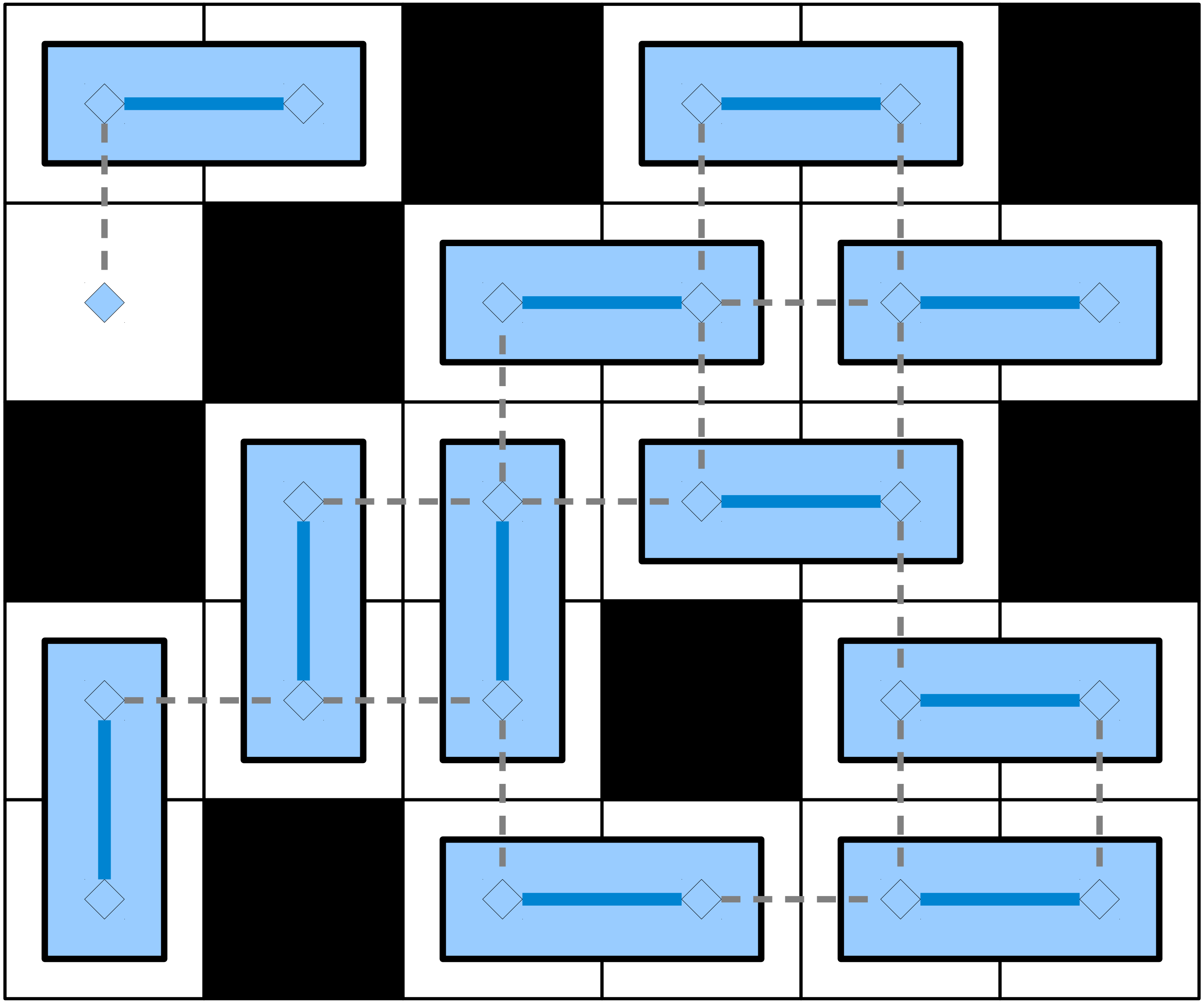

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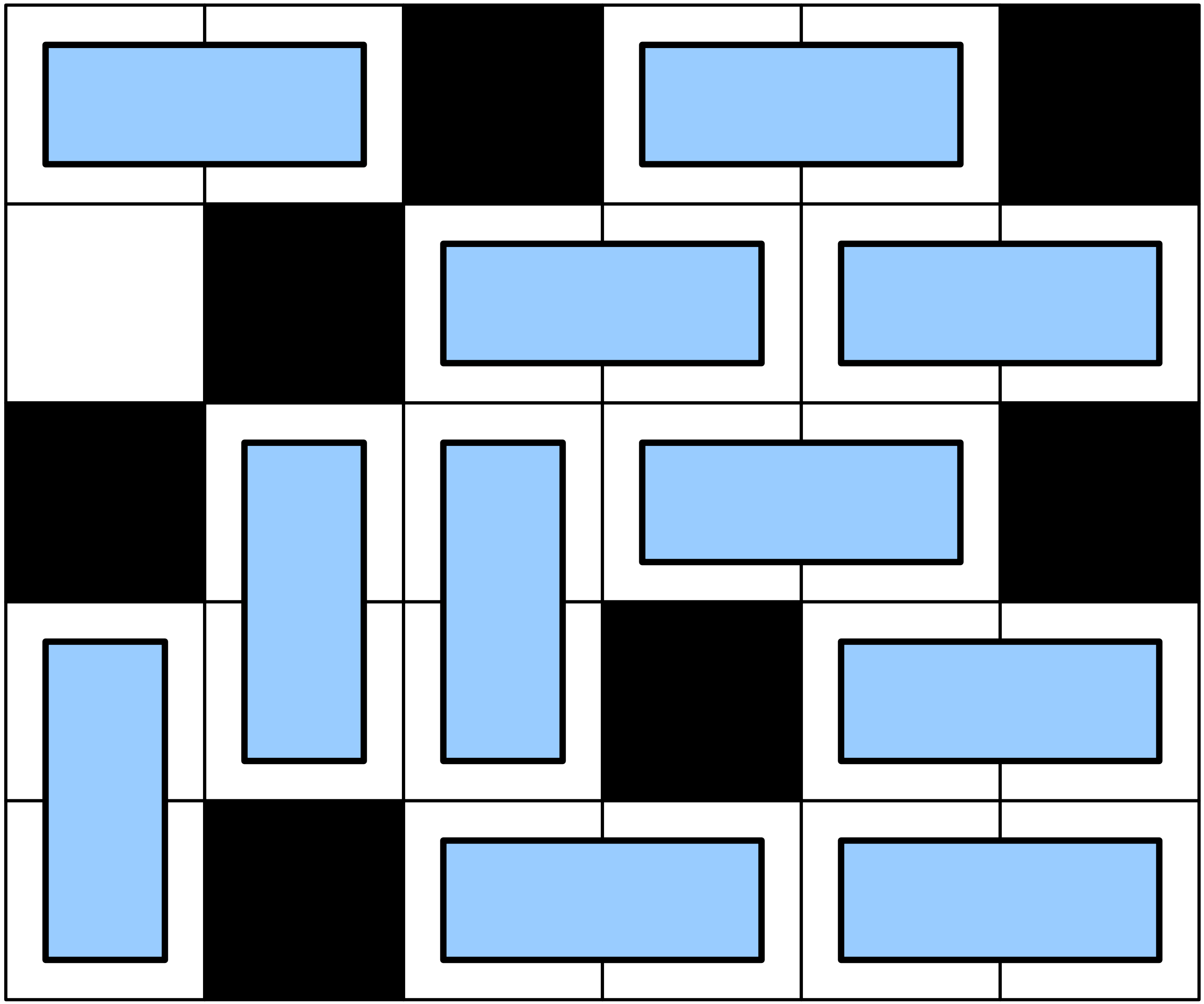

In Pseudocode

```
boolean canPlaceDominoes(Grid G, int k) {
    return hasMatching(gridToGraph(G), k);
}
```

Intuition:

Tiling a grid with dominoes can't be "harder" than solving maximum matching, because if we can solve maximum matching efficiently, we can solve domino tiling efficiently.

Another Example

Reachability

- Consider the following problem:

  Given an directed graph *G* and nodes *s* and *t* in *G*, is there a path from *s* to *t*?

- This problem can be solved in polynomial time (use DFS or BFS).

Converter Conundrums

- Suppose that you want to plug your laptop into a projector.
- Your laptop only has a VGA output, but the projector needs HDMI input.
- You have a box of connectors that convert various types of input into various types of output (for example, VGA to DVI, DVI to DisplayPort, etc.)
- ***Question:*** Can you plug your laptop into the projector?

Converter Conundrums

Connectors

RGB to USB
VGA to DisplayPort
DB13W3 to CATV
DisplayPort to RGB
DB13W3 to HDMI
DVI to DB13W3
S-Video to DVI
FireWire to SDI
VGA to RGB
DVI to DisplayPort
USB to S-Video
SDI to HDMI

