

# Language Model Programming: Lecture 3

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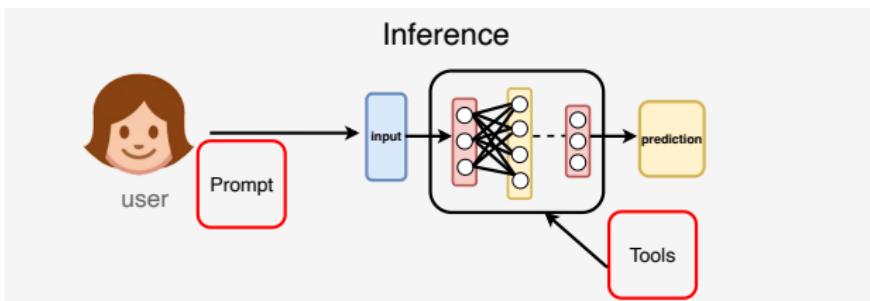
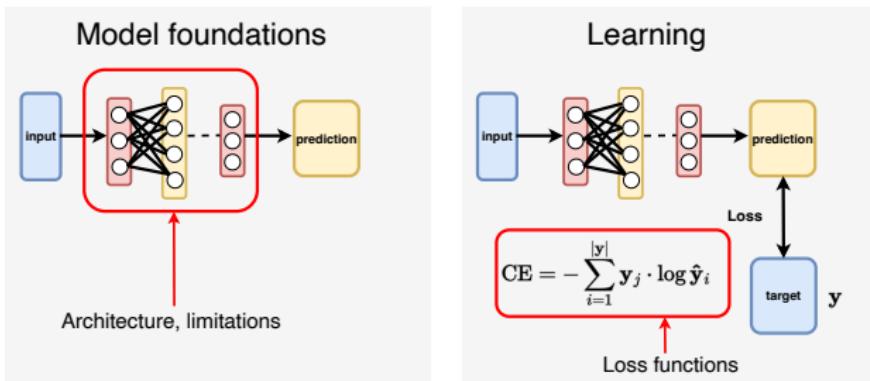


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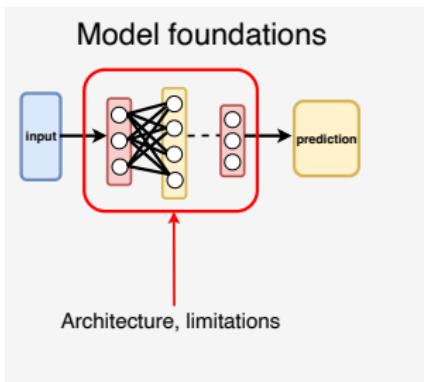


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# Reminder of bigger picture



# Reminder of bigger picture



## RASPy

```
def flip():
    length = {key(1) == query{1}.value(z)
    flip = (key(length - indices - 1) == query{indices}).value(tokens)
    return flip
flip()
```

Input h e l l o

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 |   |   |   |   |   |
| 1 |   |   |   |   |   |
| 1 |   |   |   |   |   |
| 1 |   |   |   |   |   |
| 5 | 5 | 5 | 5 | 5 | 5 |

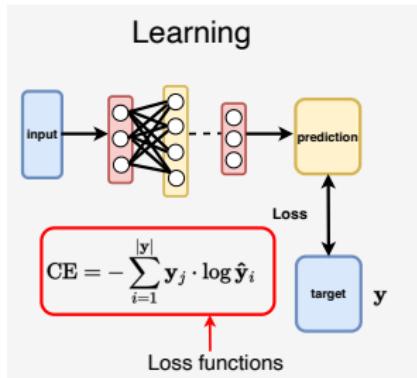
Layer 1

Layer 2

Final o l l e h

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | h |
| 3 |   |   |   |   |   |
| 2 |   |   |   |   |   |
| 1 |   |   |   |   |   |
| 0 |   |   |   |   |   |

