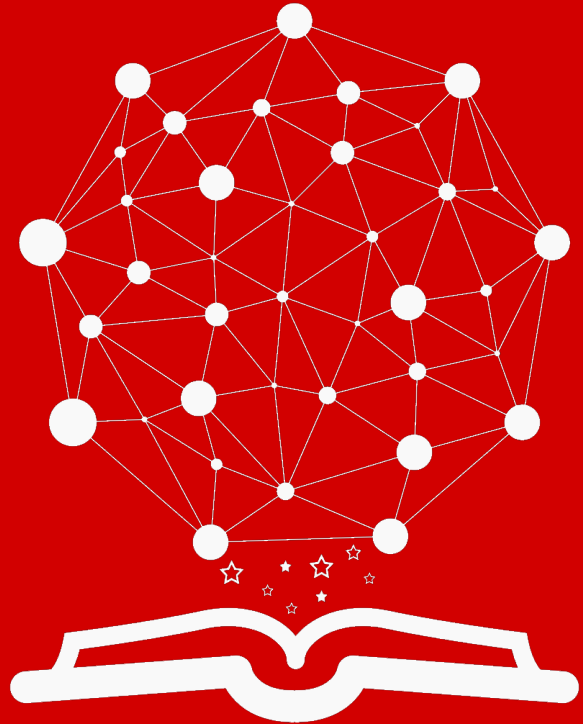


# Pushing the boundaries of rational AI through Knowledge and Reasoning



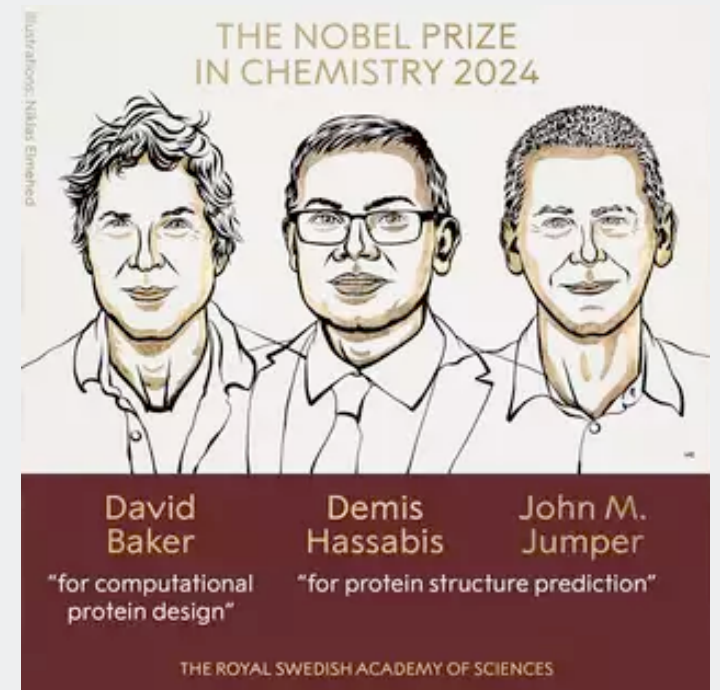
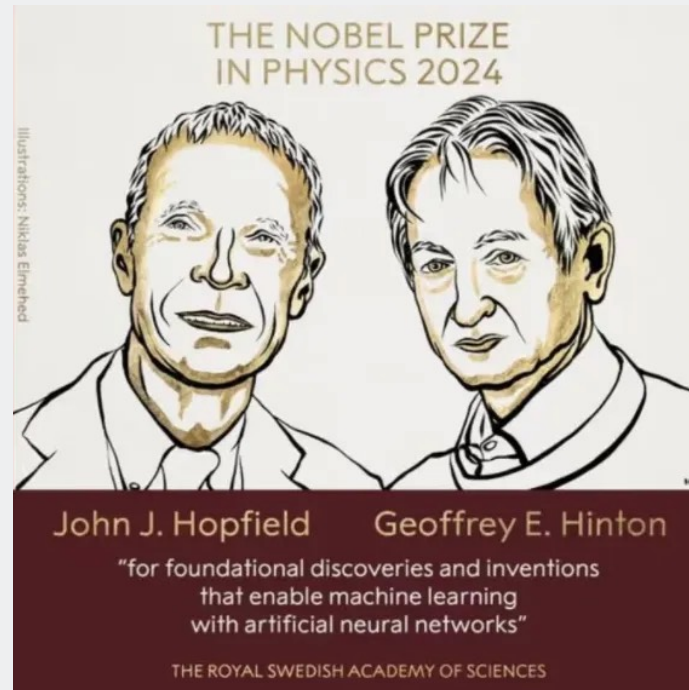
Institute of Logic and Computation

**Magdalena Ortiz**

Professor for Knowledge

Representation and Reasoning

# AI today



Photograph: Jonathunder Medal: Erik Lindberg

# How it started

1970s: optimism, great achievements

1959: MIT AI Lab -  
McCarthy & Minsky

1956: Dartmouth Summer  
Research Project on AI  
McCarthy, 1956



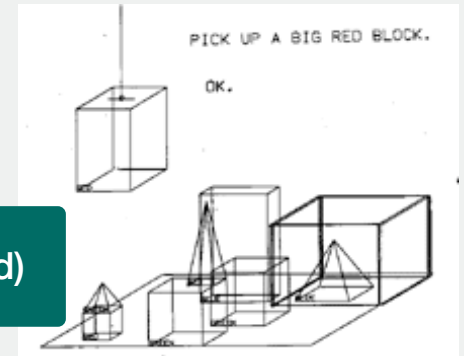
1950: Can machines think?  
Turing and the Imitation Game



1960: LISP (McCarthy & co)

1966: ELIZA  
(Weizenbaum, MIT)

1968: SHRDLU (Winograd)

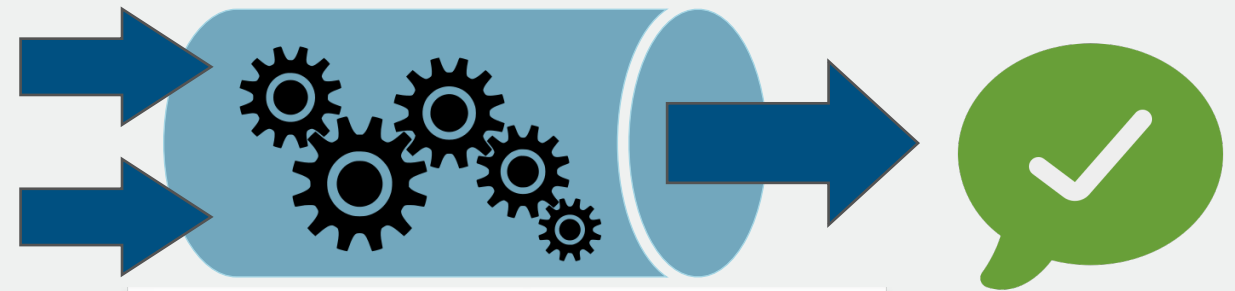
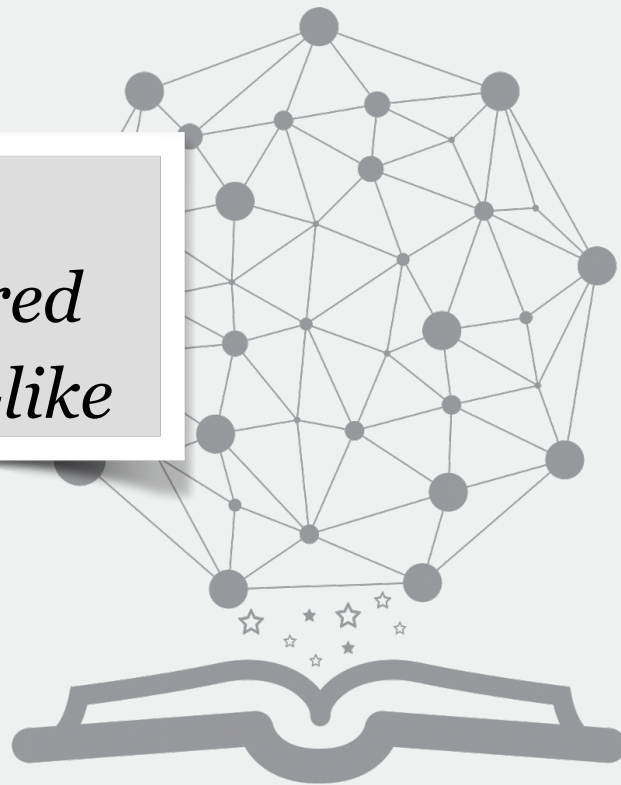


```
come to  
EEEEEE LL IIII ZZZZZZ AAAA  
EE LL II ZZ AA AA  
EEEE LL II ZZZ AAAAAA  
EE LL II ZZ AA AA  
EEEEEE LLLLL IIII ZZZZZZ AA AA  
... is a mock Rogerian psychotherapist.  
The original program was described by Joseph Weizenbaum in 1966.  
This implementation by Norbert Landsteiner 2005.  
  
ELIZA: Is something troubling you ?  
YOU: Men are all alike.  
ELIZA: What is the connection, do you suppose ?  
YOU: They're always bugging us about something or other.  
ELIZA: Can you think of a specific example ?  
YOU: Well, my boyfriend made me come here.  
ELIZA: Is it important to you that your boyfriend made you come here ?  
YOU: He says I'm depressed much of the time.  
ELIZA: I am sorry to hear that you are depressed.  
YOU: It's true. I am unhappy.  
ELIZA: Can you explain what made you unhappy ?  
YOU: 
```