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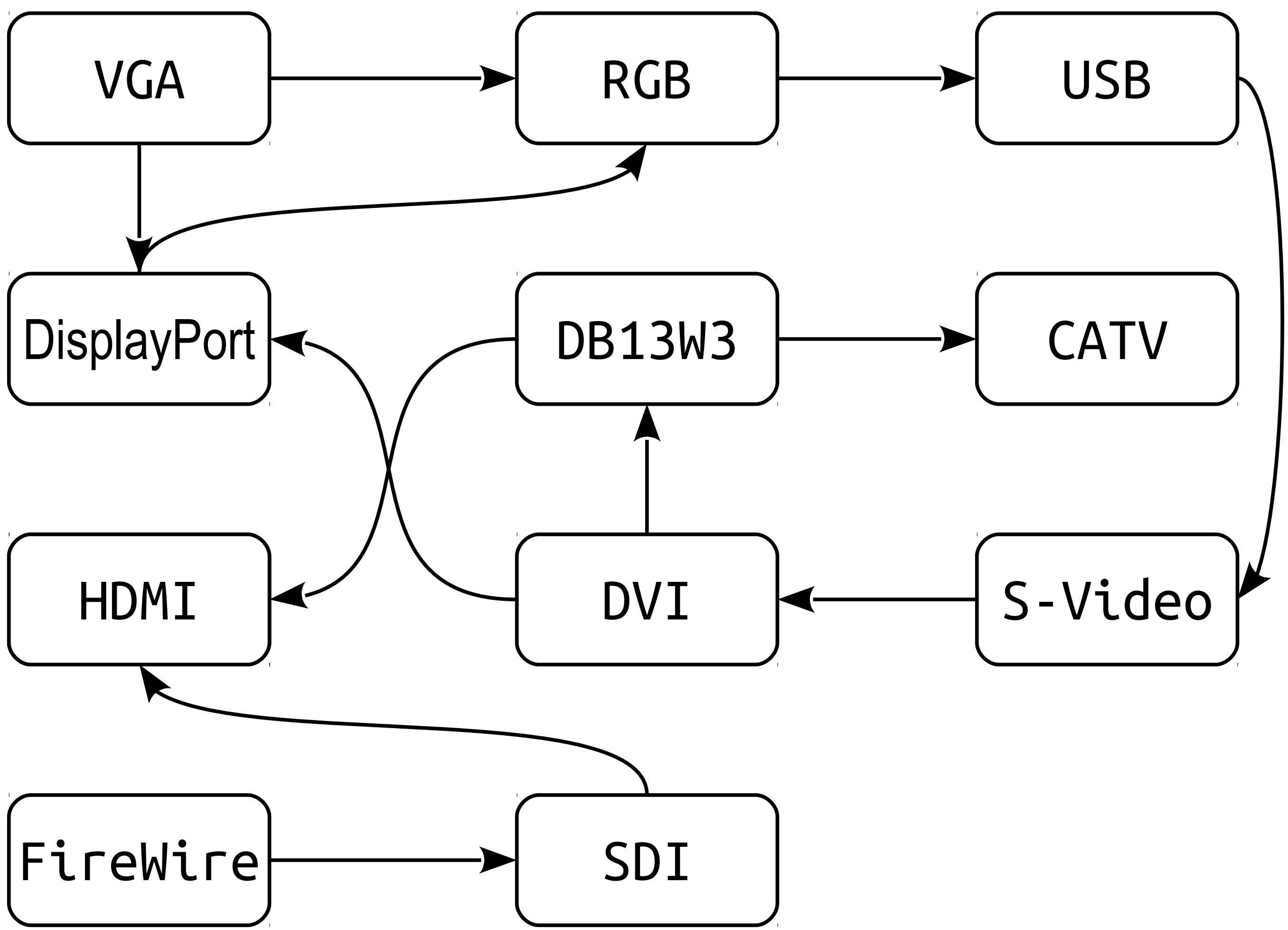
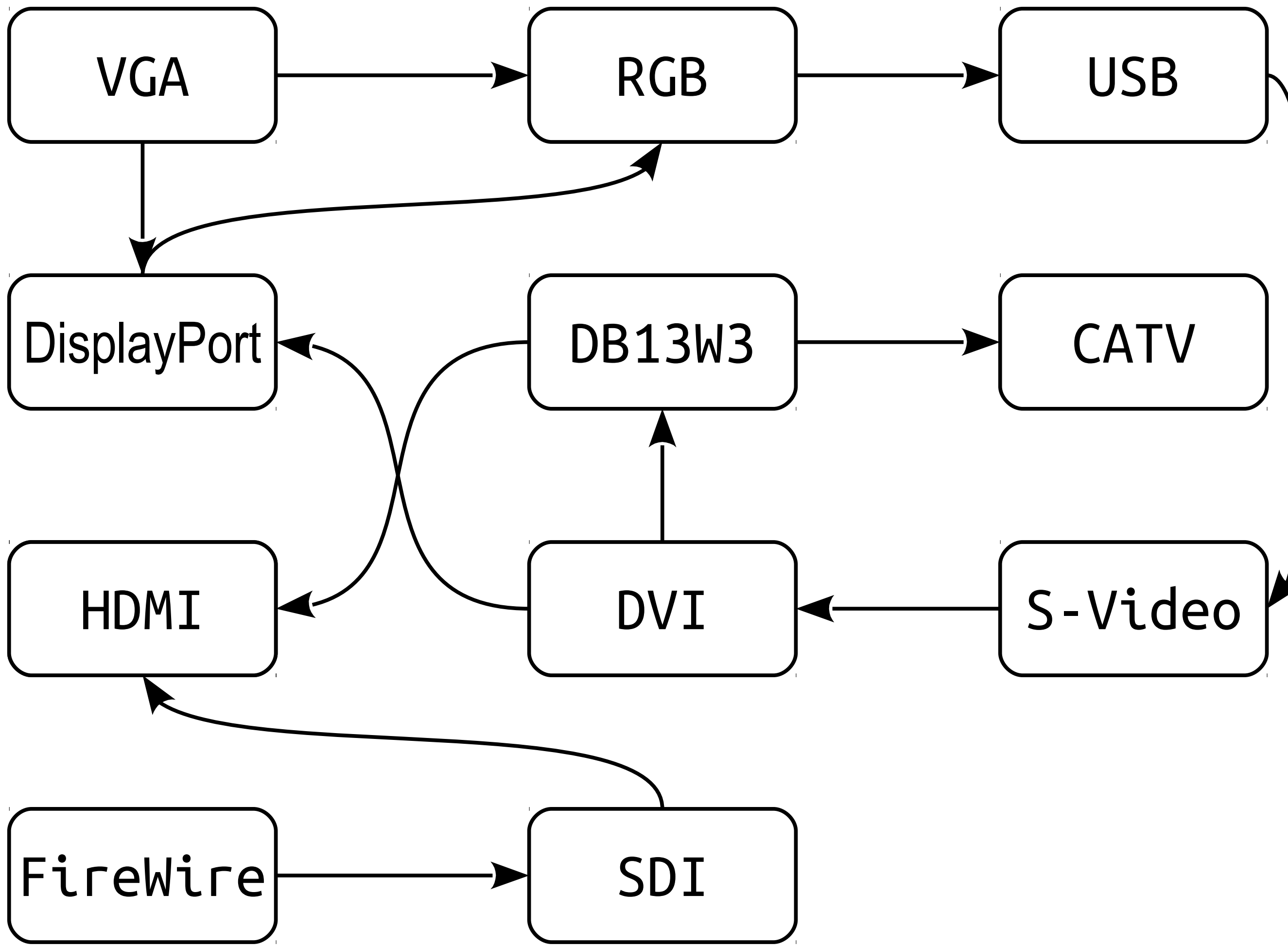


