In Pursuit of the Holy Grail of Natural Language Understanding: Past, Present, and Future

September 2019

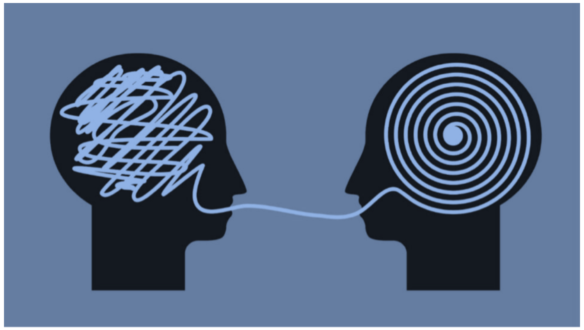
Daniel Khashabi

ALLEN INSTITUTE *for* ARTIFICIAL INTELLIGENCE

My Background

- Recently finished PhD (UPenn)
- Been working with Allen Institute for AI (AI2)
  - On-and-off since 2015, and full-time since this August

- Research theme:
  - Artificial Intelligence, through the lens of **natural language** understanding



  - Not specified:
    - What **solution** we use to achieve this goal

- Not a CP person!

ALLEN INSTITUTE
for ARTIFICIAL INTELLIGENCE

- Founded in 2014 by Paul Allen (Microsoft co-founder)
  - Non-profit research organization
  - Mission: contribute to humanity through high-impact AI research and engineering

Oren Etzioni
CEO

Project Aristo (2014-2019)

- **Vision: The Knowledgeable Machine**
  - Large volumes of general and scientific knowledge, stored in a "computable“ form, supporting reasoning and explanation

- **Measurable goal:**
  - Pass elementary-school **science exams** as written
    - Currently 4th grade and 8th grade exams

- *Credit goes to dozens of researchers who have contributed to this project.*

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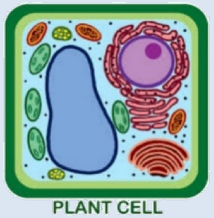
Example Question: Reasoning by Chaining

The cell structure that makes a plant cell more rigid than an animal cell is the
(A) cell membrane.
(B) cytoplasm.
(C) cell wall.
(D) ribosome.



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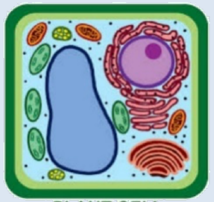

PLANT CELL

Plants use cellulose for their cell walls.

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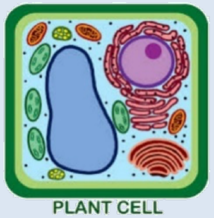

Plants use cellulose for their cell walls.

All fibers are assembled of chains of cellulose molecules, arranged as a rigid structure.

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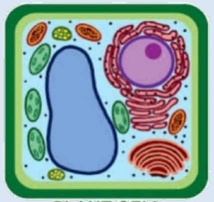

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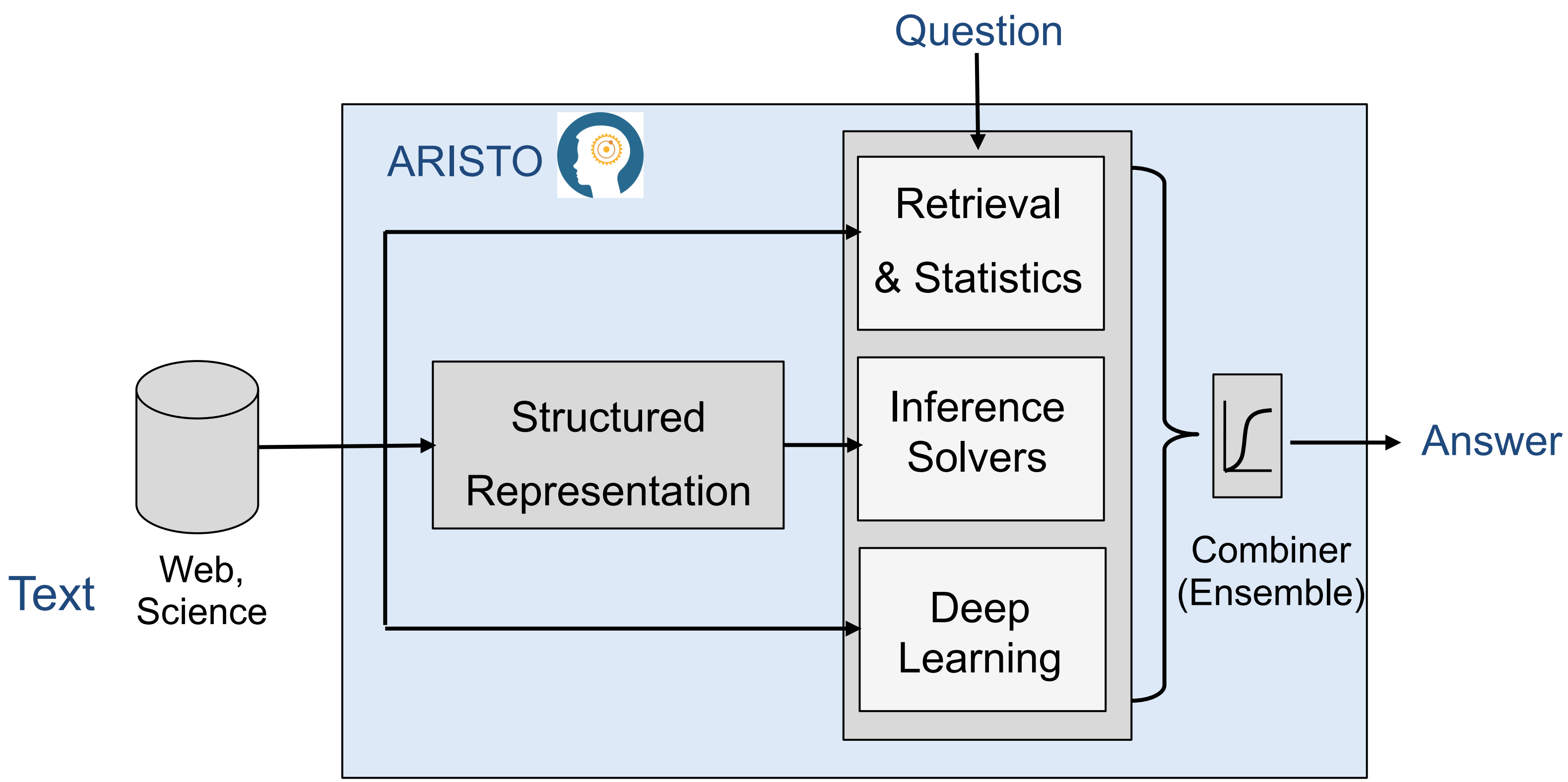
Aristo: an over-simplified overview

- An ensemble architecture
  - To deal with questions with a variety of difficulty



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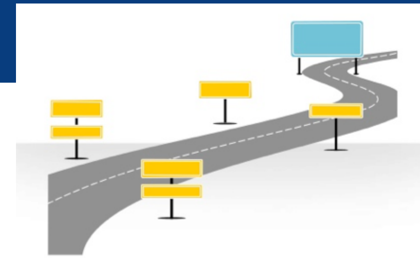
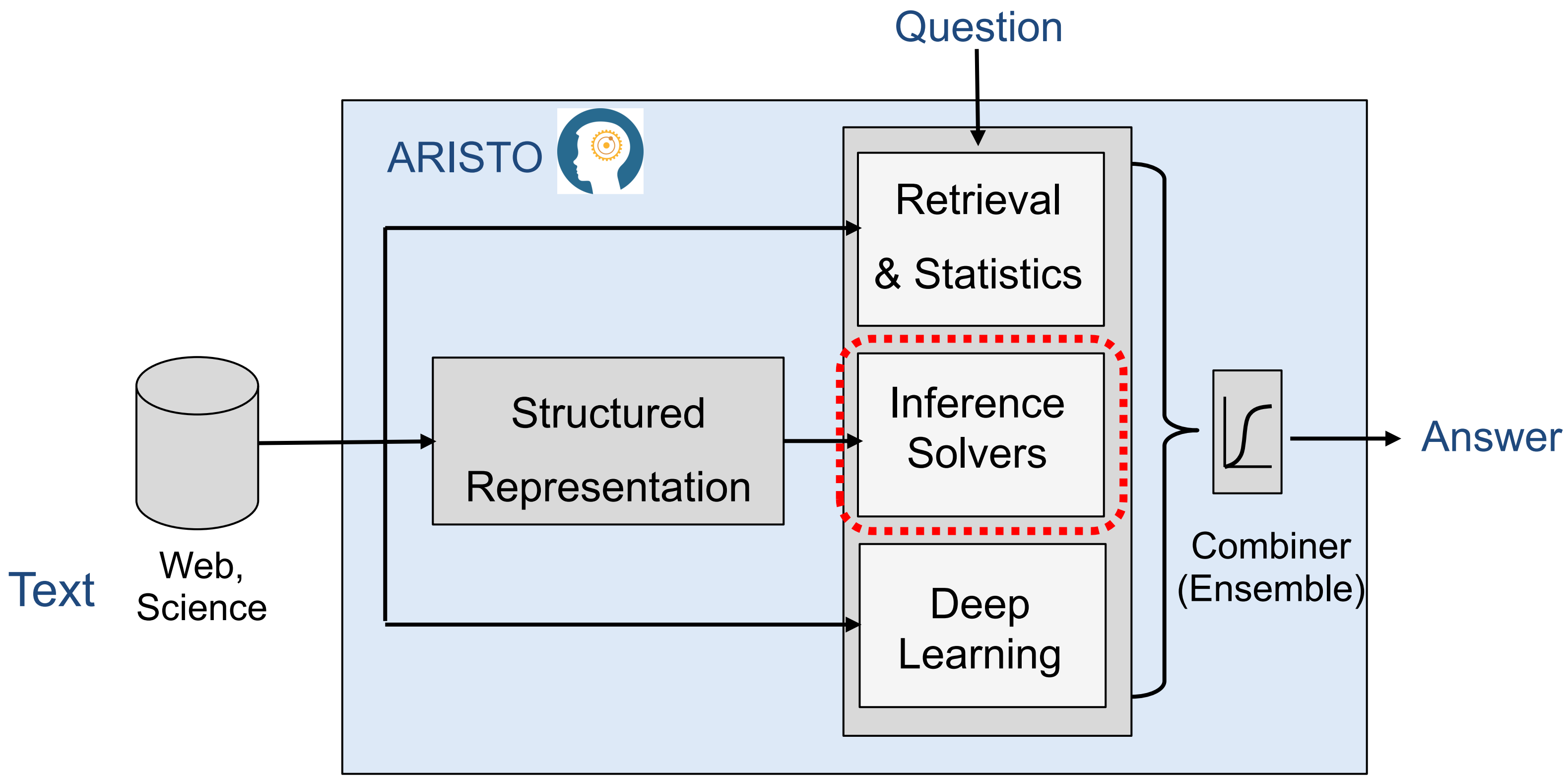
Road map