# Reminder of bigger picture



```
1 // File path_planner.scl
2 type actor(x: i32, y: i32), goal(x: i32, y: i32), enemy(x: i32, y: i32)
3
4 const UP = 0, DOWN = 1, RIGHT = 2, LEFT = 3
5 rel safe_cell(x, y) = range(0, 5, x), range(0, 5, y), not enemy(x, y)
6 rel edge(x, y, x, yp, UP) = safe_cell(x, y), safe_cell(x, yp), yp == y + 1
7 // Rules for DOWN, RIGHT, and LEFT edges are omitted...
8
9 rel next_pos(p, q, a) = actor(x, y), edge(x, y, p, q, a)
10 rel path(x, y, x, y) = next_pos(x, y, _)
11 rel path(x1, y1, x3, y3) = path(x1, y1, x2, y2), edge(x2, y2, x3, y3, _)
12 rel next_action(a) = next_pos(p, q, a), path(p, q, r, s), goal(r, s)
```

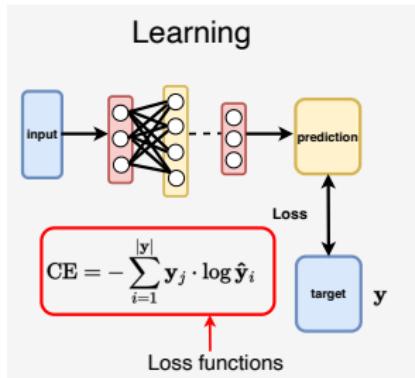
Fig. 3. The logic program of the PacMan-Maze application in Scallop.

# Reminder of bigger picture

## Declarative Programming

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```

Fig. 3. The logic program of the PacMan-Maze application in Scallop.



## Task-specific model from last time

```
1 import torch
2 from transformers import \
3     AutoModelForSequenceClassification as hf_model
4
5 class NLIModel(torch.nn.Module):
6     def __init__(self, model_name):
7         super().__init__()
8         self.model = hf_model.from_pretrained(
9             model_name, ## base transformer
10            num_labels=3 ## 3 labels for NLI
11        )
12     def forward(self, features): ### forward pass
13         output = self.model(**features)
14         prob = output.logits.softmax(dim=-1)
15         return (output.loss, prob)
```

- ▶ Fine-tuning with task-specific parameters.

# Newer techniques for model fine-tuning

```
1 from transformers import T5ForConditionalGeneration
2 from peft import get_peft_model, LoraConfig, TaskType
3
4 model = T5ForConditionalGeneration.from_pretrained(
5     "t5-large"
6 )
7 peft_config = LoraConfig(
8     task_type=TaskType.SEQ_2_SEQ_LM,
9     r=8, lora_alpha=32,
10 )
11 model = get_peft_model(model, peft_config)
12 model.print_trainable_parameters()
13 # trainable params: 2359296 ||
14 # all params: 740027392 ||
15 # trainable%: 0.31881198257050464
```

see [peft library](#)

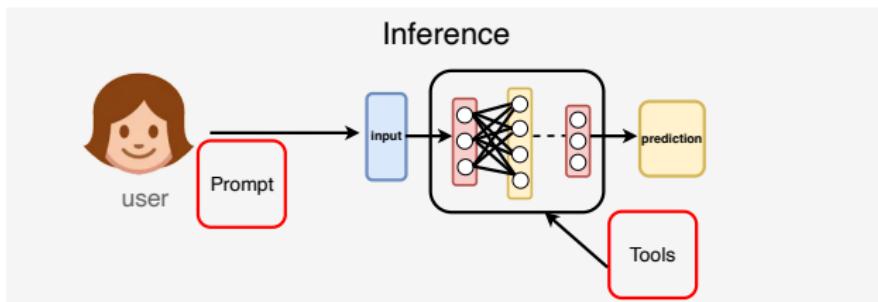
- ▶ **Parameter efficient fine-tuning:** Fine-tuning without tuning *all* of a model's parameters, rather a smaller set of *extra* parameters.

Questions about last lecture?

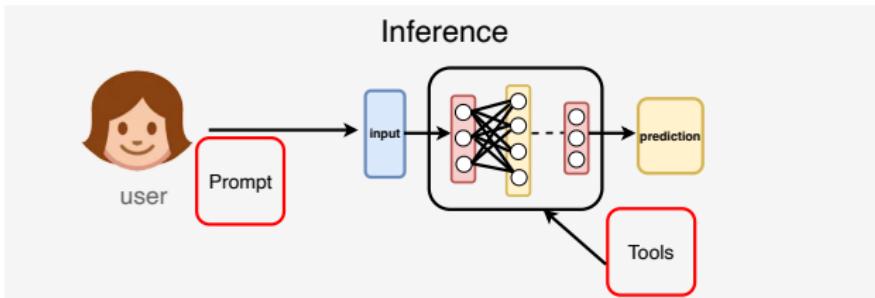
# Goals for lecture today

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```

Fig. 3. The logic program of the PacMan-Maze application in Scallop.