# The rationality approach to AI

**Knowledge + Reasoning  $\Rightarrow$  Intelligence**

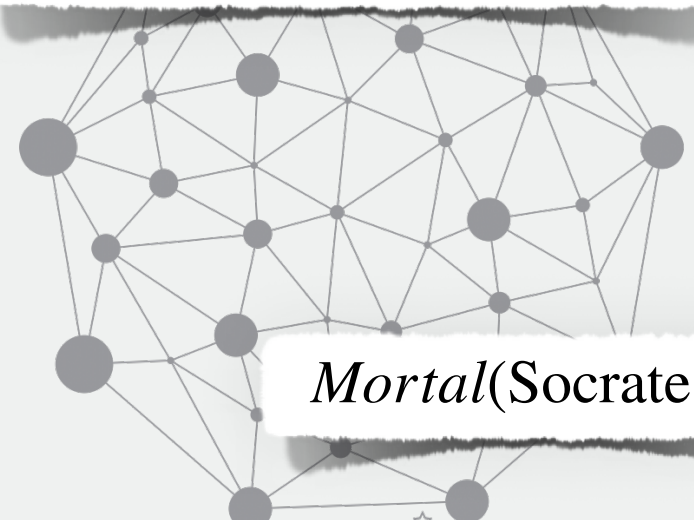
*explicit  
structured  
human-like*



*general purpose  
problem independent*

# Knowledge + Reasoning $\Rightarrow$ Intelligence

$\forall x \text{ Person}(x) \rightarrow \text{Mortal}(x).$   
 $\text{Person}(\text{Socrates}).$



$\text{Mortal}(\text{Socrates})?$

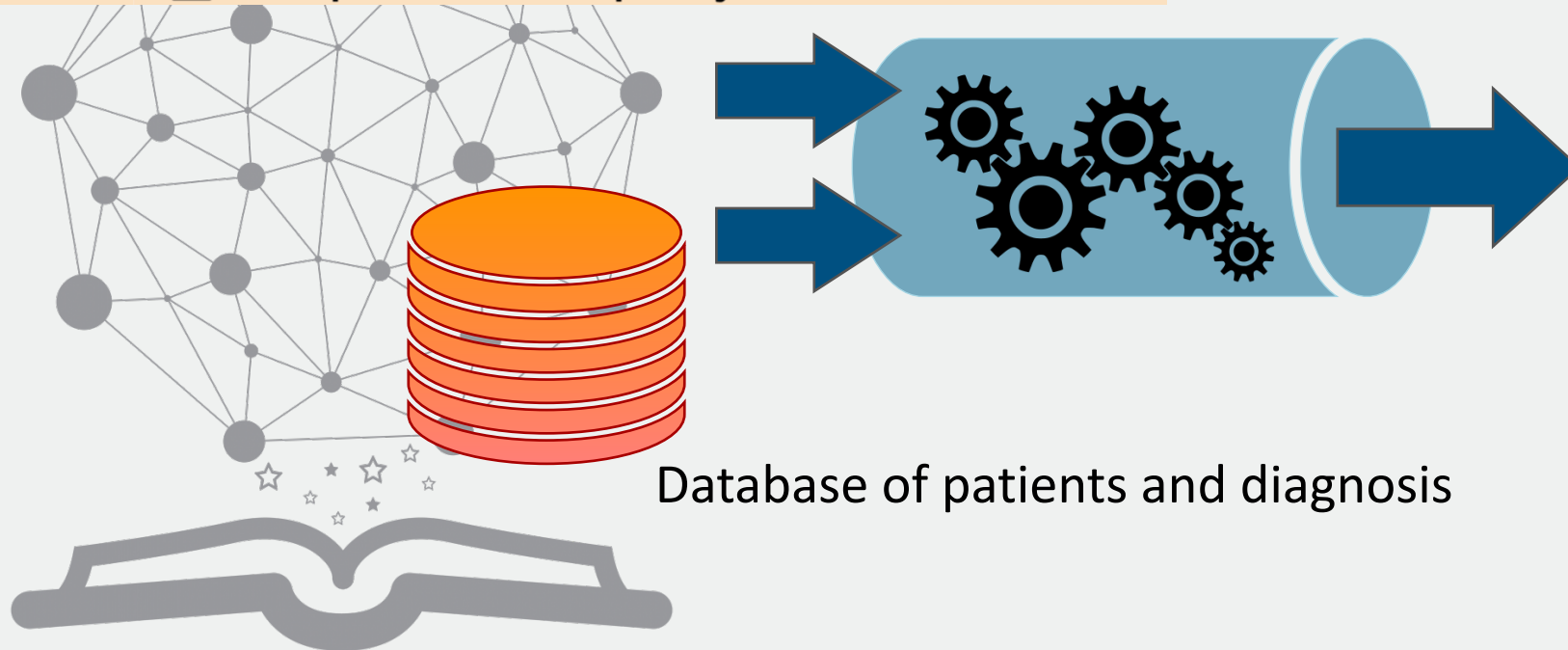


yes



# Knowledge + Reasoning $\Rightarrow$ Intelligence

Pneumonia	$\sqsubseteq$	Inflammation $\sqcap$ $\exists$ affects.Lung
Bronchitis	$\sqsubseteq$	Inflammation $\sqcap$ $\exists$ affects.Bronchi
Lung	$\sqsubseteq$	$\exists$ partOf.RespirSyst
Bronchi	$\sqsubseteq$	$\exists$ partOf.RespirSyst



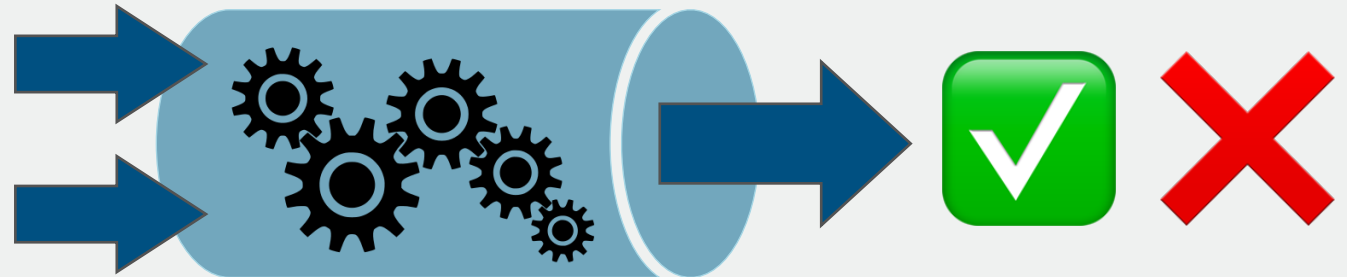
In patients with respiratory inflammation:  
.....