I. Aristo Inference Solvers

II. Beyond inference Modules



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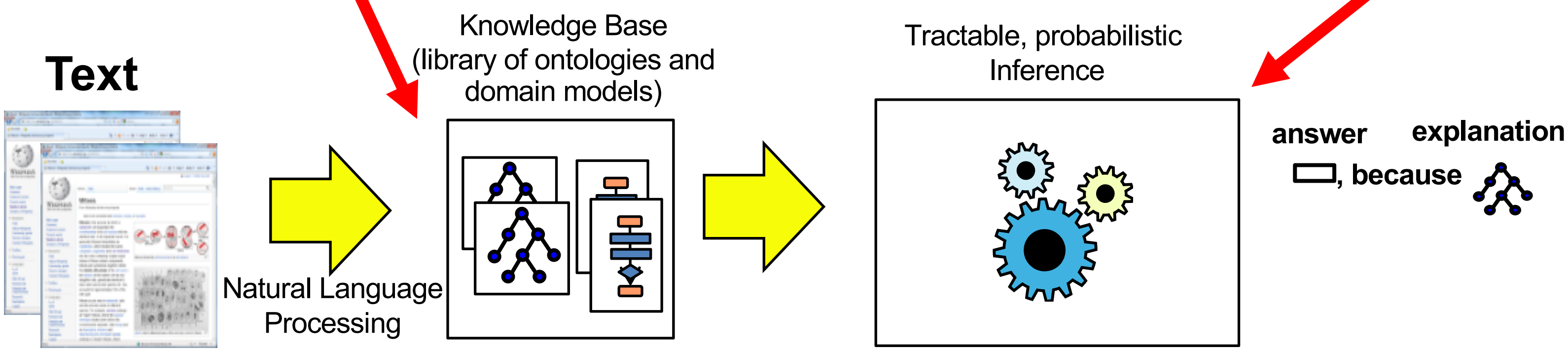
Aristo Inference Modules

Khashabi et al, AAAI-2018
Khot et al, ACL-2017
Khashabi et al, IJCAI-2016

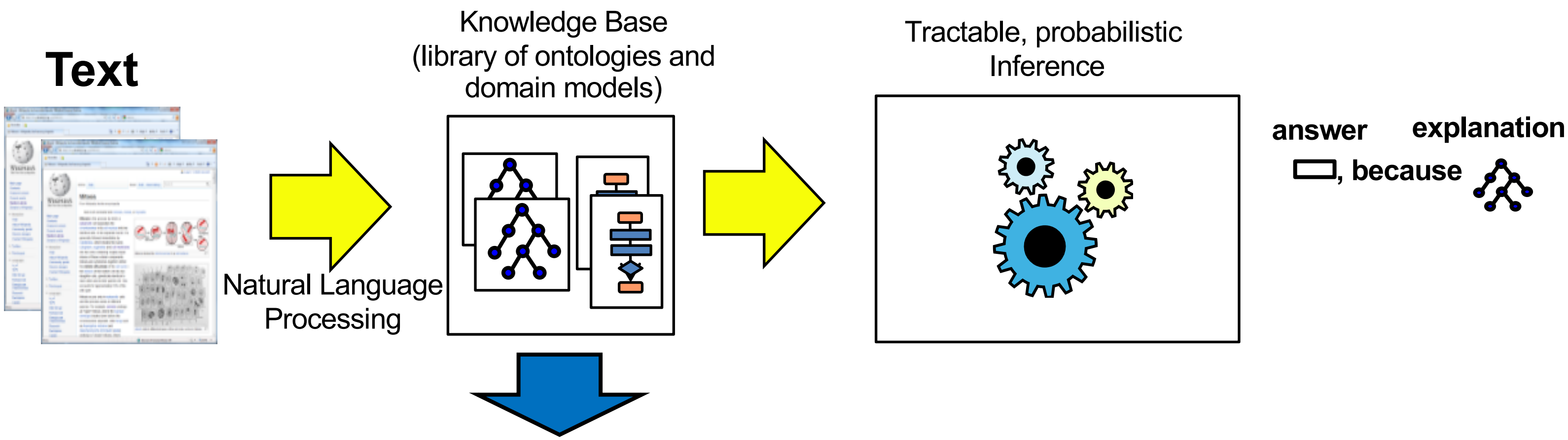
Aristo Inference Modules

- General structure of **inference frameworks**
  - Text & questions converted to an intermediate representation
  - A “probabilistic” inference for question-answering



- Three key scientific questions:
  1. How do we identify and represent the **meaning** of text?
  2. What mechanisms support **robust reasoning** with incomplete and incorrect knowledge?

Knowledge in Tabular Representation



One giant database of science knowledge

Hemisphere	*Orbital Event*	*Month*
northern	summer solstice	Jun
northern	winter solstice	Dec
northern	autumn equinox	Sep
. . .		
southern	summer solstice	Dec
southern	autumn equinox	Mar
. . .		

Energy, Forces, Adaptation, Phase Transition, Organ Function, Tools, Units, Evolution, …

Simple structure, flexible content

- Can acquire knowledge in automated and semi-automated ways
- No Cyc-like claims of "completeness" or "adequacy"

[Dalvi et al, 2016]

TableILP: Main Idea

Q: In New York State, the longest period of daylight occurs during which month?

Cities, States, Countries	**Orbital Events:** **Geographical properties & Timing**
Potential Link: **Regions and Hemispheres**	

(A) December
(B) June
(C) March
(D) September

TableILP: Main Idea

Search for the best **Support Graph** connecting the Question to an Answer through Tables.

Q: In New York State, the longest period of daylight occurs during which month?

Subdivision	Country
New York State	USA
California	USA
Rio de Janeiro	Brazil
…	…

Orbital Event	Day Duration	Night Duration
Summer Solstice	Long	Short
Winter Solstice	Short	Long
….	….	…

Country	Hemisphere
United States	Northern
Canada	Northern
Brazil	Southern
…..	…

Hemisphere	Orbital Event	Month
North	Summer Solstice	June
North	Winter Solstice	December
South	Summer Solstice	December
South	Winter Solstice	June

Semi-structured Knowledge

(A) December
(B) June
(C) March
(D) September

TableILP: Main Idea

Search for the best **Support Graph** connecting the Question to an Answer through Tables.

Link this information to identify the best supported answer!

Q: In **New York State**, the **longest** **period of daylight** occurs during which **month**?