Converter Conundrums



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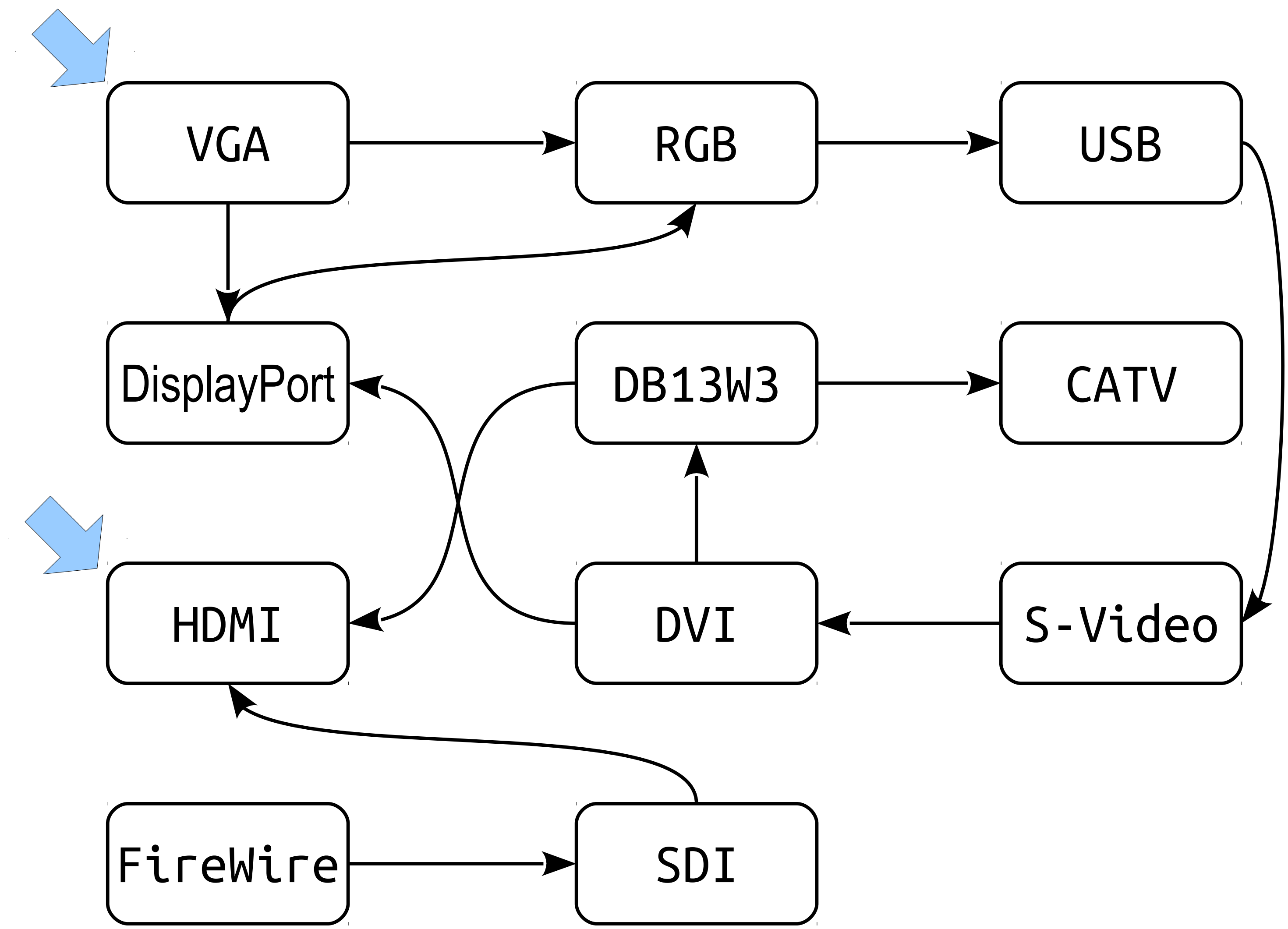