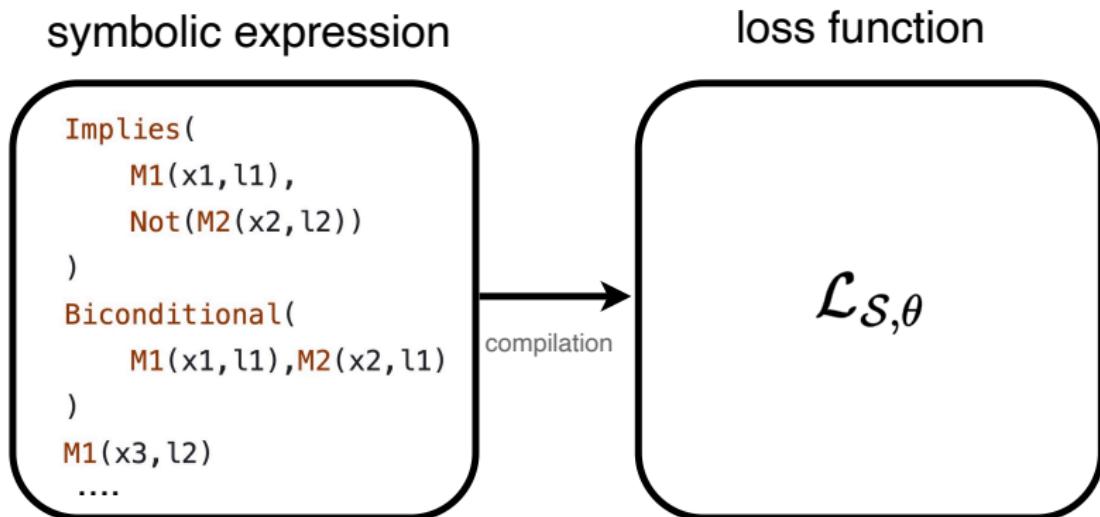


# Goals for lecture today



- ▶ Extend our declarative approach from yesterday to **model inference** problems, model consistency.
- ▶ Fill in some missing parts about how to implement these high-level languages, logic programming.
- ▶ **next lecture:** Explore LLM prompting, imperative style programming.

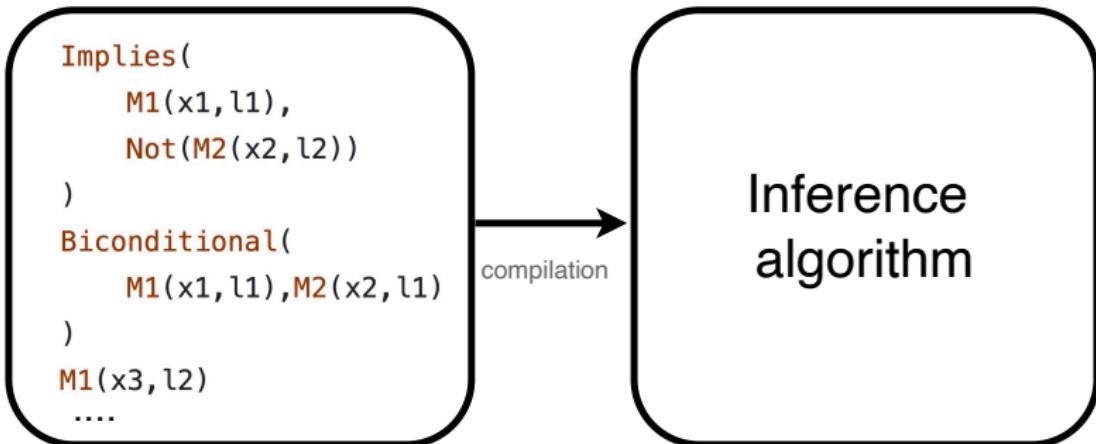
## Connecting with the last lecture



- ▶ Saying what we want the model to do (and what it can do), without saying how (applied to structure prediction).