# Knowledge + Reasoning $\Rightarrow$ Intelligence

Description of a dynamic system's evolution



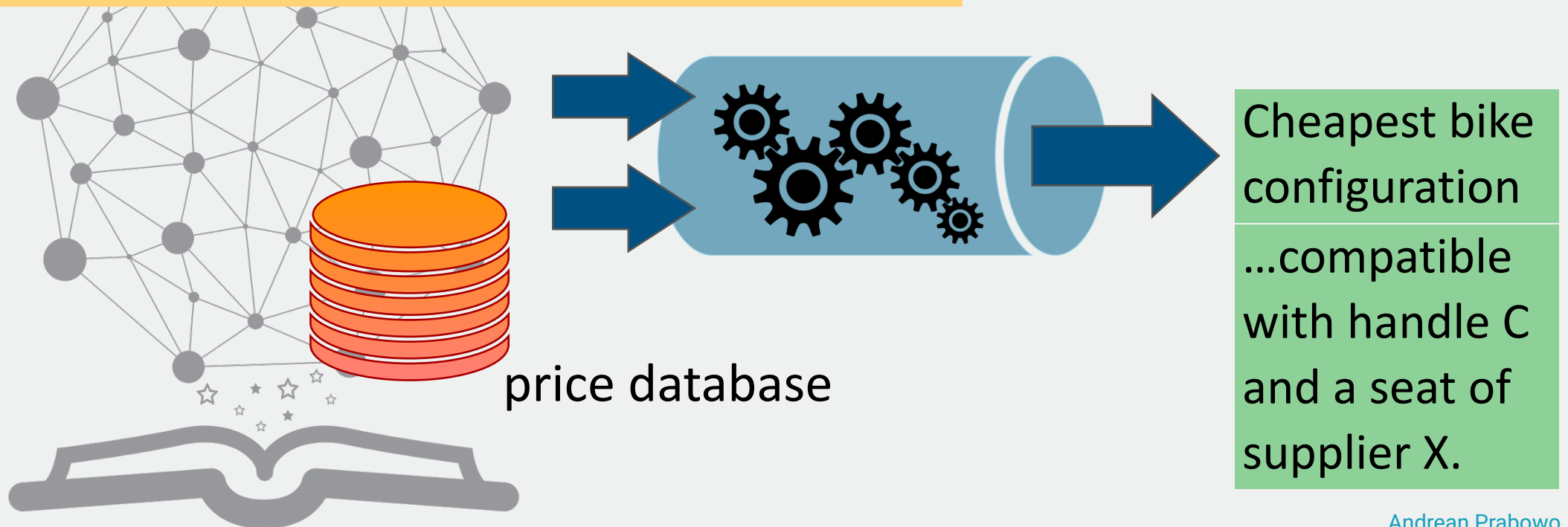
Safety conditions



[Andreas Prabowo](#)

# Knowledge + Reasoning $\Rightarrow$ Intelligence

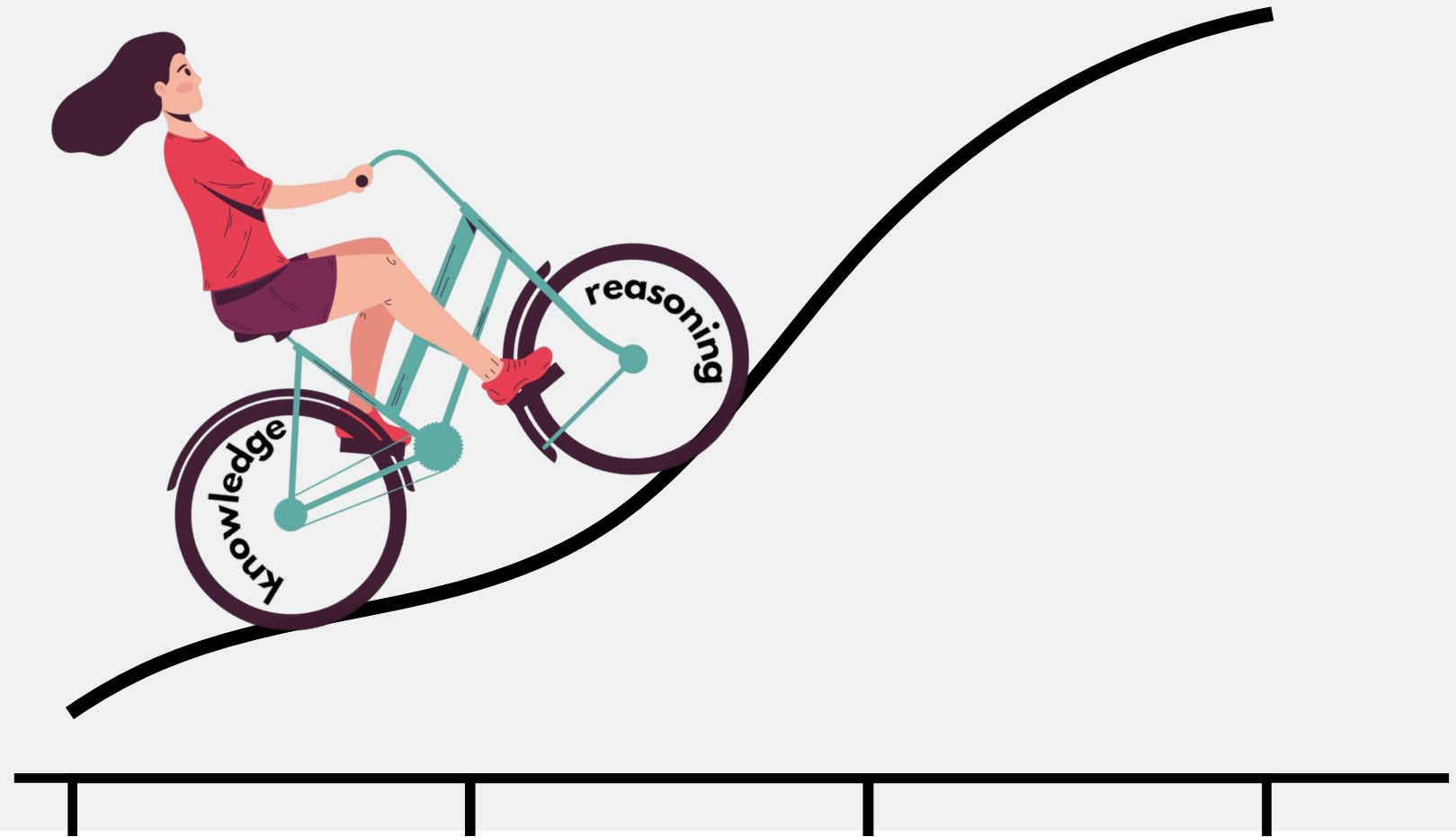
All bikes have 1 frame and 2 wheels of the same type.  
Frame A is compatible with wheel models 1 and 3.  
Frame B is compatible with wheel model 2.