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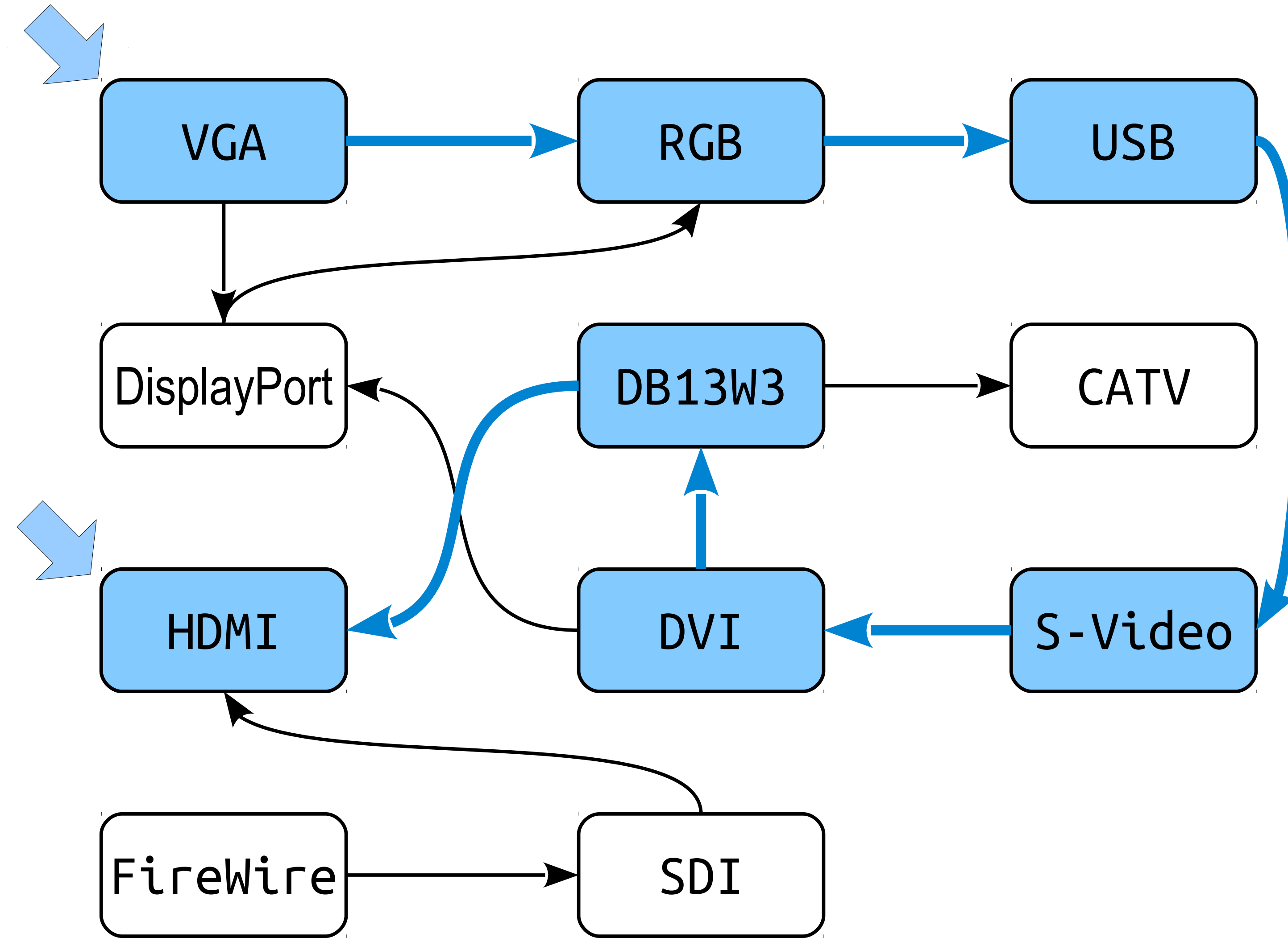

Converter Conundrums

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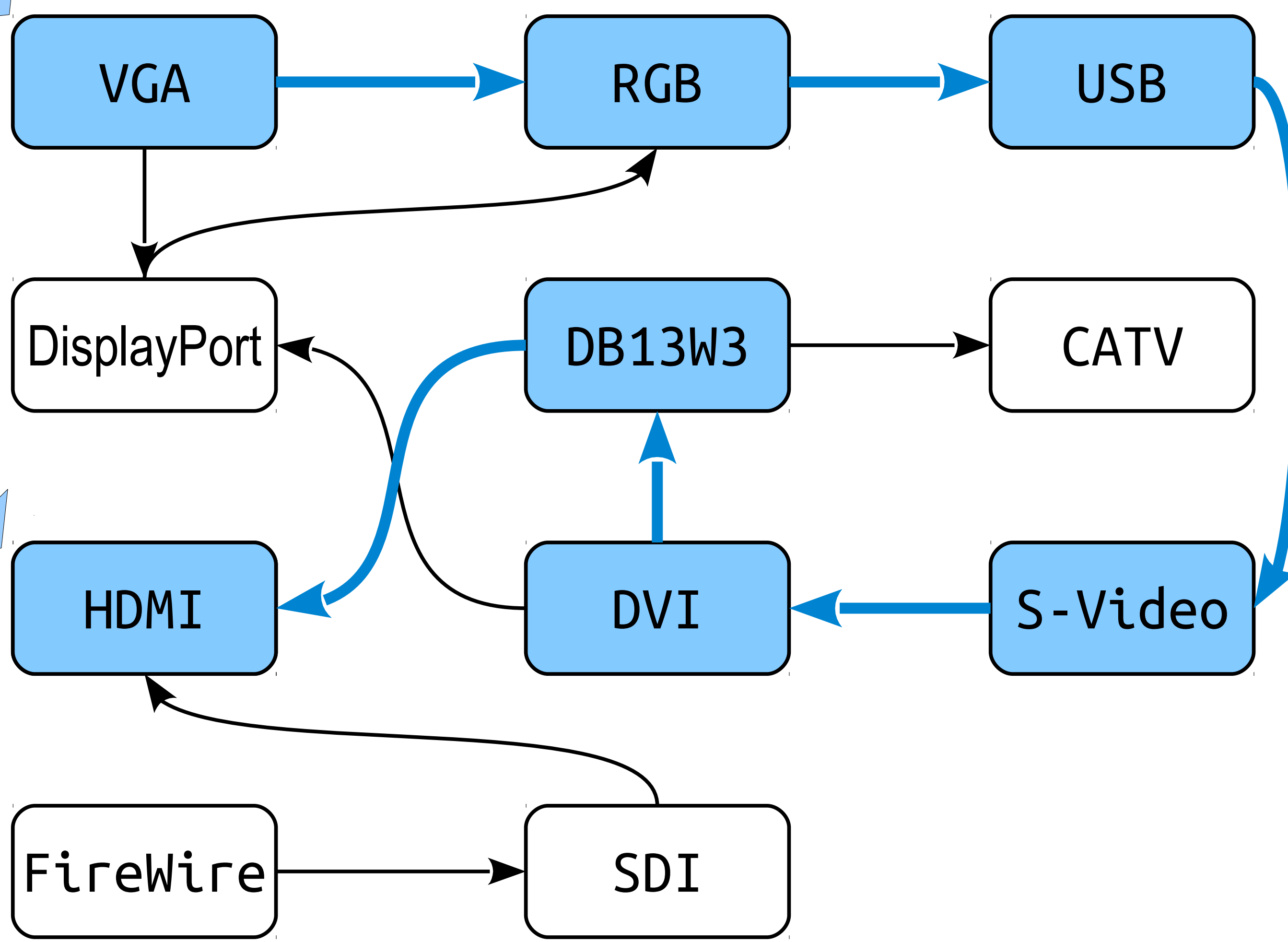