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symbolic expression



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# Connecting with the last lecture

```
1 import problog as p          ## pip install problog
2 PROGRAM = p.program.PrologString("""
3 0.8::stress(ann).
4 0.4::stress(bob).
5 0.6::influences(ann,bob).
6 0.2::influences(bob,carl).
7
8 smokes(X) :- stress(X).
9 smokes(X) :- influences(Y,X), smokes(Y).
10
11 query(smokes(carl))."""
12 p.get_evaluatable().create_from(PROGRAM).evaluate()
13 ## => {smokes(carl): 0.1376000000000003}
```

## A motivating example

## Another mistake involving geography

**USER**

Which country is physically bigger, Germany or Poland? Please answer one word.

**ASSISTANT**

Poland

## Another mistake involving geography

**USER** Which country is physically bigger, Germany or Poland? Please answer one word.

**ASSISTANT** Poland

**USER** Is Poland physically bigger than Germany? Please answer only yes/no

**ASSISTANT** No.

# Querying ChatGPT

```
1 COUNTRIES = ["Germany", "France", "Poland"]
2 PROMPT_1 = f"Which country is physically bigger" +\
3 "{c1} or {c2}? Please provide a one word answer."
4 PROMPT_2 = f"Is {c2} physically bigger than" +\
5 "{c1}, answer only yes/no."
6
7 for c1 in COUNTRIES:
8     for c2 in [c for c in COUNTRIES if c != c1]:
9         prompt_1 = PROMPT_1.format(c1=c1,c2=c2)
10        answer1 = query_chatgpt(prompt_1)
11        prompt_1 = PROMPT_2.format(c1=c1,c2=c2)
12        answer2 = query_chatgpt(prompt_1)
```

# Querying ChatGPT

```
1  from openai import OpenAI
2  client = OpenAI() #<---- requires API key
3
4  def query_chatgpt(prompt):
5      response = client.chat.completions.create(
6          model="gpt-3.5-turbo",
7          messages = [{{
8              "role": "user",
9              "content" : [
10                 {
11                     "type" : "text",
12                     "text" : prompt
13                 }],}}],
14          temperature=0., logprobs=True
15      )
16      out_text = response.choices[0].message.content
17      prob = math.exp(
18          response.choices[0].logprobs.content[0].logprob
19      )
20      return (out_text,prob)
```

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```

## ► What it returns (gpt-3.5-turbo)

| (c1,c2) | bigger, c1 or c2? | c2 bigger c1? | invariance? |
|---------|-------------------|---------------|-------------|
| (DE,FR) | FR (c2)           | No            | no          |
| (DE,PL) | PL (c2)           | No            | no          |
| (FR,DE) | DE (c2)           | No            | no          |
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| (PL,DE) | DE (c2)           | No            | no          |
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## More advanced prompting

- ▶ **Caveats:** very sensitive to prompt, order, not best model or prompting strategy, **be skeptical.**

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- ▶ **Caveats:** very sensitive to prompt, order, not best model or prompting strategy, **be skeptical**.

**USER** Which country is physically bigger, Germany or Poland? Please explain step by step.

**ASSISTANT** To determine which country is physically bigger, we can compare their respective land areas.

1. Germany: The total land area of Germany is approximately 357,022 square kilometers.

2. Poland: The total land area of Poland is approximately 312,696 square kilometers.

By comparing these numbers, we can see that Germany has a larger land area than Poland. Specifically, Germany is around 44,326 square kilometers bigger than Poland. Therefore, Germany is physically bigger than Poland.

What we want a model to do (semantics)

## Thinking about semantics again

| (c1,c2) | bigger, c1 or c2? | c2 bigger c1? | <i>invariance?</i> |
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- ▶ Invariance constraints.