Subdivision	Country
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Semi-structured Knowledge

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Abductive reasoning

[Peirce, 1883]

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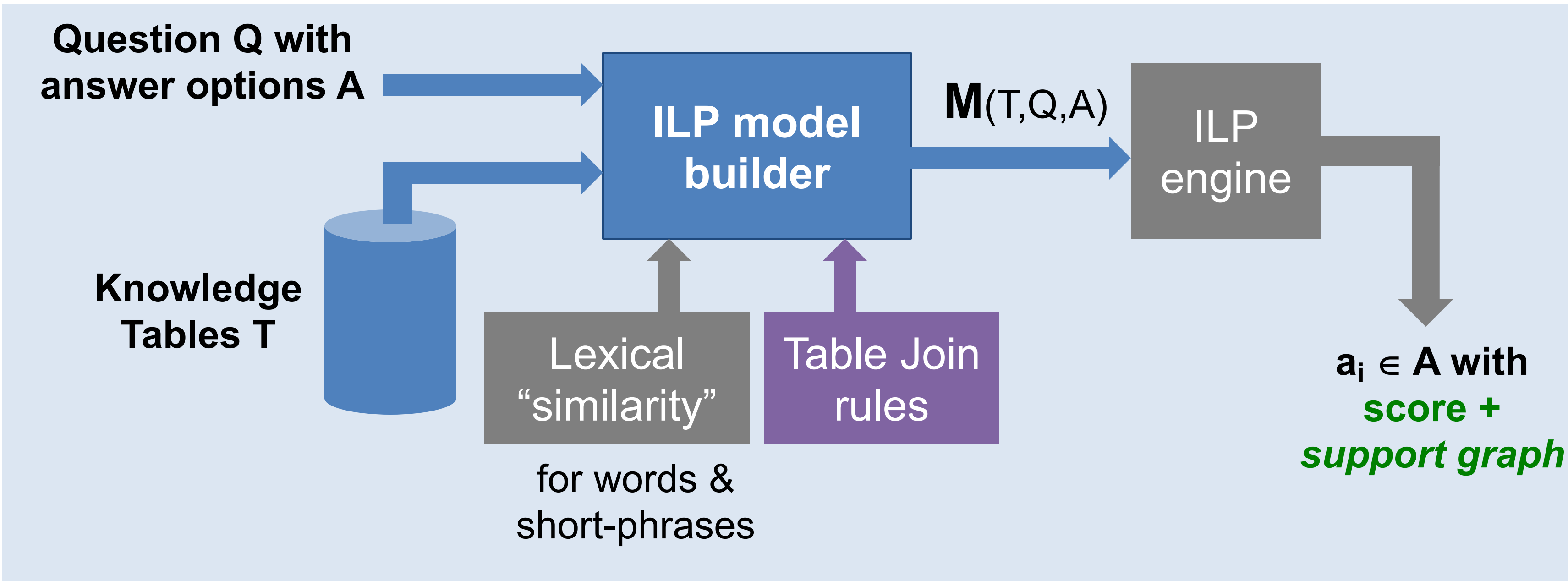
TableILP Solver: Overview

A discrete **optimization** approach to QA for multiple-choice questions



M(G,Q,A) →

$$\max \sum_i c_i x_i \qquad \begin{cases} \sum_i a_{1i} x_i \le b_1 \\ \quad \cdots \\ \sum_i a_{ki} x_i \le b_k \end{cases}$$

$$\forall\, x_i \in \mathbb{N} \cup \{0\}$$

Optimization using Integer Linear Program (ILP) formalism

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ILP Model: Design Challenges

Goal: *Design ILP objective function, s.t. maximizing it subject to the constraints yields a "desirable" support graph*

Not our focus ✗

Natural Language (Question, …) → **Conceptual def of: Constraints, Objective** → **ILP CP SAT …** → **Solution**

What we study ✓

Not our focus ✗

ILP Model: Design Challenges

Goal: *Design ILP objective function, s.t. maximizing it subject to the constraints yields a "desirable" support graph*

Not so straightforward!

$$\max \sum_i c_i x_i \qquad \begin{cases} \sum_i a_{1i} x_i \le b_1 \\ \quad \dots \\ \sum_i a_{ki} x_i \le b_k \end{cases}$$

$$\forall\, x_i \in \mathbb{N} \cup \{0\}$$

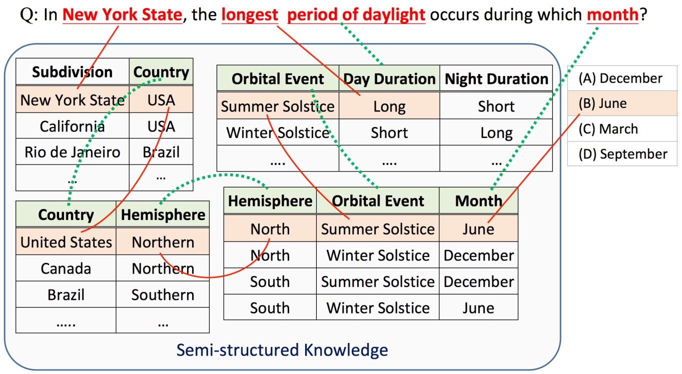
- Many possible "proof structures"
- Imperfect lexical "similarity" blackbox
- Partial or missing knowledge
- Question logic (negation, conjunction, comparison)
- Scalability of ILP solvers
- …

ILP Model: Some Details

$$\max \sum_i c_i x_i$$

$$\forall\, x_i \in \mathbb{N} \cup \{0\}$$

$$\begin{cases} \sum_i a_{1i} x_i \le b_1 \\ \quad \ldots \\ \sum_i a_{ki} x_i \le b_k \end{cases}$$



ILP Model: Some Details

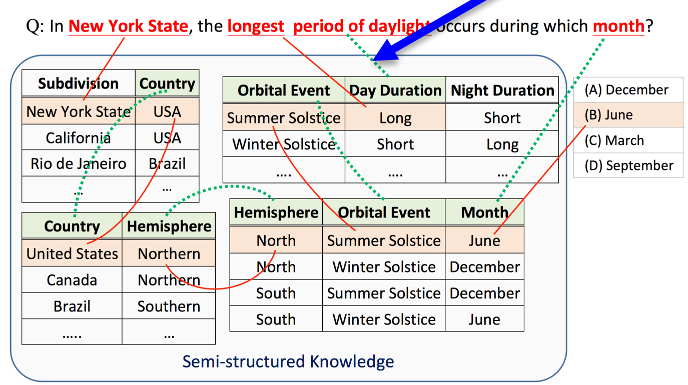
Variables define the space of “support graphs”:

- Each variable corresponds to to a node or edge.
- *x=1* iff nodes / edges are part of the semantic graph.

$$\max \sum_i c_i x_i \qquad \begin{cases} \sum_i a_{1i} x_i \leq b_1 \\ \quad \dots \\ \sum_i a_{ki} x_i \leq b_k \end{cases}$$

$$\boxed{\forall\, x_i \in \mathbb{N} \cup \{0\}}$$

Support Graph



ILP Model: Some Details

Objective Function:

"better" support graphs = higher objective value

- Reward good behavior:
  - High lexical match links, nearby alignments, column header match, WH-terms (*"which of energy …"*), etc.
- Penalize spurious overuse of frequently occurring terms

$$\boxed{\max \sum_i c_i x_i} \qquad \begin{cases} \sum_i a_{1i} x_i \le b_1 \\ \quad \ldots \\ \sum_i a_{ki} x_i \le b_k \end{cases}$$

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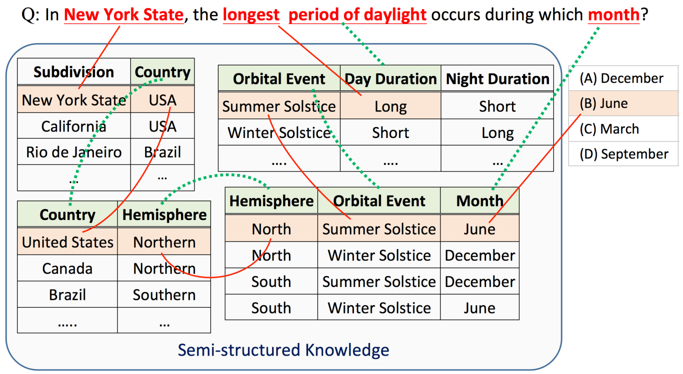

ILP Model: Some Details

Constraints:

- ~50 high-level constraints
- Scalability + consider only meaningful support graphs

- **Structural Constraints:**
  Many possible Proof Structures:
  - Basic Lookup, Parallel Evidence, Evidence Chaining, Semantic Relation Matching

- **Semantic Constraints:**
  Meaningful proof structures
  - Connectedness, question coverage, appropriate table use, etc.

$$\max \sum_i c_i x_i \qquad \forall\, x_i \in \mathbb{N} \cup \{0\}$$

$$\begin{cases} \sum_i a_{1i} x_i \leq b_1 \\ \quad \dots \\ \sum_i a_{ki} x_i \leq b_k \end{cases}$$