In Pseudocode

```
boolean canPlugIn(List<Plug> plugs) {
  return isReachable(plugsToGraph(plugs),
                     VGA, HDMI);
}
```

Intuition:

Finding a way to plug a computer into a projector can't be “harder” than determining reachability in a graph, since if we can determine reachability in a graph, we can find a way to plug a computer into a projector.

```
bool solveProblemA(string input) {
    return solveProblemB(transform(input));
}
```

Intuition:

Problem A can't be “harder” than problem B, because solving problem B lets us solve problem A.

```
bool solveProblemA(string input) {
    return solveProblemB(transform(input));
}
```

- If A and B are problems where it's possible to solve problem A using the strategy shown above*, we write

$$A \leq_p B.$$

- We say that ***A is polynomial-time reducible to B***.

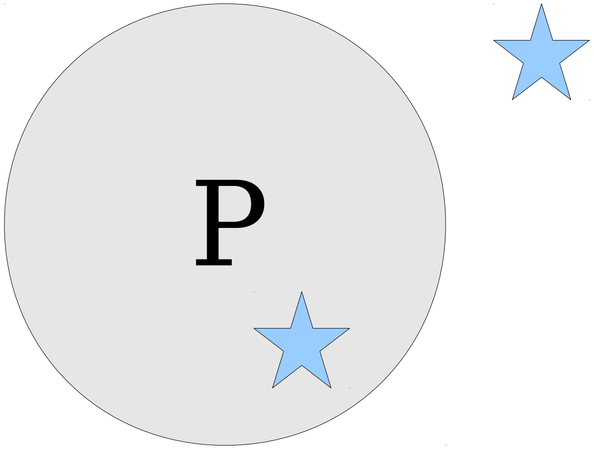
* Assuming that `transform` runs in polynomial time.

```
bool solveProblemA(string input) {
    return solveProblemB(transform(input));
}
```

- This is a powerful general problem-solving technique. You'll see it a lot in CS161.

Polynomial-Time Reductions

- If $A \leq_p B$ and $B \in \mathbf{P}$, then $A \in \mathbf{P}$.



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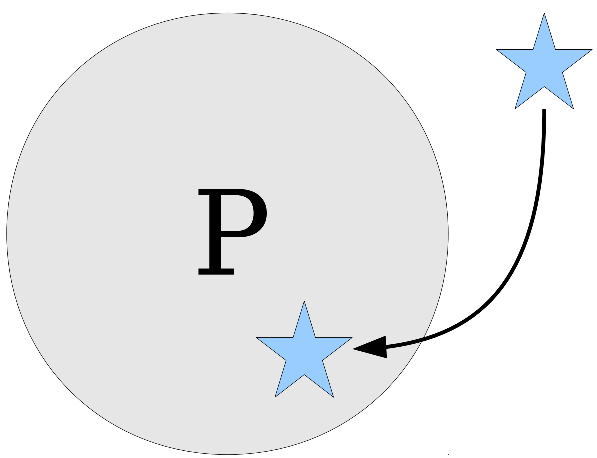

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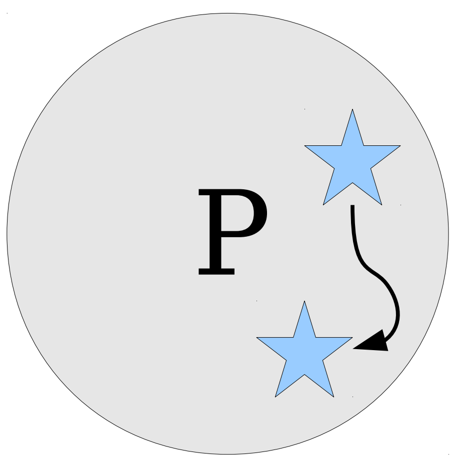

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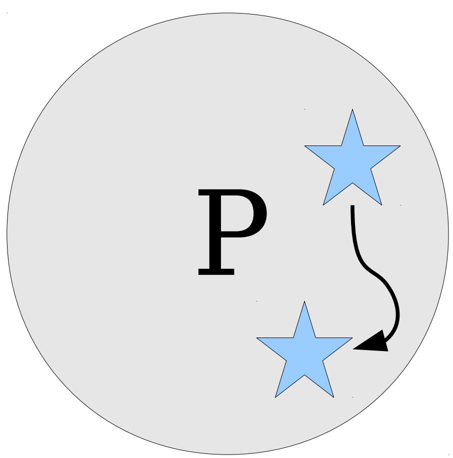
- If $A \leq_p B$ and $B \in \mathbf{P}$, then $A \in \mathbf{P}$.
- If $A \leq_p B$ and $B \in \mathbf{NP}$, then $A \in \mathbf{NP}$.