**C1**(c1, c2), **C2**(c1, c2), **Y**(c2, c1), **N**(c2, c1)

first: *c1/c2 is bigger*; second: *c2 is bigger than c1, yes/no.*

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## ► Invariance constraints.

$$\mathbf{C1}(c1, c2), \mathbf{C2}(c1, c2), \mathbf{Y}(c2, c1), \mathbf{N}(c2, c1)$$

first:  $c1/c2$  is bigger; second:  $c2$  is bigger than  $c1$ , yes/no.

$$\forall(c1, c2).$$

$$(\mathbf{C2}(c1, c2) \leftrightarrow \mathbf{Y}(c2, c1)) \wedge \\ (\mathbf{C1}(c1, c2) \leftrightarrow \mathbf{N}(c2, c1))$$

# Thinking about semantics again

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## ► Order constraints:

$$\forall(c1, c2).$$

$$((\mathbf{C2}(c1, c2) \rightarrow \neg \mathbf{C2}(c2, c1)) \wedge \\ (\mathbf{C1}(c1, c2) \rightarrow \neg \mathbf{C1}(c2, c1)) \wedge \\ (\mathbf{Y}(c1, c2) \rightarrow \neg \mathbf{Y}(c2, c1)) \wedge \\ (\mathbf{N}(c1, c2) \rightarrow \neg \mathbf{N}(c2, c1)))$$

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**Not exhaustive:** label uniqueness, transitivity constraints, etc.

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**Observation:** even (seemingly) simple problems have a rich semantics.

# Thinking about semantics again

- ▶ Taking the simple case of just  $\text{C1}(c1, c2)$ ,  $\text{C2}(c1, c2)$ ,  $\text{Y}(c2, c1)$ ,  $\text{N}(c2, c1)$ , we can again think in terms of our *possible world* semantics:

| worlds         |  |
|----------------|--|
| w <sub>1</sub> | $\text{C1}(c1, c2), \neg\text{C2}(c1, c2), \text{Y}(c2, c1), \neg\text{N}(c2, c1)$ |
| w <sub>2</sub> | $\text{C1}(c1, c2), \neg\text{C2}(c1, c2), \neg\text{Y}(c2, c1), \text{N}(c2, c1)$ |
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What kind of problems do we want to solve?

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What kind of problems do we want to solve?

- ▶ **Model testing:** Does my model satisfy a particular set of constraints? behavioral testing.
- ▶ **Model correction:** Can I use constraints to fix errors, arrive at new predictions?

## Our model from before

```
1 ## run forward pass
2 loss,probabilities = nli_model({
3     "input_ids": batch_data.input_ids,
4     "labels"    : labels,
5 })
6 print(probabilities)
7 #####tensor([[0.3339, 0.3034, 0.3627]], ....)
```

# Getting prediction confidences from generative models

- ▶ Standard is to take a product over the generated token probabilities.

| (c1,c2) | bigger, c1 or c2? | c2 bigger c1? | <i>invariance?</i> |
|---------|-------------------|---------------|--------------------|
| (DE,FR) | FR (c2) 0.752     | No 0.957      | <b>no</b>          |
| (DE,PL) | DE (c1) 0.986     | No 0.990      | <b>yes</b>         |
| (FR,DE) | FR (c1) 0.575     | No 0.898      | <b>yes</b>         |
| (FR,PL) | FR (c1) 0.956     | No 0.991      | <b>yes</b>         |
| (PL,DE) | DE (c2) 0.997     | No 0.654      | <b>no</b>          |
| (PL,FR) | FR (c2) 0.998     | No 0.882      | <b>no</b>          |

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**Main topic:** Can we improve consistency through inference time probabilistic reasoning over model outputs?

## Probabilistic reasoning over predictions

## Graphical models: defining what we want to do

- ▶ **Probabilistic graphical models (PGM)**: models of complex joint probability distributions expressed in terms of graphs. E.g.,

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(over two random variables  $\mathbf{A}, \mathbf{B}$ ) we might have the *directed* graph:

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**Bayesian network**: a classic type of PGM, takes the form:

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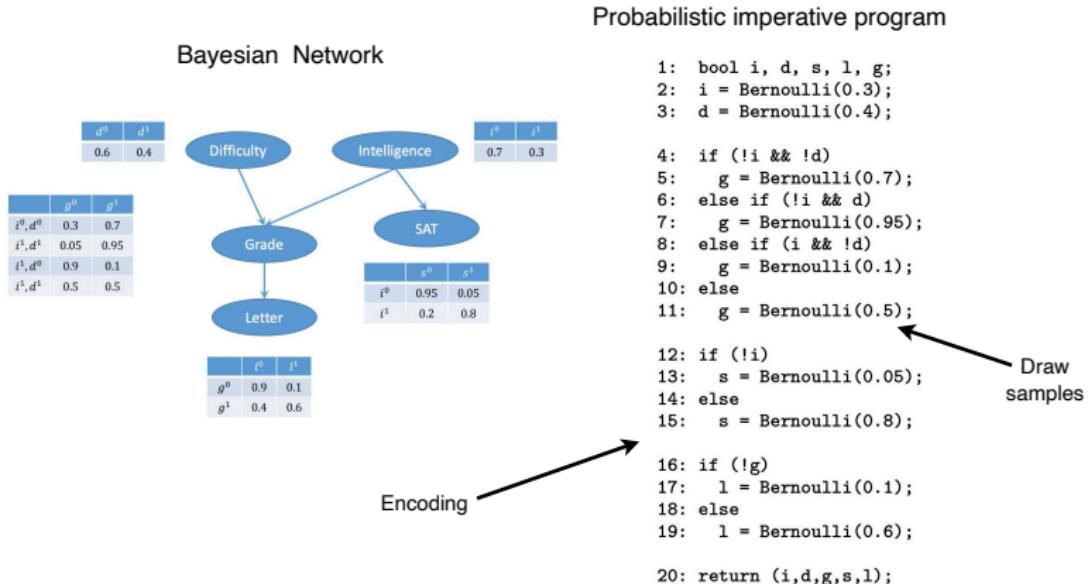
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- ▶ **Directed graphical model**, involves having the following, *conditional probability tables (CPTs)* (example from [Park \(2002\)](#)):

| A     | $p(\mathbf{A})$ | A     | B     | $p(\mathbf{B} \mid \mathbf{A})$ |
|-------|-----------------|-------|-------|---------------------------------|
| $a_1$ | .3              | $a_1$ | $b_1$ | .2                              |
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# Other encodings of Bayesian networks



from Gordon et al. (2014)

Some proposals about framing LLM prompting in terms of probabilistic (imperative) programming (Dohan et al., 2022).

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- ▶ The particular **inference problem** we will focus on:

**Most Probable Explanation (MPE):** *Finding the most probable complete variable assignment (given evidence).*

# MPE Inference and MAXSAT

For  $p(\mathbf{A}, \mathbf{B})$  we have the CPTs:

| $\mathbf{A}$ | $p(\mathbf{A})$ | $\mathbf{A}$ | $\mathbf{B}$ | $p(\mathbf{B}   \mathbf{A})$ |
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**MAXSAT:** Finding the maximum number of clauses of a formula that can be made true, common in some NLP work on LLMs.

SAT and related problems (slight detour)

## Boolean satisfiability

- ▶ Given a formula  $K$ , does there exist an interpretation that makes the formula true? E.g.,

$$K := (\textcolor{blue}{E} \wedge \neg \textcolor{red}{C} \wedge \neg \textcolor{blue}{N}) \vee (\neg \textcolor{blue}{E} \wedge \textcolor{red}{C} \wedge \neg \textcolor{blue}{N}) \vee (\neg \textcolor{blue}{E} \wedge \neg \textcolor{red}{C} \wedge \textcolor{blue}{N})$$

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**satisfying assignment:**  $\text{E}$  is true,  $\text{C}$  is false,  $\text{N}$  is false.

# Using propositional SAT solvers

```
1 ## to install: pip install z3-solver
2 from z3 import *
3
4 solver = Solver()
5 P,Q,R,S = Bools("P Q R S")
6
7 ### [((P^Q)→R)→S), formula, adds to solver
8 Gamma = [ Implies(Implies(And(P,Q),R),S) ]
9 solver.add(Gamma)
10
11 ## check if satisfiable
12 solver.check() ## => "sat",
13 ## finds a satisfying model
14 solver.model() ## => [S = True, R = False, ...]
```

# Boolean satisfiability and model counting

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Model counting is a variation of this, how many satisfying assignments does a formula have? weighted variant

$$\text{WMC}(K, \theta) := \sum_{\mathbf{w} \models K} \prod_{\mathbf{w} \models X_i} P_\theta(X_i) \cdot \prod_{\mathbf{w} \models \neg X_i} (1 - P_\theta(X_i))$$

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Our probabilistic model from the last lecture can be expressed as a Bayesian network, but a simple one.