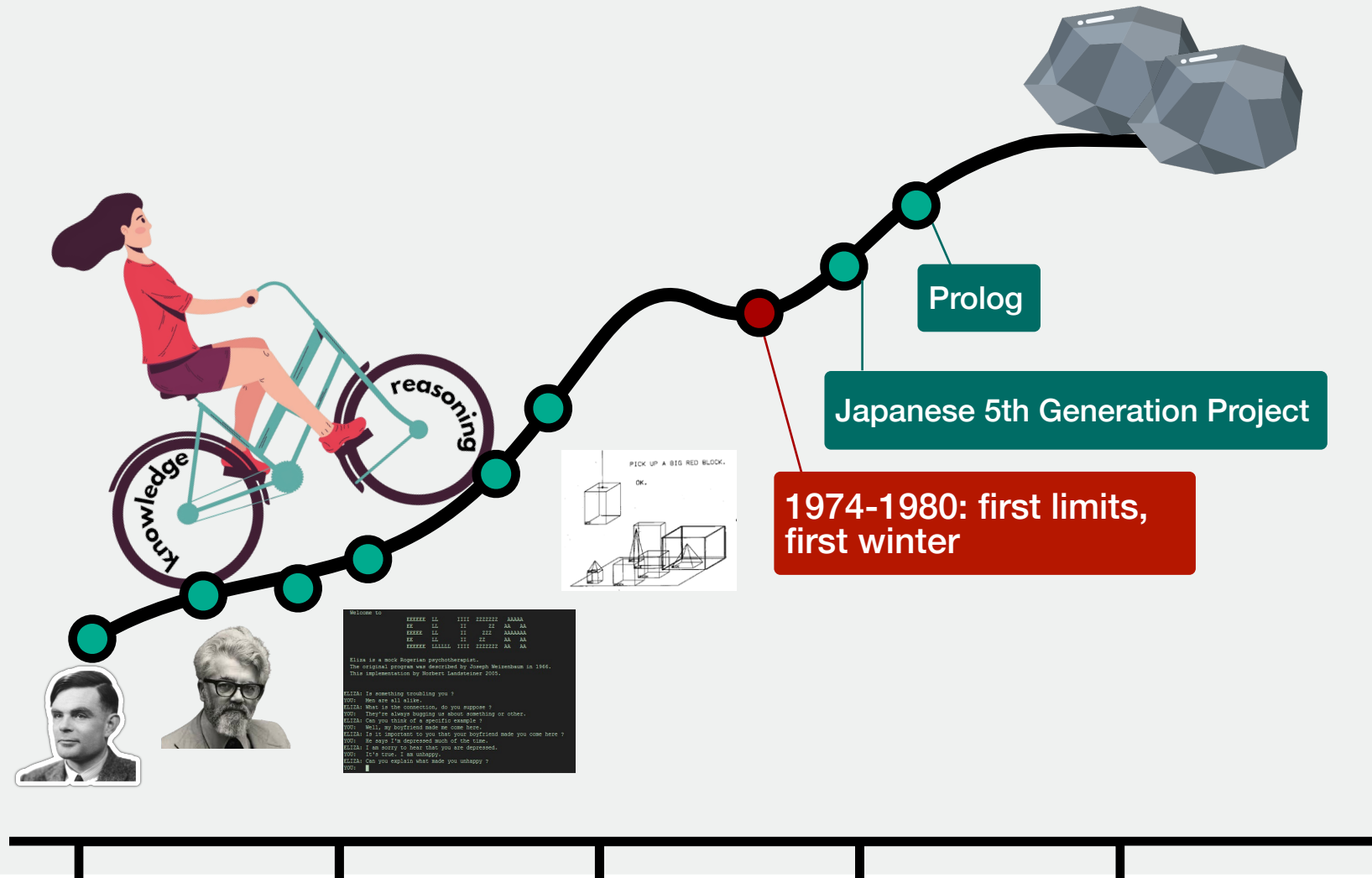
[Andreas Prabowo](#)



# Rationality approach to AI



# It had a good run! but...



# High-precision logic engineering

To each problem, the right language



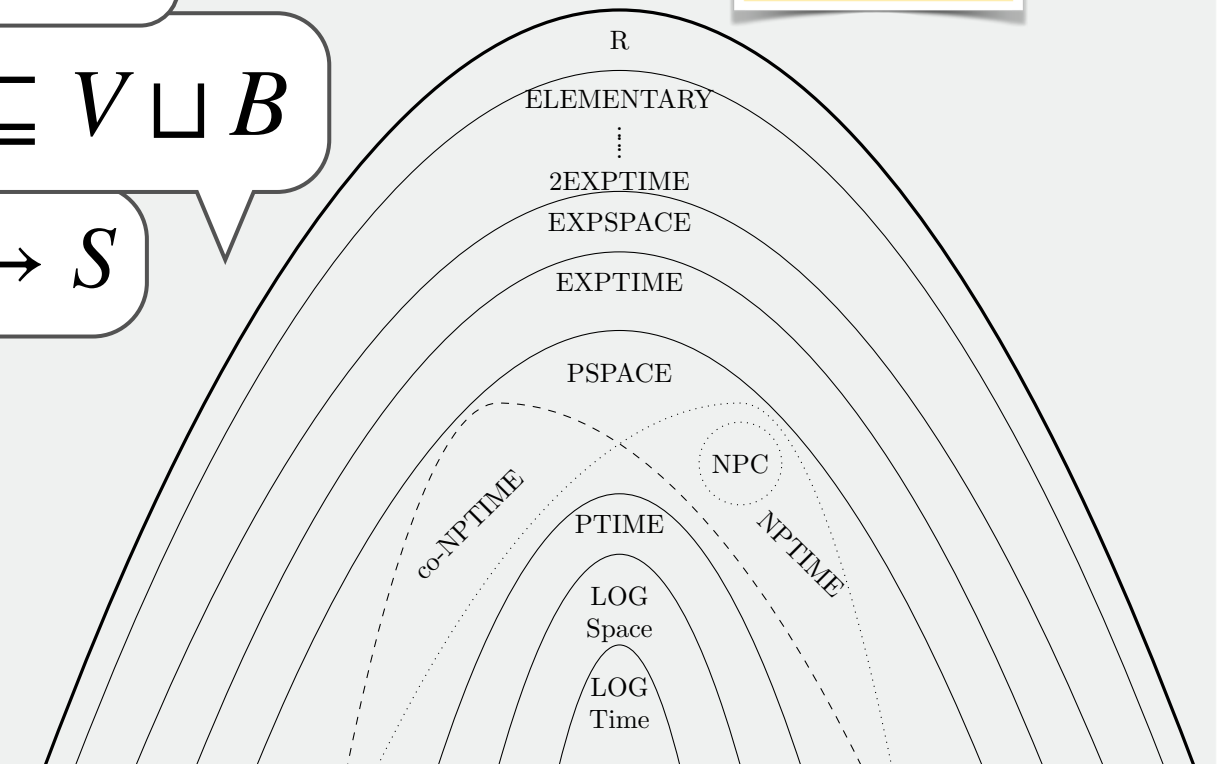
$$\forall \vec{x} P(x) \wedge \dots$$

$$C(X) \leftarrow A(X)$$

$$I \sqsubseteq V \sqcup B$$

$$P \wedge \neg Q \rightarrow S$$

$$\varphi \models \psi?$$



# A lightweight superstar for medical and life science terminologies

*Description Logics: a modular family of languages  
balancing **cost of inference vs. expressiveness***

$\mathcal{EL}$

Pneumonia	$\sqsubseteq$	Inflammation $\sqcap \exists \text{affects.Lung}$
Bronchitis	$\sqsubseteq$	Inflammation $\sqcap \exists \text{affects.Bronchi}$
Lung	$\sqsubseteq$	$\exists \text{partOf.RespirSyst}$
Bronchi	$\sqsubseteq$	$\exists \text{partOf.RespirSyst}$

**polynomial  
reasoning!**

- SNOMED CT >350,000 **clinical terms**, multilingual, >80 countries
- 1000s of **ontologies**, 1000000s of **biomedical concepts**

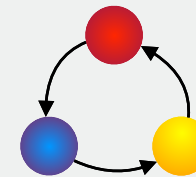
BioPortal, OBO Foundry, NCI thesauri, WHO classifications, ICH (pharmaceutical regulation)...