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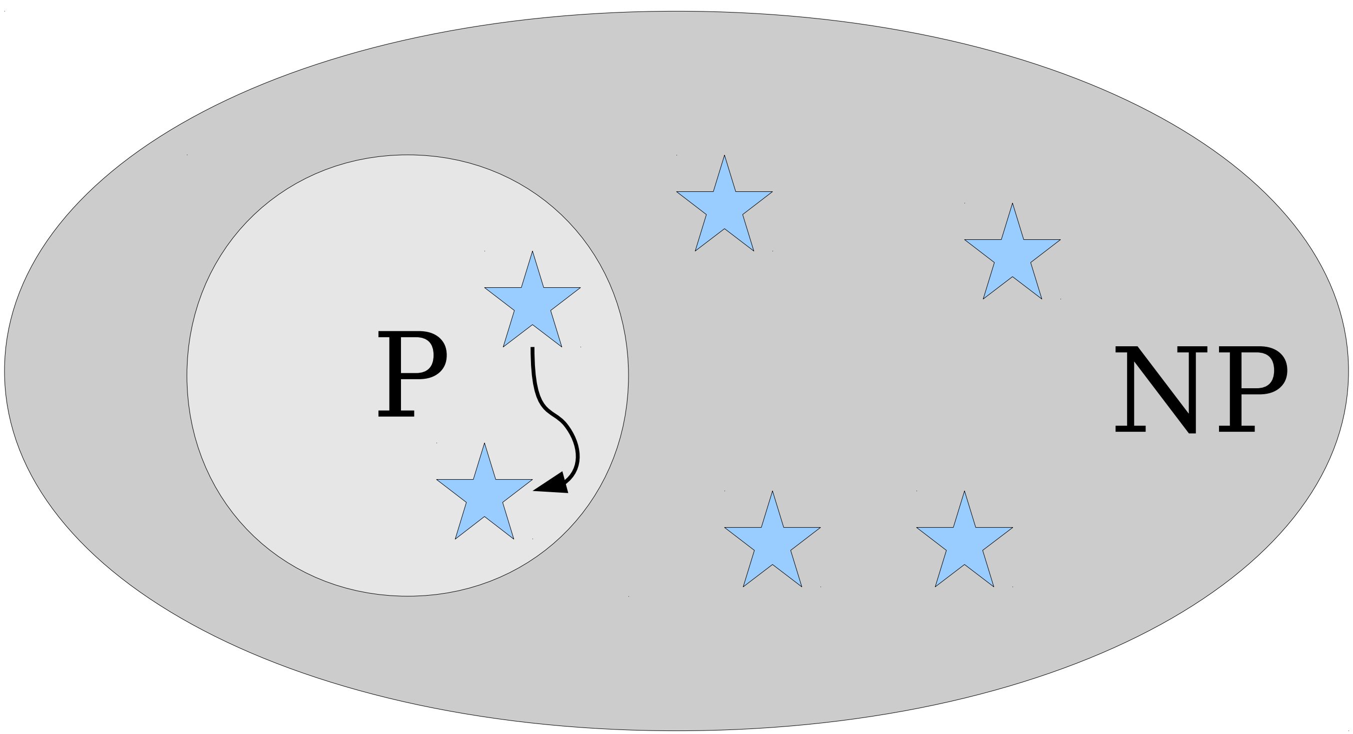