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Semi-structured Knowledge

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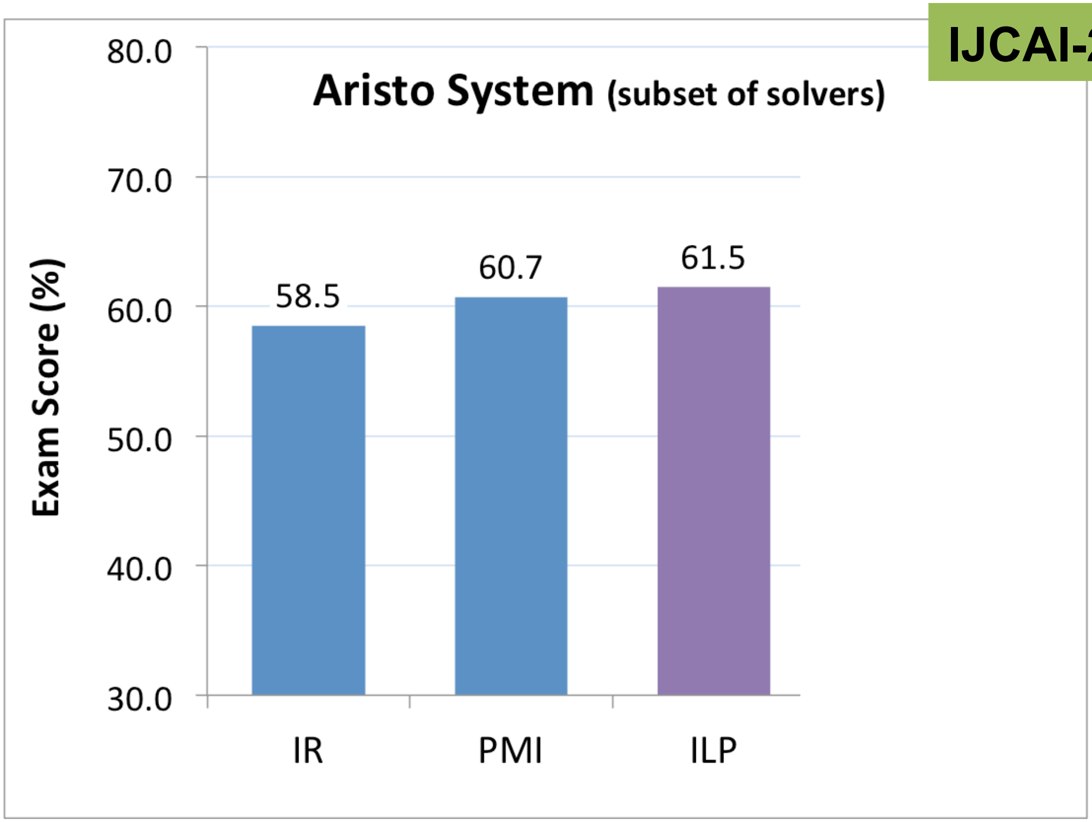
Some Empirical Results



IJCAI-2016

More details in:
K et al, IJCAI-2016.

Ensemble performs 8-10% higher than IR baselines

Beyond Tables

- Issues with tabular representation:
  - Hard to extract; the schemas could be limiting
- Alternative representation:
  - Rich representation
  - Easy to automatically extract
- Idea: **Reason over (multiple) semantic abstractions of text**
  - Use off-the-shelf, pre-trained NLP modules for automatic extraction of representations
- Same ILP-based reasoning formalism as before

Mapping Text to Semantic Representations

- NLP field has developed tools to extract and represent many interesting phenomena in language:

  - **Example 1:** Co-reference

≈

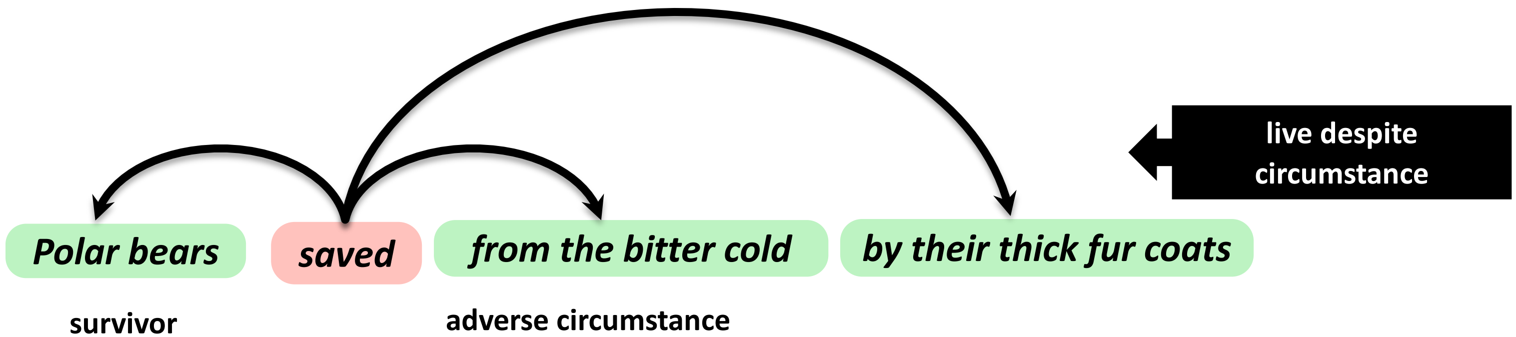
Polar bears ***their***

... Polar bears, saved from the bitter cold by their thick fur coats, are among the animals in danger of extinction …

Mapping Text to Semantic Representations

- NLP field has developed tools to extract and represent many interesting phenomena in language:

  - **Example 3:** events described by verbs



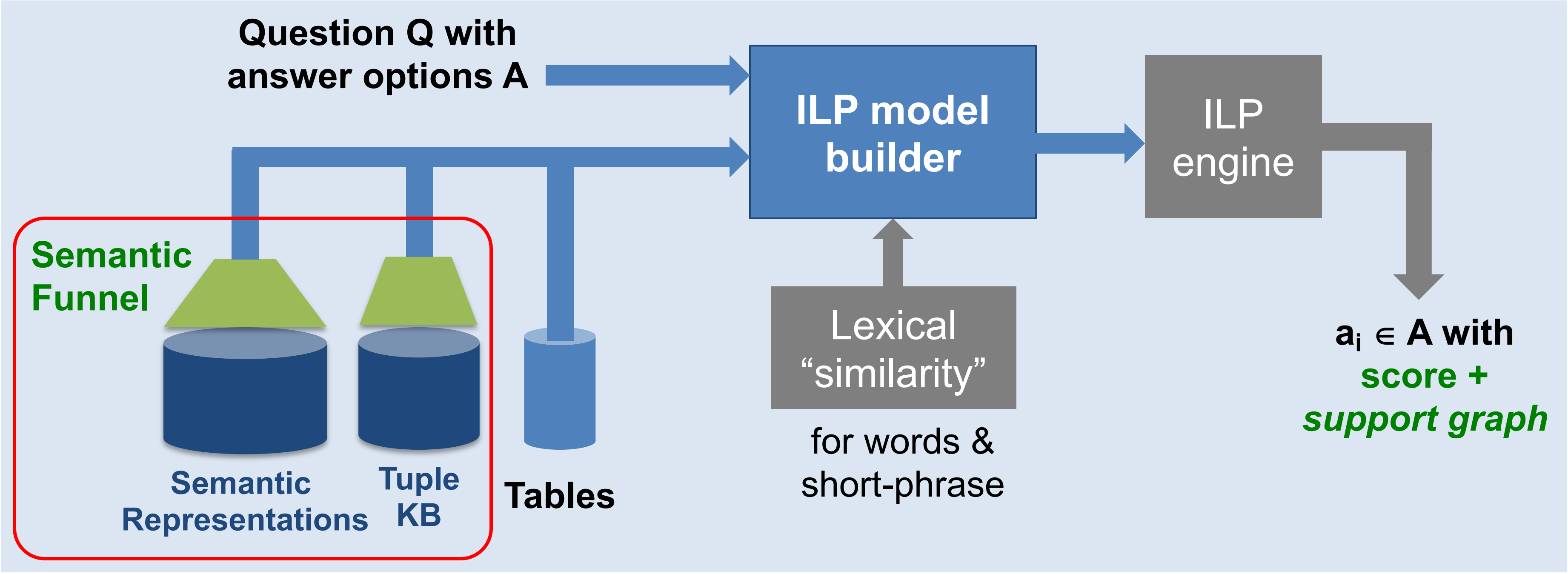
... Polar bears, saved from the bitter cold by their thick fur coats, are among the animals in danger of extinction …

Verb Semantic Roles [Punyakanok et al. 2008]

Inference Solvers, Beyond Tables

- Extend model to consume various semantic representations.
  - *Trickier than it appears:* Can no longer rely on tables as a coherent collection of domain-relevant pieces of knowledge
  - Must revisit tuple selection, chaining, …

Khashabi et al, AAAI-2018
Khot et al, ACL-2017



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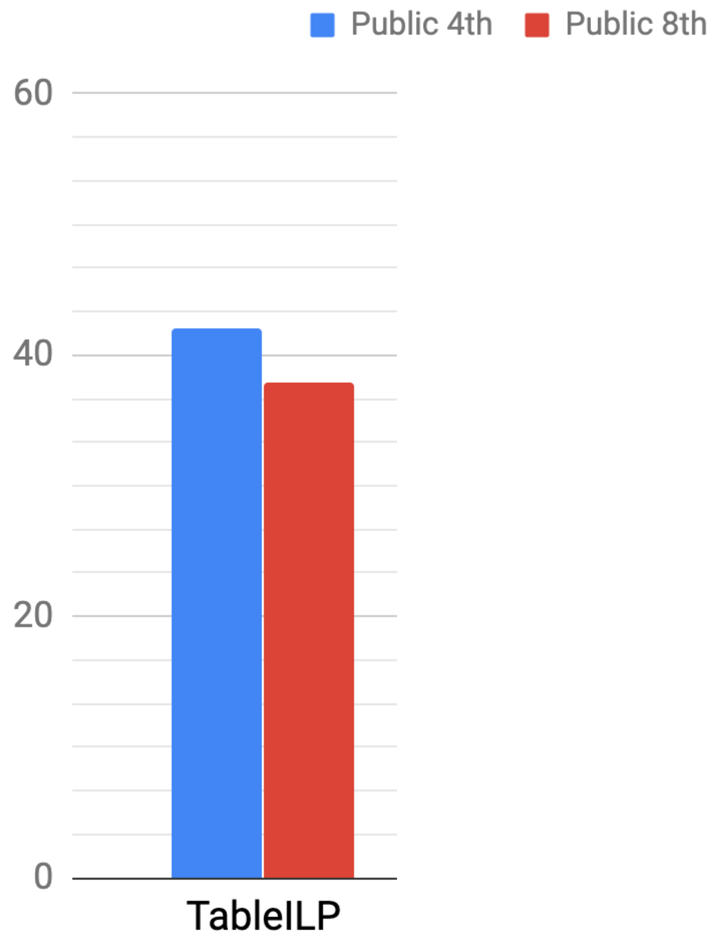
Some Empirical Results



AAAI-2018

ACL-2017

Top scoring systems
in their own time.