# The case of Guardedness

## Tailoring elegant fragments

$$\exists \vec{x} (A(\vec{x}) \wedge \varphi(\vec{x})) \quad \forall \vec{x} (A(\vec{x}) \rightarrow \varphi(\vec{x}))$$

- beautiful **model theory**
- admits **elegant** tools (e.g. tree automata)
- computationally **robust**
- excellent for **describing structured domains** and their evolution
  - modal logics, description logics, dynamic and temporal logics...



but terrible for asking database questions!

# Combining languages

```
MATCH (n:Inflammation) -[:AFFECTS]-> (b:Organ)
      (b:)-[:PART-OF]+-> (c:RespSystem)
WHERE n.type = 'Chronic'
RETURN n;
```

$$q(\vec{x}) \leftarrow \exists \vec{y} \rho_1(\vec{x}_1) \wedge \dots \wedge \rho_n(\vec{x}_n)$$

$$\rho ::= R \mid \rho \cdot \rho \mid \rho \cup \rho \mid \rho^*$$



$\varphi$

**inherently different** from  
languages for describing  
structured knowledge

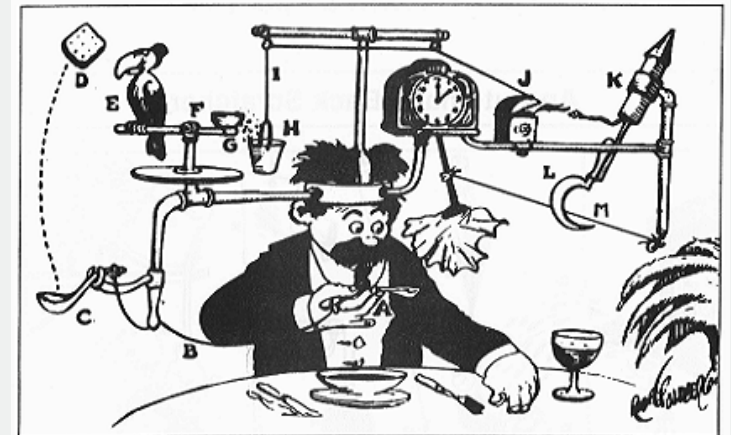
$$\varphi \models \psi$$

Pneumonia	$\sqsubseteq$	Inflammation $\sqcap$ $\exists$ affects.Lung
Bronchitis	$\sqsubseteq$	Inflammation $\sqcap$ $\exists$ affects.Bronchi
Lung	$\sqsubseteq$	$\exists$ partOf.RespirSyst
Bronchi	$\sqsubseteq$	$\exists$ partOf.RespirSyst

$$\exists \vec{x} (A(\vec{x}) \wedge \varphi(\vec{x})) \quad \forall \vec{x} (A(\vec{x}) \rightarrow \varphi(\vec{x}))$$



$\psi$



Rube Goldberg (published Collier's, Sept 1931)

# Not for the faint hearted!

$$\varphi := \exists \vec{x} (A(\vec{x}) \wedge \varphi(\vec{x}))$$

$$\forall \vec{x} (A(\vec{x}) \rightarrow \varphi(\vec{x}))$$

$$\psi := q(\vec{x}) \leftarrow \exists \vec{y} \rho_1(\vec{x}_1) \wedge \dots \wedge \rho_n(\vec{x}_n)$$

$$\rho ::= R \mid \rho \cdot \rho \mid \rho \cup \rho \mid \rho^*$$

nice  
model theory



$$\varphi \models \psi$$

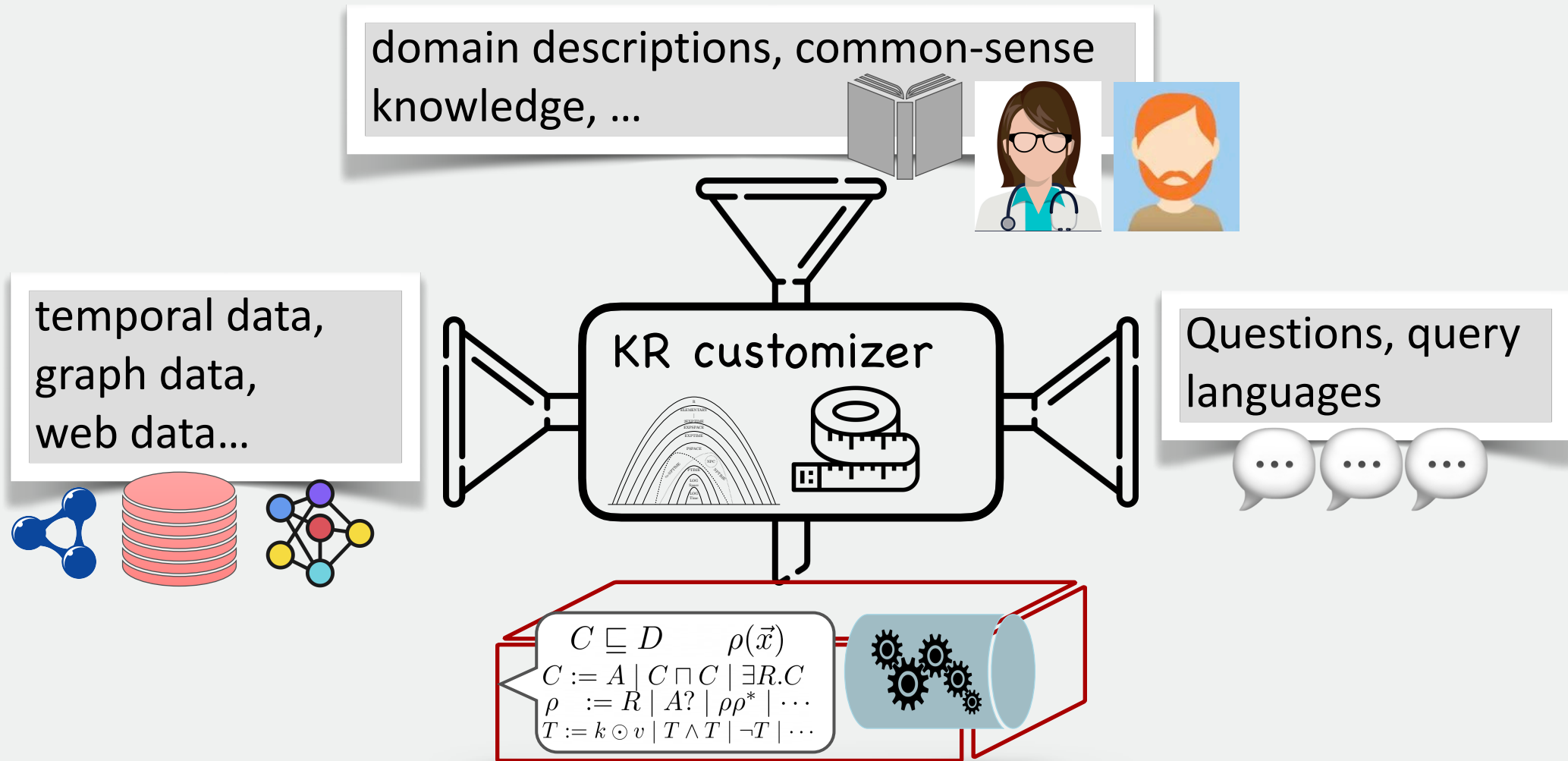
elegant proof  
techniques



tombstone by Freepik

	IQs		CQs		2RPQs		C2RPQs	
	Data complexity	Combined complexity	Data complexity	Combined complexity	Data complexity	Combined complexity	Data complexity	Combined complexity
DL-Lite DL-Lite <sub>R</sub>	in AC <sub>0</sub>	NLOGSPACE	in AC <sub>0</sub>	NP	NLOGSPACE	P	NLOGSPACE	PSPACE
EL, ELH	P	P	P	NP	P	P	P	PSPACE
ELI, ELHI <sub>L</sub> , Horn-SHOIQ	P	EXP	P	EXP	P	EXP	P	EXP
ALC, ALCHQ	coNP	EXP	coNP	EXP	coNP	EXP	coNP-hard	2EXP
ALCI, SH, SHIQ	coNP	EXP	coNP	2EXP	coNP	EXP	coNP-hard	2EXP
SHOIQ	coNP-hard	coNEXP	coNP-hard	coN2 EXP-hard <sup>a</sup>	coNP-hard	coNEXP	coNP-hard	coN2 EXP-hard <sup>b</sup>