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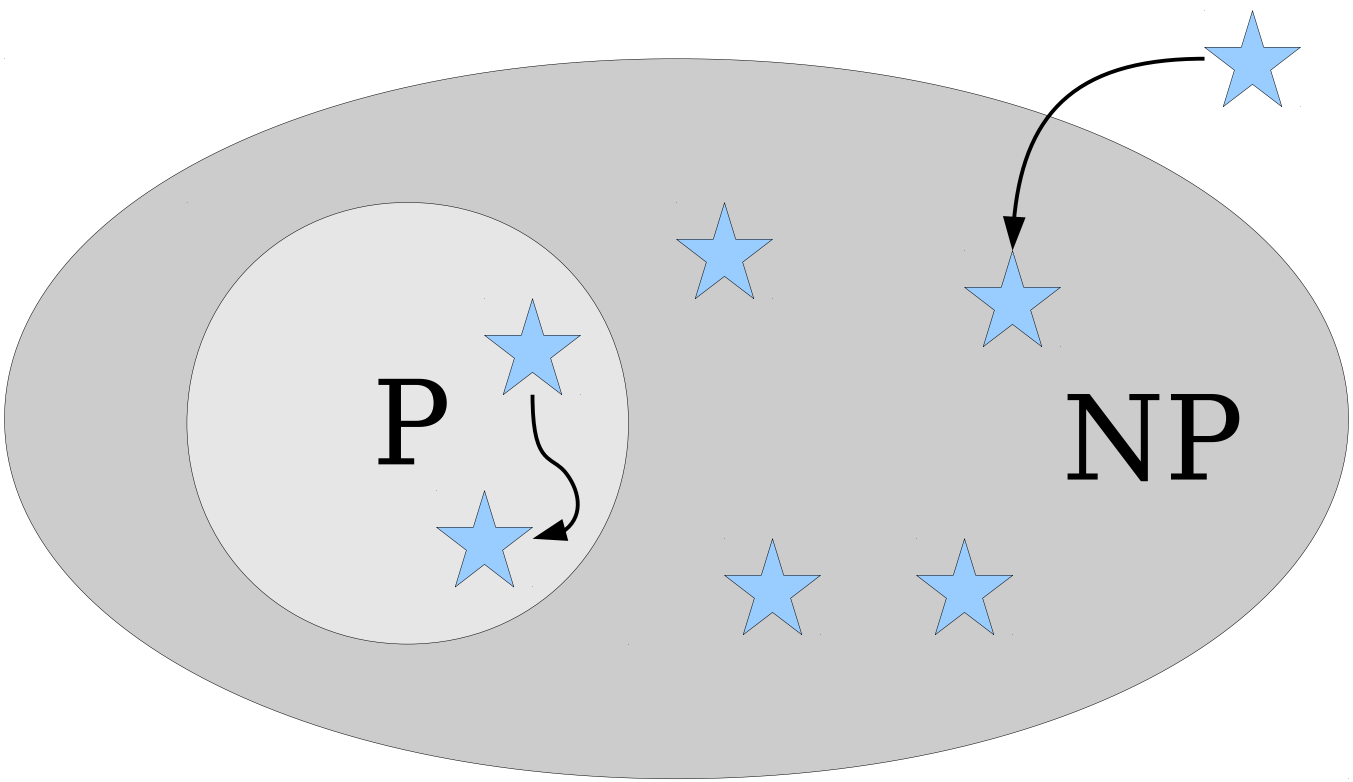

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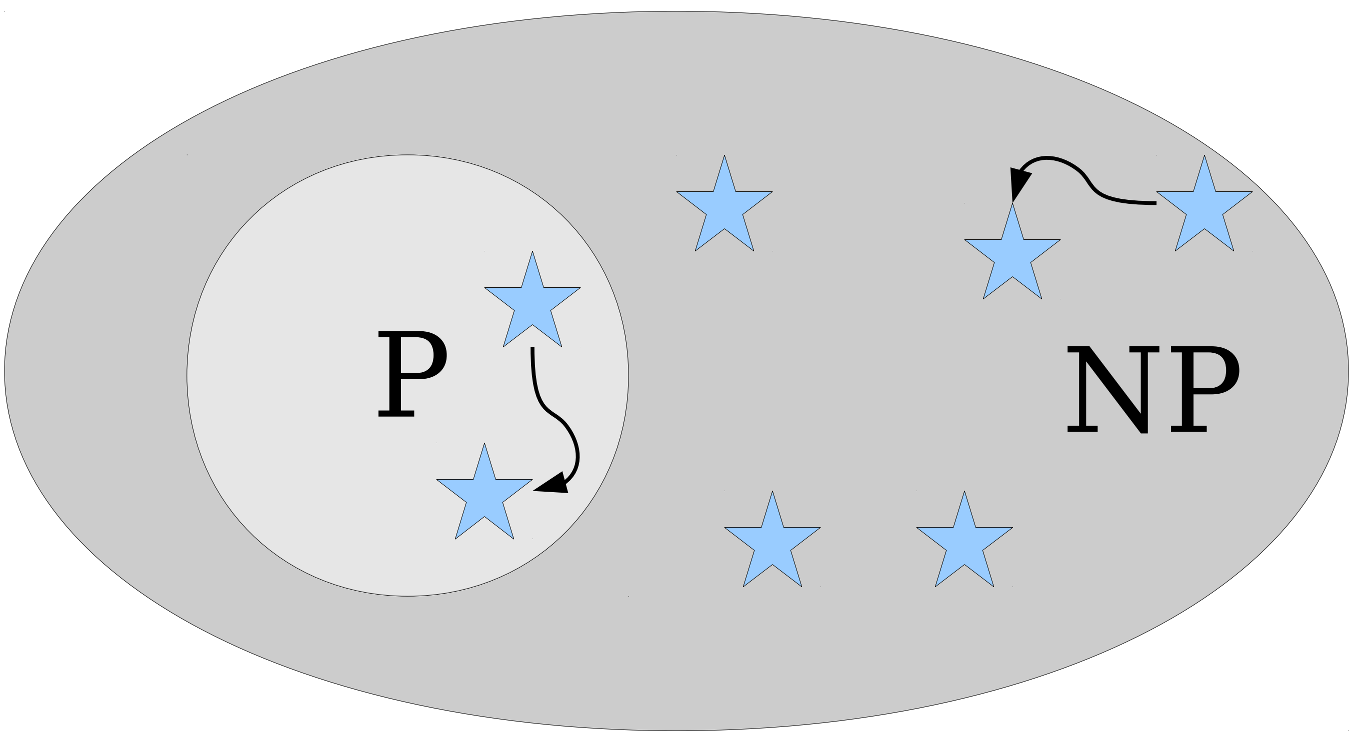

This $\leq_p$ relation lets us rank the relative difficulties of problems in **P** and **NP**.

What else can we do with it?

Next Time

- ***NP-Completeness***
  - What are the hardest problems in **NP**?