More details in
the related papers

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interim Summary

- The importance of the ability to chain information
- Structured, Multi-Step Reasoning:
  - Use science knowledge in small, reusable, swappable pieces
- State-of-the-art results on science benchmarks
- Benefits of the approach:
  - ✓ **Principled** approach
  - ✓ **Explainable** answers

Machine Reasoning [in Aristo]: Today and Future

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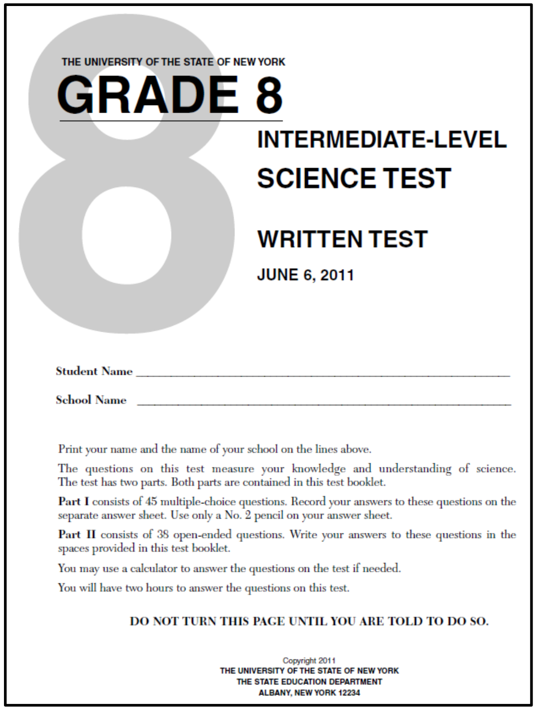
Progression on NY Regents 8th Grade (NDMC)


THE UNIVERSITY OF THE STATE OF NEW YORK

GRADE 8

INTERMEDIATE-LEVEL SCIENCE TEST

WRITTEN TEST

JUNE 6, 2011

Student Name ____________

School Name ____________

Print your name and the name of your school on the lines above.

The questions on this test measure your knowledge and understanding of science. The test has two parts. Both parts are contained in this test booklet.

Part I consists of 45 multiple-choice questions. Record your answers to these questions on the separate answer sheet. Use only a No. 2 pencil on your answer sheet.

Part II consists of 38 open-ended questions. Write your answers to these questions in the spaces provided in this test booklet.

You may use a calculator to answer the questions on the test if needed.

You will have two hours to answer the questions on this test.

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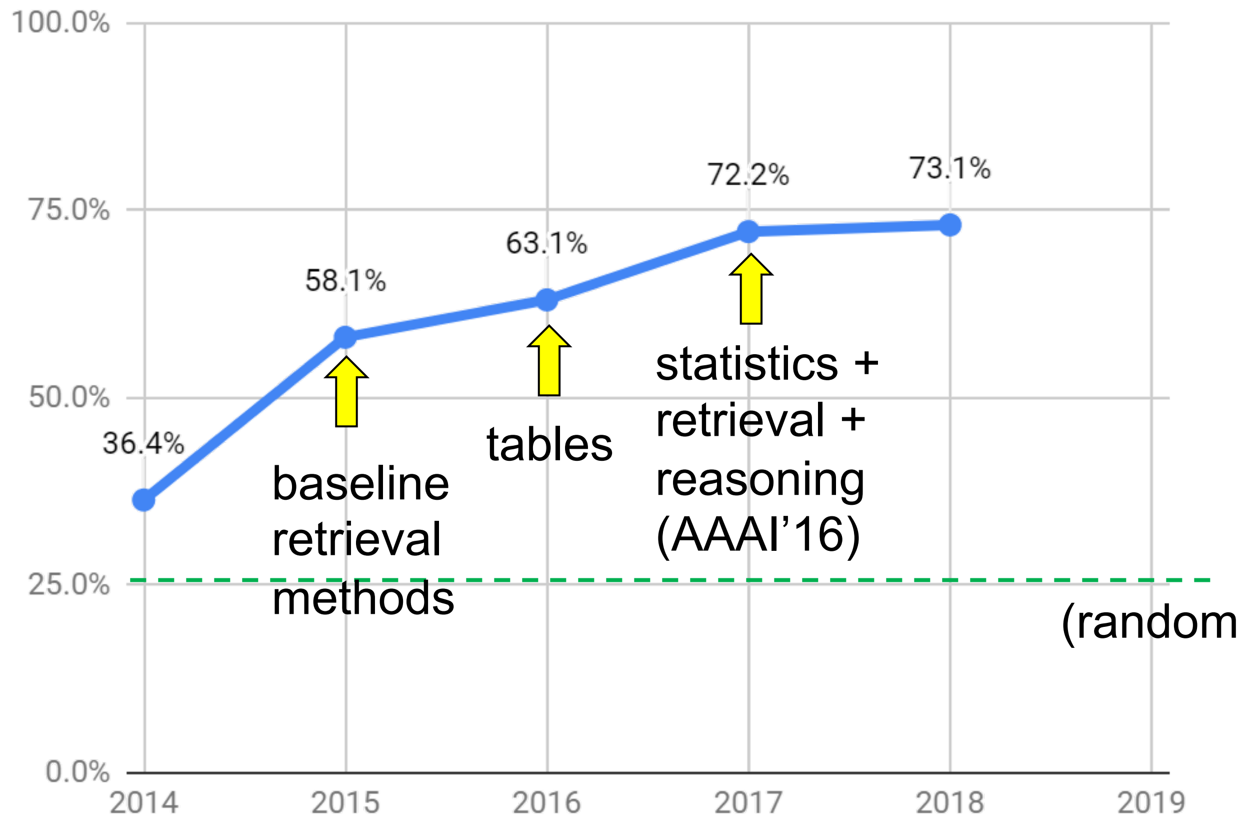

(hidden test set, questions as written, NDMC, 5 years/119 qns)