# Rightsizing on demand



graph icon by Becris - Flaticon



# Some semantic challenges

Zeit time	Aktuell actual	Zug train	nach to	Bahnsteig platform
15:07		S7	Floridsdorf Kurzzug	2
15:22		S7 ✈	Fischamend Geiselbergstraße ~ Zentralfriedhof ~ Kaiserebersdorf ~ Schwechat ~ Mannswörth ~ Flughafen Wien	1
15:37		S7	Floridsdorf Remweg ~ Wien Mitte ~ Wien Praterstern ~ Traisengasse ~ Handelskai	2
15:52		S7 ✈	Flughafen Wien Kurzzug	1
16:07		S7	Floridsdorf Kurzzug	2
16:22		S7 ✈	Wolfsthal Kurzzug	1
16:37		S7	Floridsdorf Kurzzug	2
16:52		S7 ✈	Flughafen Wien Kurzzug	1

All trains to the airport depart from platform 1.

All ingredients are

## GOURMET WOOD FIRED PIZZAS

### Alla Puttanesca

Tomato, chilli, capers, black olives, mozzarella and oregano

### Alla Margherita

Tomato, bocconcini, parmesan, mozzarella and fresh basil

### Prosciutto Cotto e Funghi

Prosciutto ham, field mushrooms, tomato, mozzarella and oregano

$$\neq \forall x (train(x) \wedge goesTo(x, airport)) \rightarrow departPlatform(x, 1)$$

## Kundenrezensionen

★★★★★ 4,8 von 5

[Rezension schreiben](#)

6 globale Bewertungen

5 Sterne  78%

4 Sterne  22%

3 Sterne  0%

2 Sterne  0%

1 Stern  0%

All buyers are happy and recommend the product?

$$\neq \forall x buyer(x) \rightarrow recommends(x, product)$$

# An unachievable dream?

Dozens of works since the 1980s, but it is **hard!**

	$ALC$	$ALCQO$	$ALCI$	$ALCIO$
<b>Concept circ.</b> $\#M \leq n, \#F \leq n$ (unrestricted)	<b>NP<sup>NExp</sup></b>			
	<b>NExp<sup>NP</sup></b> even if $\prec = \emptyset$ , and either $TBox = \emptyset$ or $ABox = \emptyset$			
<b>Minim. roles</b> $TBox = \emptyset$	<b>NExp<sup>NP</sup></b> even if $\#M \leq 1, \#F \leq 0$		<b>Undecidable</b>	
	<b>Undecidable</b>			
<b>Fixed roles</b>	<b>Highly undecidable</b> , even if $TBox = \emptyset, \prec = \emptyset$			

*The Complexity of Circumscription in DLs (Bonatti, Lutz, & Wolter 2009)*

With hard work and advanced techniques, **feasible approaches** to non-monotonicity

	Pointwise Circumscription		
	basic	varying roles	general
DL-Lite <sup>H</sup>	$\leq P$	NP-c*	$\leq NExp^\dagger$
DL-Lite <sup>H</sup>	$\geq NP$	$\geq NP$	$\leq NExp^\dagger$
DL-Lite <sup>H</sup> <sub>bool</sub>	$\geq \Sigma_2^P$	$\geq \Sigma_2^P$	$\leq NExp^\dagger$

*Bonatti, Di Stefano, O., Šimkus (2023)*

**Theorem:** Answering safe-range queries is feasible **in co-NP** in data complexity for **ALCHOIQ with closed predicates.**

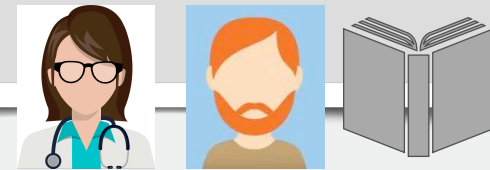
*S. Lukumbuzya, M. O and M. Šimkus (2023)*

# Tailoring advanced solutions in an ever-evolving landscape

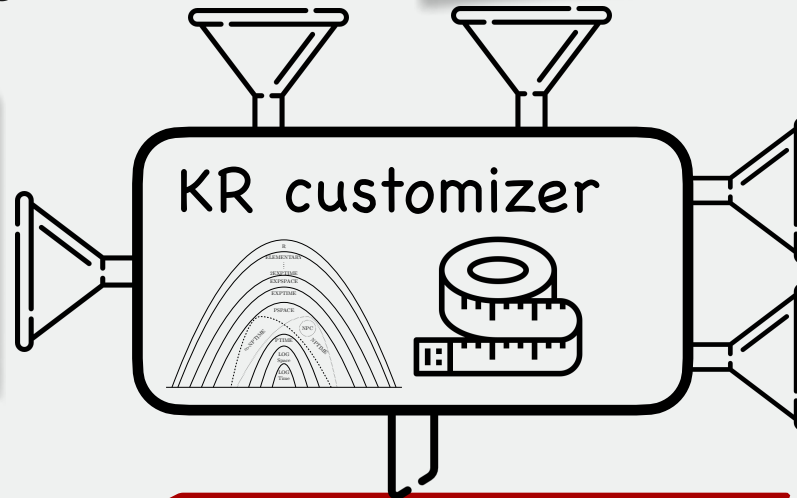
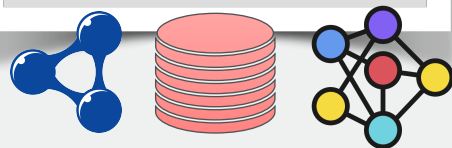
Constraints, restrictions on the data



domain descriptions, common-sense knowledge, ...



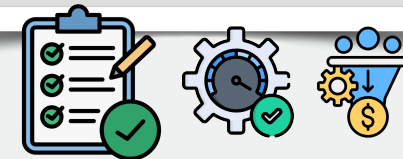
temporal data,  
graph data,  
web data...



questions, query languages



advanced requirements



$$\begin{aligned}
 &C \sqsubseteq D \quad \rho(\vec{x}) \\
 &C := A \mid C \sqcap C \mid \exists R.C \\
 &\rho := R \mid A? \mid \rho\rho^* \mid \dots \\
 &T := k \odot v \mid T \wedge T \mid \neg T \mid \dots
 \end{aligned}$$


# Advanced reasoning

The aims:

- *correct*
- *optimal*
- *practicable*

algorithms for **different types** of data, knowledge, constraints, queries, requirements....

- **explanations**

- how is a conclusion derived?
- why is a desired conclusion missing?