## Generalizing model counting

- ▶ Model counting is a variation of this, how many satisfying assignments does a formula have? Notation change,  $l$  (literal,  $X_i$  or  $\neg X_i$ )

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Generalize the symbols  $\sum$ ,  $\prod$  and  $P_\theta$  ([Kimmig et al., 2011, 2017](#)):

$$\text{AMC}(K) := \bigoplus_{w \models K} \bigotimes_{w \models l} a(l)$$

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$$\text{AMC}(K) := \bigoplus_{\mathbf{w} \models K} \bigotimes_{\mathbf{w} \models l} a(l)$$

| Task      | $A$                   | $\oplus$ | $\otimes$ | $\bar{0}$ | $\bar{1}$ | $a(l)$                    | $a(\neg l)$               |
|-----------|-----------------------|----------|-----------|-----------|-----------|---------------------------|---------------------------|
| SAT       | {true, false}         | $\vee$   | $\wedge$  | false     | true      | true                      | true                      |
| #SAT (MC) | $\mathbb{N}$          | $+$      | $\times$  | 0         | 1         | 1                         | 1                         |
| MAXSAT    | $\mathbb{N}$          | max      | $\times$  | 0         | 1         | 1                         | 1                         |
| WMC       | $\mathbb{R}_{\geq 0}$ | $+$      | $\times$  | 0         | 1         | $\in \mathbb{R}_{\geq 0}$ | $\in \mathbb{R}_{\geq 0}$ |
| WMAXSAT   | $\mathbb{R}_{\geq 0}$ | max      | $\times$  | 0         | 1         | $\in \mathbb{R}_{\geq 0}$ | $\in \mathbb{R}_{\geq 0}$ |
| PROB      | $\mathbb{R}_{\geq 0}$ | $+$      | $\times$  | 0         | 1         | $\in [0, 1]$              | $1 - a(l)$                |
| MPE       | $\mathbb{R}_{\geq 0}$ | max      | $\times$  | 0         | 1         | $\in [0, 1]$              | $1 - a(l)$                |
| FUZZY     | [0,1]                 | max      | min       | 0         | 1         | $\in [0, 1]$              | $1 - a(l)$                |

Algebraic structure, semiring  $(A, \oplus, \otimes, \bar{0}, \bar{1})$ .

# Generalizing model counting

Generic algorithm

---

**Algorithm 2:** General search algorithm for commutative semirings

---

```

input: A CNF formula  $\Delta$ , variables  $V$ 
1 Function  $\text{SS}(\Delta, V)$ :
  2 if  $\{\} \in \Delta$  then
    3 return  $\bar{0}$ 
  4 else if  $\Delta = \{\}$  then
    5 if  $V$  is not empty then
      6 return  $\bigotimes_{v \in V} (a(v) \oplus a(\neg v))$ 
    7 return  $\bar{1}$ 
  8 select literal  $l$  from  $\Delta$  ;
  9 let  $V'$  be  $V$  with variable in  $l$  removed ;
  10 return  $(a(l) \otimes \text{SS}(\Delta|l, V')) \oplus (a(\neg l) \otimes \text{SS}(\Delta|\neg l, V'))$  ;

```

---

discrete

uncertain reasoning

| Task      | $A$                   | $\oplus$ | $\otimes$ | $0$   | $1$  | $a(l)$                    | $a(\neg l)$               |
|-----------|-----------------------|----------|-----------|-------|------|---------------------------|---------------------------|
| SAT       | {true, false}         | $\vee$   | $\wedge$  | false | true | true                      | true                      |
| #SAT (MC) | $\mathbb{N}$          | $+$      | $\times$  | 0     | 1    | 1                         | 1                         |
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| WMC       | $\mathbb{R}_{\geq 0}$ | $+$      | $\times$  | 0     | 1    | $\in \mathbb{R}_{\geq 0}$ | $\in \mathbb{R}_{\geq 0}$ |
| WMAXSAT   | $\mathbb{R}_{\geq 0}$ | max      | $\times$  | 0     | 1    | $\in \mathbb{R}_{\geq 0}$ | $\in \mathbb{R}_{\geq 0}$ |
| PROB      | $\mathbb{R}_{\geq 0}$ | $+$      | $\times$  | 0     | 1    | $\in [0, 1]$              | $1 - a(l)$                |
| MPE       | $\mathbb{R}_{\geq 0}$ | max      | $\times$  | 0     | 1    | $\in [0, 1]$              | $1 - a(l)$                |
| FUZZY     | [0,1]                 | max      | min       | 0     | 1    | $\in [0, 1]$              | $1 - a(l)$                |