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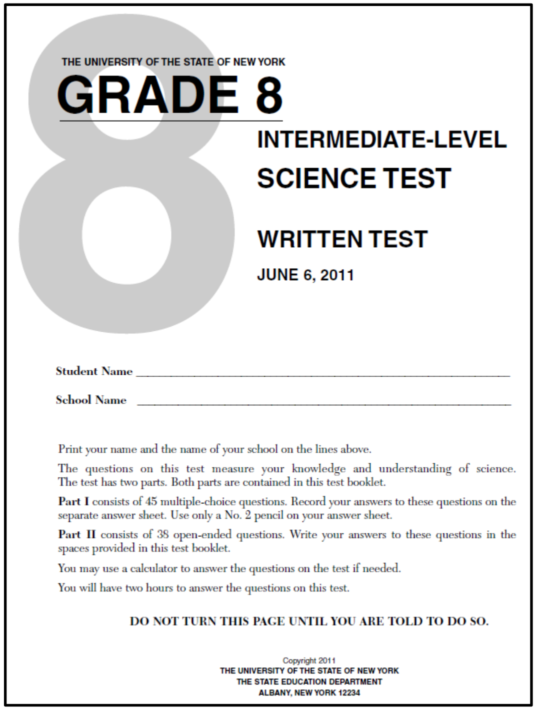
Progression on NY Regents 8th Grade (NDMC)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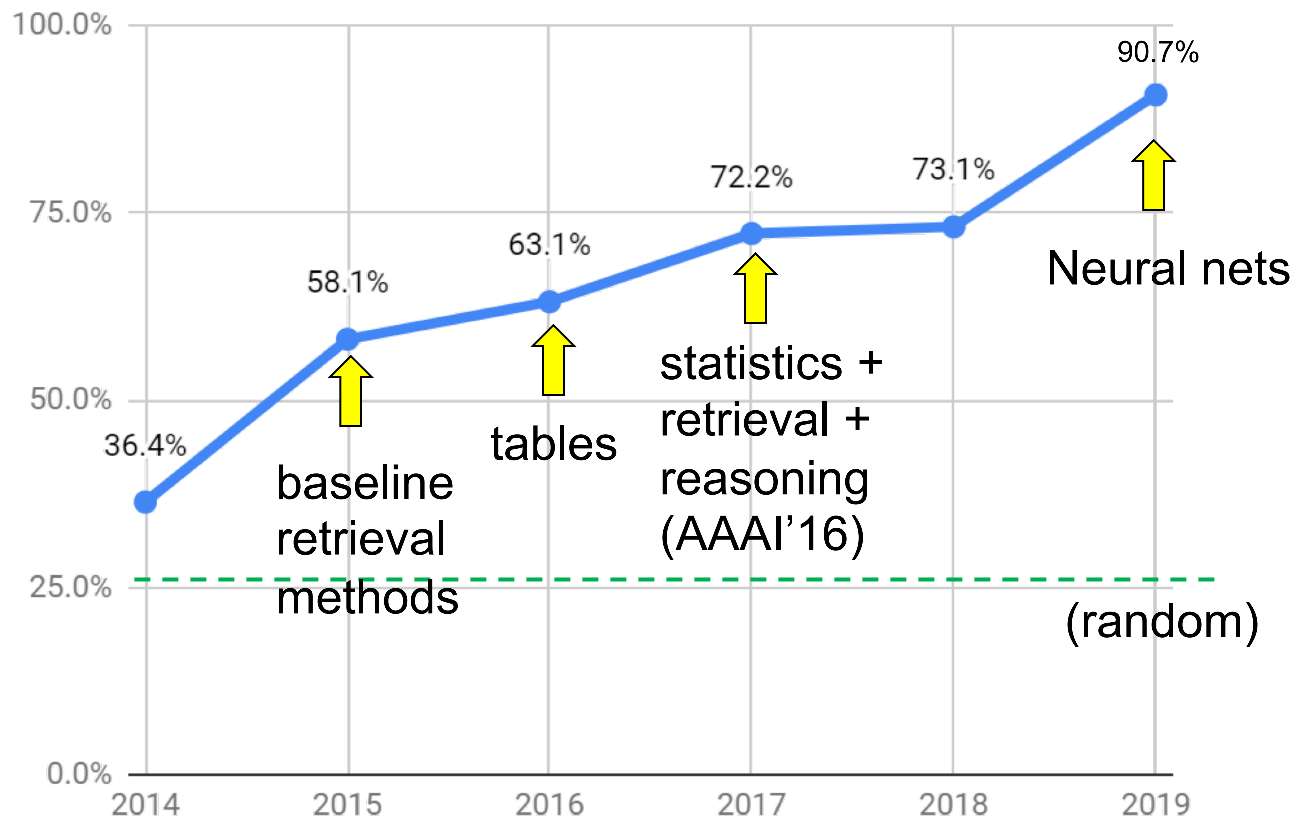

Aristo aces 8th grade (non-diagram multiple choice) >90%

(hidden test set, questions as written, NDMC, 5 years/119 qns)

Aristo’s Success

The New York Times

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A Breakthrough for A.I. Technology: Passing an 8th-Grade Science Test

By Cade Metz

Sept. 4, 2019

SAN FRANCISCO — Four
scientists competed in a c
could pass an eighth-grad
money on the line.

They all flunked. Even the
better than 60 percent on t
and logic skills that studen
high school.

But on Wednesday, the All
prominent lab in Seattle, u
test with room to spare. It correctly answered more than 90 percent of the questions on an eighth-grade science test and more than 80 percent on a 12th-grade exam.

Details in: Clark et al, arXiv-2019

From ‘F’ to ‘A’ on the N.Y. Regents Science Exams: An Overview of the Aristo Project*

Peter Clark, Oren Etzioni, Daniel Khashabi, Tushar Khot, Bhavana Dalvi Mishra, Kyle Richardson, Ashish Sabharwal, Carissa Schoenick, Oyvind Tafjord, Niket Tandon, Sumithra Bhakthavatsalam, Dirk Groeneveld, Michal Guerquin, Michael Schmitz

Allen Institute for Artificial Intelligence, Seattle, WA, U.S.A.

Abstract

AI has achieved remarkable mastery over games such as Chess, Go, and Poker, and even *Jeopardy!*, but the rich variety of standardized exams has remained a landmark challenge. Even in 2016, the best AI system achieved merely 59.3% on an 8th Grade science exam challenge (Schoenick et al., 2016).

What constraints are there on the interaction? What guidelines are provided to the judges? Second, recent Turing Test competitions have shown that, in certain formulations, the test itself is gameable; that is, people can be fooled by systems that simply retrieve sentences and make no claim of being intelligent (Aron, 2011; BBC, 2014). John Markoff of The New York Times wrote that the Turing Test is more

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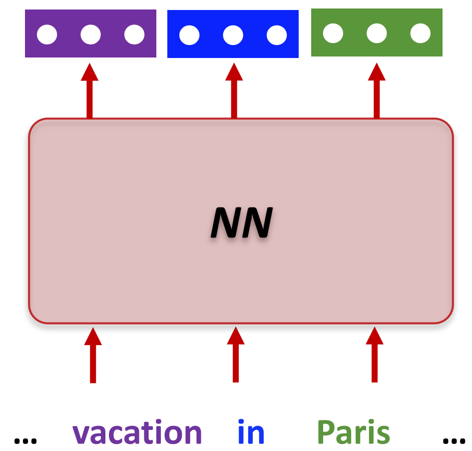
Neural Network solvers for natural language

- Big gains are achieved in the past 1-2 years

- Not just in Aristo: they have been pretty effective in a wide range of NLP problems



Many works:
[Peters et al. 18, Devlin et al.18; Radford et al.18, …]

Neural Network solvers for natural language

- My view:
  - An engineering revolution
  - Concepts and ideas were out there (for decades)

- Enabled by:

✓ **Big compute:**

Having access to many GPUs/TPUs is a must now

✓ **Massive pre-training:**

Billions are documents are used to tune them

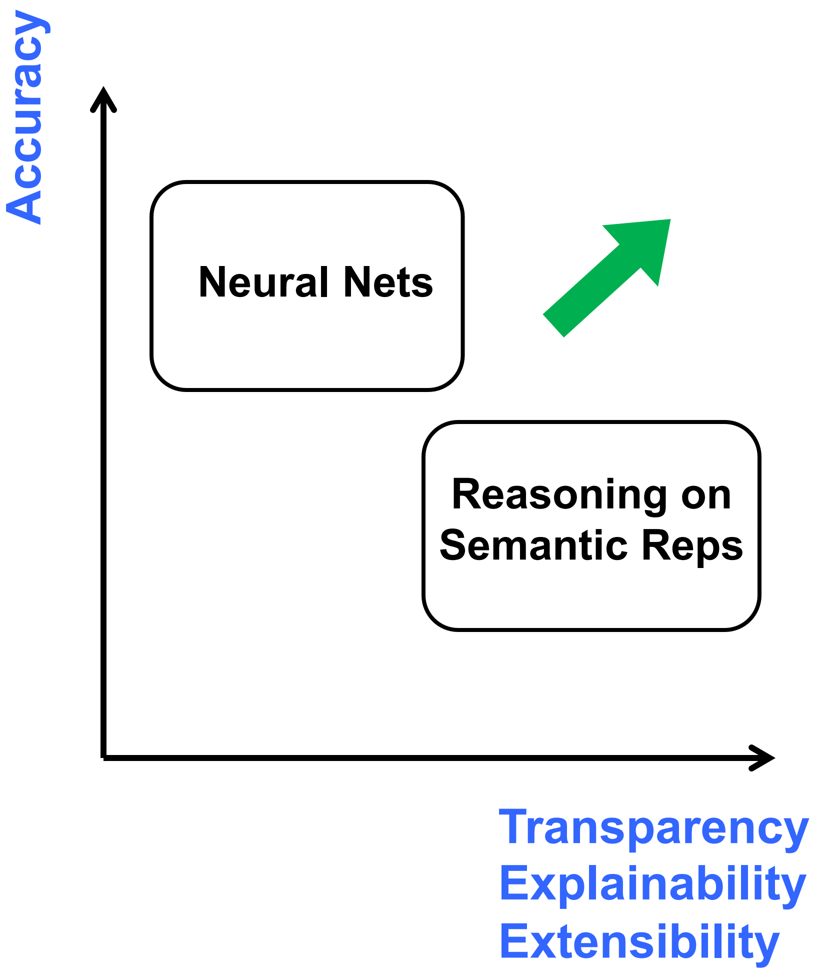
✓ **Big supervision:**

Availability of more annotated data

Neural Net resurgence

What's next? What is missing?

- Neural Nets have nearly "solved" the science challenges!
  - Do we understand why?
- In many cases, we are **not** able to explain their decisions.
  - As a result, we can't assess the extent of their reliability.
- Additionally, extending them is not trivial (largely an open problem)



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Aristo: Probing the predictions

City administrators can encourage energy conservation by
(1) lowering parking fees
(2) building larger parking lots
(3) decreasing the cost of gasoline
(4) lowering the cost of bus and subway fares

✓

City administrators can encourage energy conservation by
(1) lowering parking fees
(2) building larger parking lots
increasing (3) ~~decreasing~~ the cost of gasoline
increasing (4) ~~lowering~~ the cost of bus and subway fares

✓

So maybe it does actually work? 🤔

Aristo: Probing the predictions

City administrators can encourage energy conservation by
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✓

City administrators can encourage energy conservation by
(1) lowering parking fees
(2) building larger parking lots
(3) decreasing the cost of gasoline
(4) ~~lowering~~ the ~~cost~~ of bus and subway ~~fares~~
increasing availability

✗

Hmm 🤔 … but how should we fix this??