- **translations among languages**

- equivalent, faithful up to a vocabulary / query type...
- leveraging constraints
- absorb some components

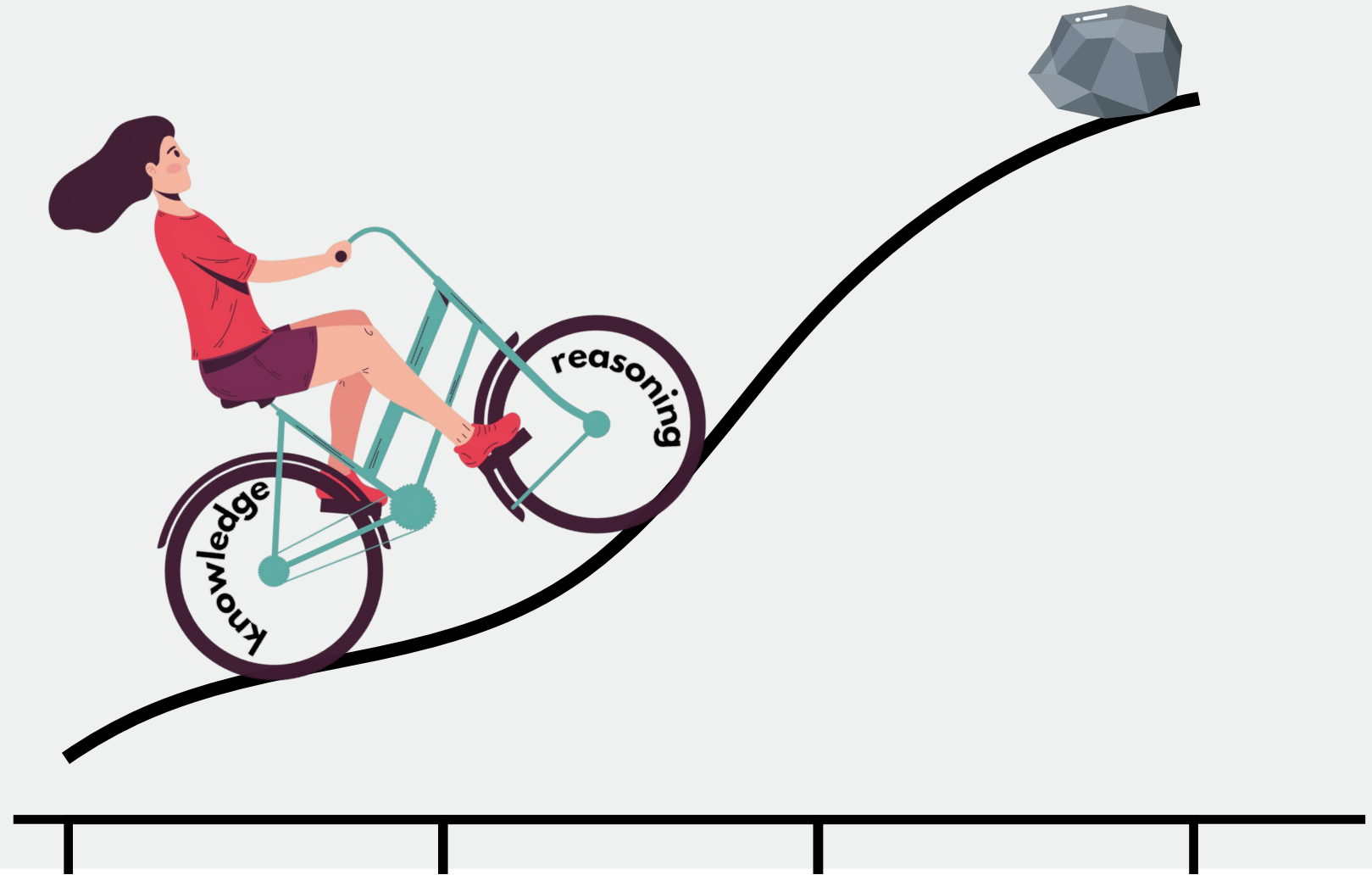
- **compilations**

- costly reasoning offline, efficient online access
- absorb some components

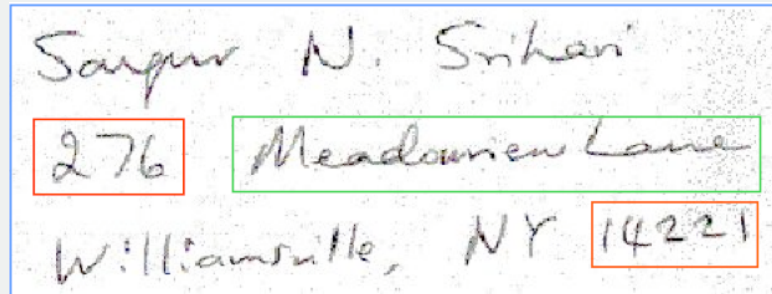
- **incremental reasoning**

- validate changes before execution
- avoid recomputation after updates

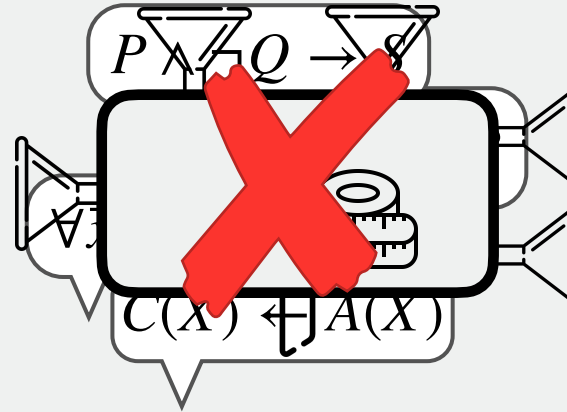
# AI = Knowledge + Reasoning?



# The learning-centric approach to AI



By lawrence87 - Sargur Srihari



Same or different person?



Same



Different



Not sure

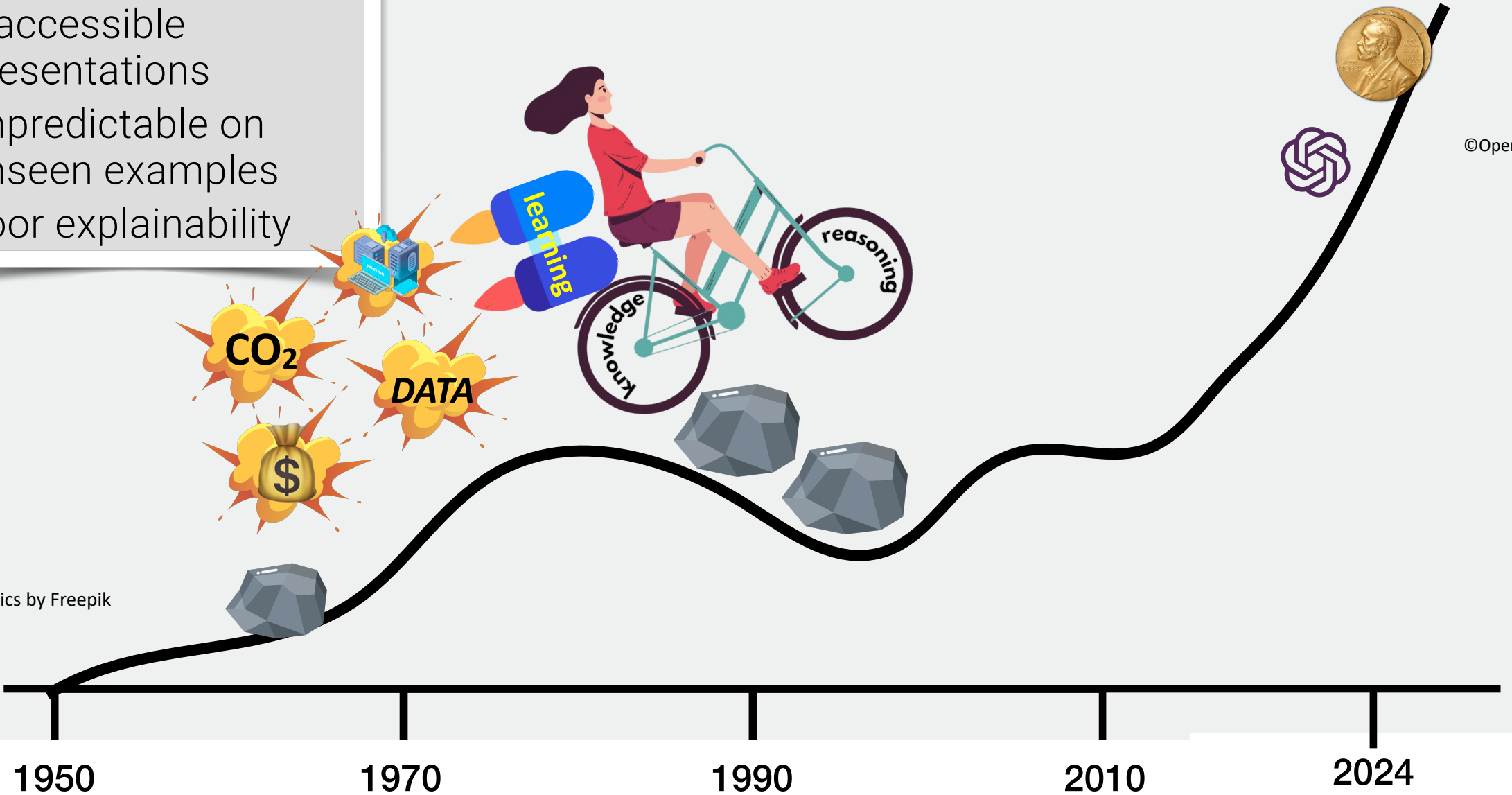
*Mimic our **learning** rather than our **reasoning***