Summary

- The Aristo experiment:
  - Working hypothesis: Real-world language and reasoning capabilities can be assessed via “well-designed” QA tasks.

- First systems for science QA effective at multi-hop inference
  - Can operate with semi-formal knowledge bases
  - Can fruitfully exploit noisier & less structured representations
  - Complementary to other methods

- **Deep learning** is playing an important role, but **is not everything** (yet)

- **Interacting <u>intelligently</u> with humans remains challenging!**
  - Requires rich linguistic understanding, common sense, domain knowledge, situational awareness, conversational memory …

Questions?

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Hiring talented interns, young investigators, researchers, engineers, and more!

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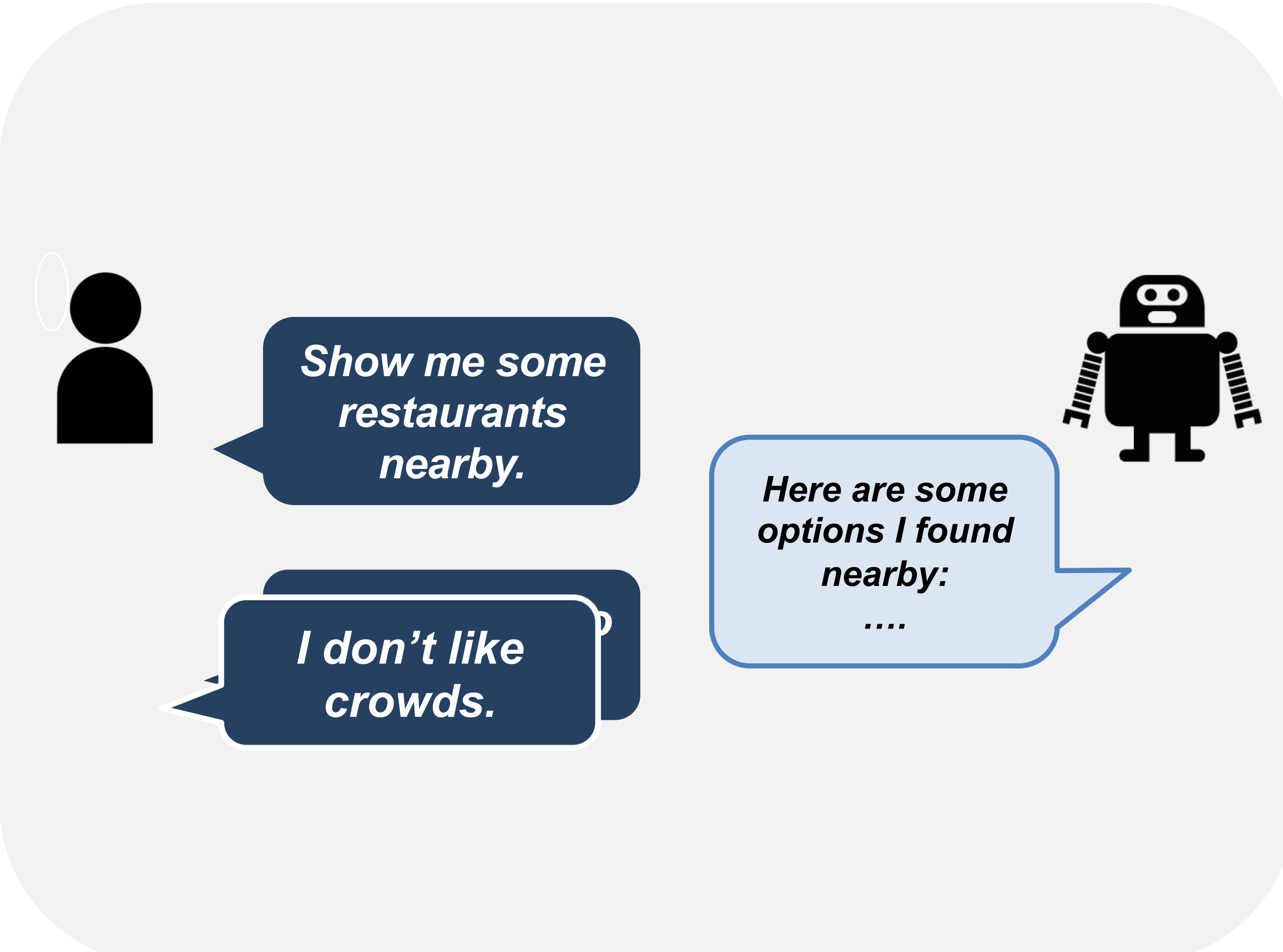

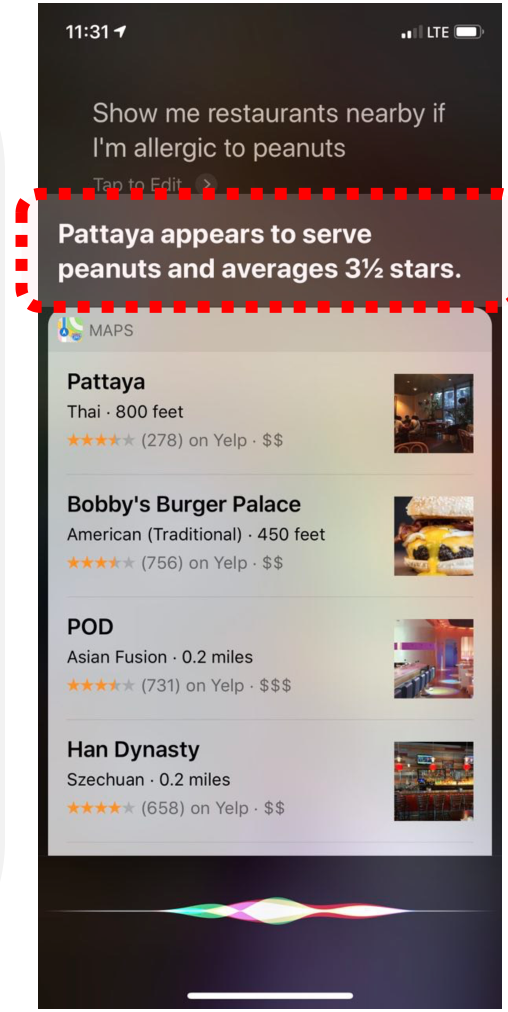

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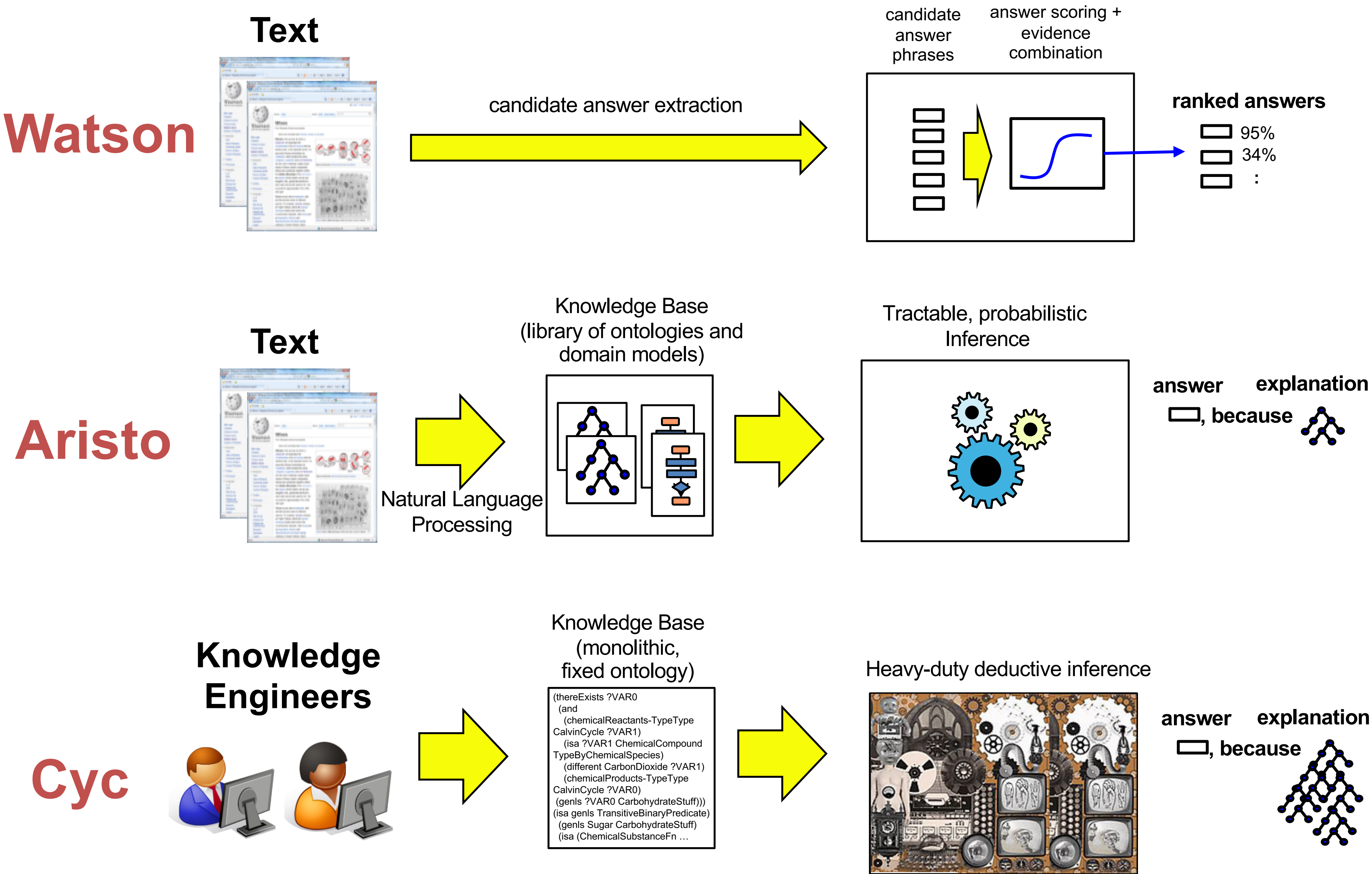
What needs to happen?

1. Define representation of functions
2. Manually author and automatically learn extraction rules
3. Attack challenges
   - Linguistic variability
     - “synthesize protein”, “protein synthesis”, “synthesizes large numbers of proteins”, “helps to synthesize proteins”, …
   - Multiword expressions
     - “cell membrane” = “membrane”, but “amino acid” ≠ “acid”
   - Ambiguous patterns
     - “cell membrane”, “cell division”, “cell biologist”
   - Non-functional actions
     - exist, differ, attempt, do, remain, appear, occur, play, show, …
   - Peripheral activities
     - nucleus + divide, ribosome + move

Aristo in Context



Example

QUESTION

Water freezing is an example of a (A) liquid turning into a solid (B) solid turning into a liquid (C) gas turning into a solid

NEW: object(freeze,water) -> d-change(water ,-, liquid, solid)?

object prop from to

explicit representation of discrete change

TEXT

Freezing involves changing water from its liquid state to its solid state by the removal of heat.

freeze -> d-change(water, -, liquid state, solid state).

object property from to

Example

QUESTION

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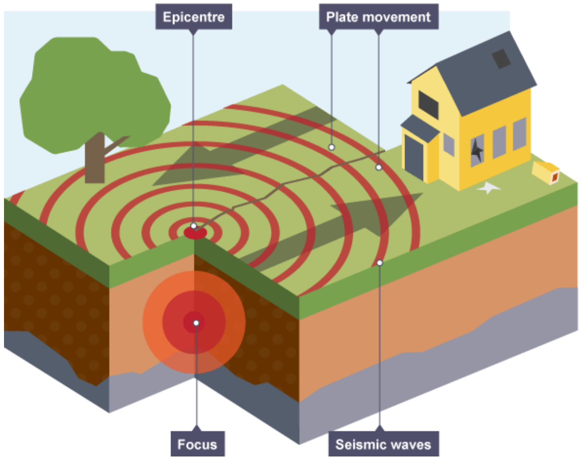
REASONING

What do earthquakes tell scientists about the history of the planet?

(A) Earth's climate is constantly changing.
(B) The continents of Earth are continually moving.
(C) Dinosaurs became extinct about 65 million years ago.
(D) The oceans are much deeper today than millions of years ago.



REASONING

ARISTO ANSWERED:

Hide

Question: What do earthquakes tell scientists about the history of the planet?

Answer: (C) Dinosaurs became extinct about 65 million years ago.

Confidence: 45.42%

as computed from these reasoners:

- *Information Retrieval:* 87.59%
- *Table Reasoning:* 6.68%
- *Topic Matching:* 65.20%
- *Tuple Reasoning:* 4.16%

Justification sentence (from Information Retrieval): The paleontological records of the history of life on this planet show that the giant dinosaurs and many other animal and plant groups became extinct about 65 million years ago.

COMMON SENSE

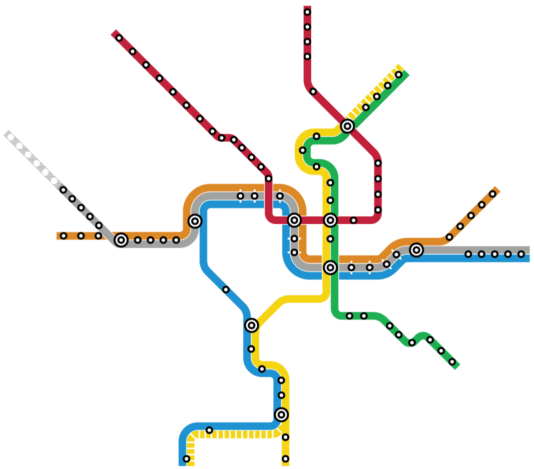
City administrators can encourage energy conservation by

(A) lowering parking fees

(B) building larger parking lots

(C) decreasing the cost of gasoline

(D) lowering the cost of bus and subway fares



COMMON SENSE

ARISTO'S BEST GUESS:

Hide

Question: City administrators can encourage energy conservation by

Aristo is not sure about this one...

Best guess: (C) decreasing the cost of gasoline

Confidence: 35.55%

as computed from these reasoners:

Information Retrieval: 14.95%
Topic Matching: 70.15%
Tuple Reasoning: 69.43%

Justification sentence (from Information Retrieval): 1970s Programs and educational materials are created to encourage gasoline and energy conservation.

Reasoning to an Answer: Qualitative Relations

How are the particles in a block of iron affected when the block is melted?
(A) The particles gain mass.
(B) The particles contain less energy.
(C) The particles move more rapidly.
(D) The particles increase in volume.

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Reasoning to an Answer: Qualitative Relations

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RETRIEVED KNOWLEDGE

As the heat of a particle increases, the particles move faster.

Retrieved knowledge

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Reasoning to an Answer: Qualitative Relations

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RETRIEVED KNOWLEDGE

As the heat of a particle increases, the particles move faster.

IDENTIFIED SPANS FOR QUALITATIVE PROPERTY:

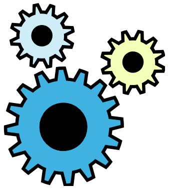
particles (0.77)
particle (0.65)
heat (0.62)

IDENTIFIED SPANS FOR QUALITATIVE DIRECTION:

more rapidly (0.93)
faster (0.93)
increases (0.93)

Retrieved knowledge

Application to question



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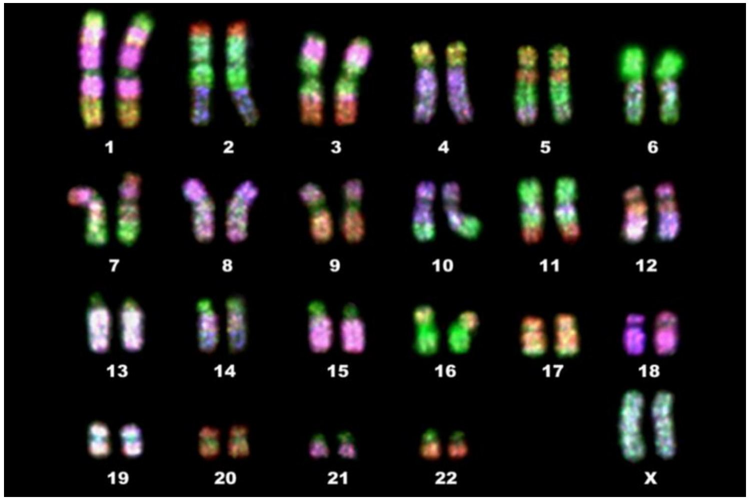
Example Question: Simple Lookup

How many chromosomes does the human body cell contain?

(A) 23
(B) 32
(C) 46
(D) 64



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Example Question: Reasoning by Chaining

Which features are the best evidence that glaciers once covered an area?

(A) wide riverbeds
(B) U shaped valleys
(C) groundwater springs
(D) underground caves

Aristo KB facts:

(glacier, causes, glacial erosion)
&
(glacial erosion, causes, valley)

→ (glacier, causes, valley)

Handling Lexical Variability

AAAI-2018

ACL-2017

Knowledge is expressed in a **variety of linguistic forms**

- Simple textual variation confuses even the best solvers
- No single knowledge representation (e.g., Open IE tuples) suffices

- Idea: **Reason over (multiple) semantic abstractions of text**
  - Use off-the-shelf, pre-trained NLP modules
  - Multiple views for a more complete semantic understanding
    - SRL frames (verbs, prepositions, comma), dependency parse, coreference sets, lexical similarity links, raw text sequence

- Unified representation as a family of **Semantic Graphs**
  - PredArg graphs, trees, clusters, sequences
  - Connected via textual similarity links

- Same ILP-based reasoning formalism as before