- learn to make predictions from data and examples
- improve performance over time

# *less control!*

- inaccessible presentations
- unpredictable on unseen examples
- poor explainability

vector graphics by Freepik



©OpenAI

I hung two t-shirts to dry outside. They took one hour to dry.

I have a 4-liter jug and a 2-liter jug. How do I measure two liters of water?



If it took one hour to dry one t-shirt, how long would it take to dry two t-shirts?

(1 hour / 2 t-shirts)

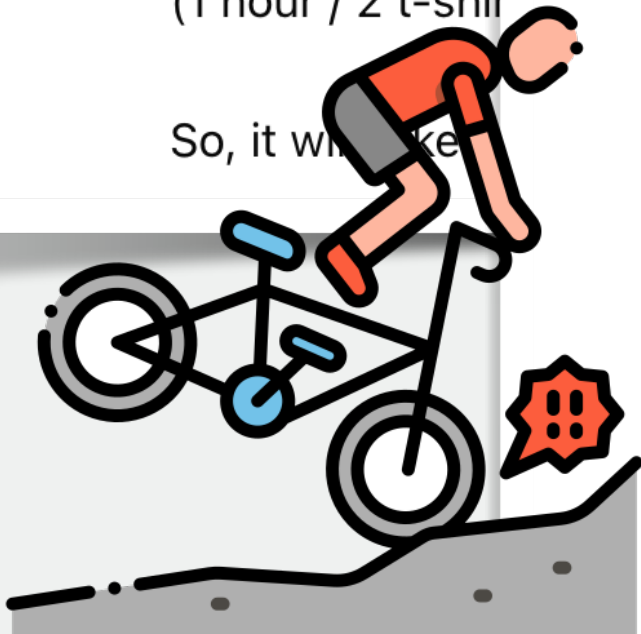
So, it will take



To measure exactly 2 liters of water using a 4-liter jug and a 2-liter jug, you can follow these steps:

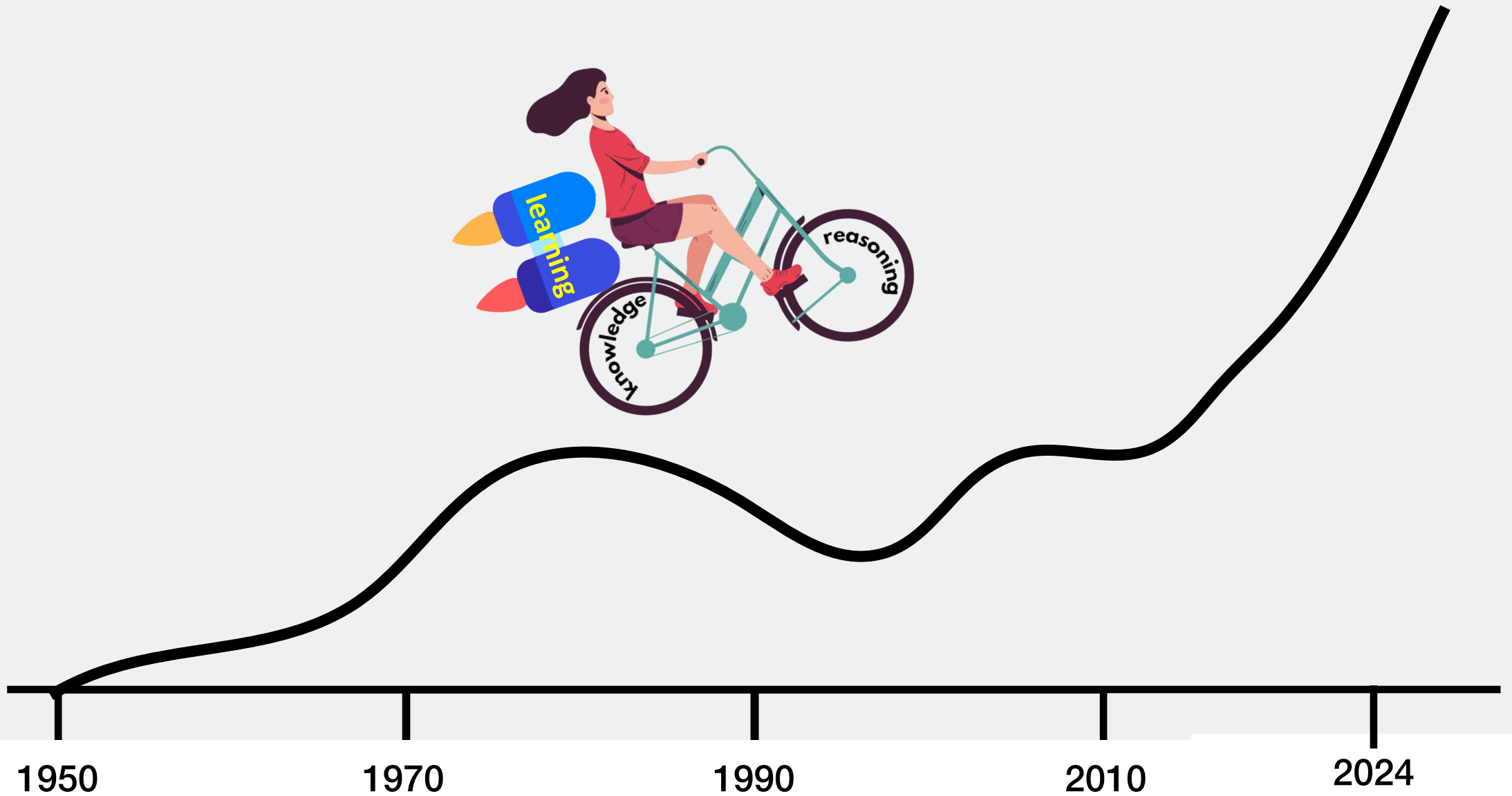
1. Fill the 4-liter jug to its maximum capacity.
2. Pour the water from the 4-liter jug into the 2-liter jug. This will leave you with 2 liters of water in the 4-liter jug.
3. Now, you have 2 liters of water in the 4-liter jug, but the 2-liter jug is empty.
4. Fill the 4-liter jug to its maximum capacity again.
5. Carefully pour the water from the 4-liter jug into the 2-liter jug. Since the 2-liter jug already has 2 liters of water, it can only hold an additional 2 liters, so you'll end up with exactly 2 liters of water in the 2-liter jug.

Now you have successfully measured 2 liters of water using a 4-liter jug and a 2-liter jug.





# Where is AI going?



# Where is AI going?



Bridging rationality- and learning-driven AI



Bilateral AI  
Cluster of Excellence