# Generalizing model counting: An aside

## An aside: gradient semirings and parameter estimation

In the last example, we showed how to use weighted model counting to compute the *success probability* of the weighted CNF formula  $S(F)$  in Eq 3 given Boolean variables  $P_1, P_2, P_3$  and their weights  $p = [0.8, 0.75, 0.4] = p_1, p_2, p_3$ . Supposing that our goal is to maximize the success probability of  $F$  (where we take  $F$  to be our *evidence*), one question we might ask is: *is it possible to learn variable weights that best realize this goal?* Such is the problem of parameter estimation that underlies virtually all machine learning problems.

Gradient-based optimization techniques are often used for solving such problems and will play a central role in the next chapter. Broadly, gradient methods rely on computing mathematical gradients, which (*loosely*) tell us about the direction we should shift our weights to get closer to our goal. Formally, gradients take the form of a vector

$$\vec{g} = \left\langle \frac{\partial S(F)}{\partial p_i}, \dots, \frac{\partial S(F)}{\partial p_n} \right\rangle \quad (6)$$

consisting of partial derivatives  $\frac{\partial S(F)}{\partial p_j}$  for each of our parameters  $p_j$ . With such quantities, we can then employ algorithms such as (stochastic) gradient ascent or its variants to make updates to our weights and ultimately train our model against data.

Semirings have also been investigated for computing gradients, including the *gradient semiring* of [Eisner, 2002] (see also Kimmig et al. [2017], Manhaeve et al. [2018]). Such a semiring is defined below:

| Task     | $A$                                     | $\oplus$ | $\otimes$ | $\mathbf{0}$      | $\mathbf{1}$      | $a(l_i)$ | $a(\neg l_i)$ |
|----------|---|----------|-----------|-------------------|-------------------|----------|---------------|
| gradient | $\mathbb{R}_{\geq 0} \times \mathbb{R}$ | Eq.8     | Eq.9      | $(0, \mathbf{0})$ | $(0, \mathbf{1})$ | Eq.7     | Eq.7          |

Here the elements of  $A$  are now tuples consisting of probabilities  $p_i$  and their gradients  $\vec{g}_i$

$$\left( p_i, \vec{g}_i \right).$$

As with our other problems, arriving at the final solution to our problem (i.e., finding the vector in Eq.6) will involve working bottom-up from our literals and our labeling function  $a$ . In the base case, the initial gradients of *positive* literals (i.e., literals without negation)  $l$  will be defined as one-shot vectors  $\vec{e}_j$  consisting of a 1 in location  $j$  and 0s elsewhere. Our labeling function can then be defined as follows (for any input literal  $x_i$ , either positive or negative):

$$a(l_i) = \begin{cases} (p_i, \vec{e}_j), & \text{if } l_i \text{ is a positive literal} \\ (1 - p_i, -\vec{e}_i), & \text{otherwise} \end{cases} \quad (7)$$

Our addition and multiplication functions will then be defined as follows (with the last rule corresponding to the *chain rule*):

$$(p_1, \vec{g}_1) \oplus (p_2, \vec{g}_2) = (p_1 + p_2, \vec{g}_1 \cdot \vec{g}_2) \quad (8)$$

$$(p_1, \vec{g}_1) \otimes (p_2, \vec{g}_2) = (p_1 \times p_2, p_2 \vec{g}_1 \cdot p_1 \vec{g}_2) \quad (9)$$

## MAXSAT example

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**Example:** the following formula

$$K := (P_0 \vee P_1)_1 \wedge (P_0 \vee \neg P_1)_2 \wedge (\neg P_0 \vee P_1)_3 \wedge (\neg P_0 \vee \neg P_1)_4$$

does not have a satisfying assignment.

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$P_0$  is true,  $P_1$  is true

**Cost:** 1 (*one violated clause*)

## MAXSAT example

- ▶ **Weighted MAXSAT:** Given clauses with weights (via some  $w$ ), find truth values that maximize the combined weights of satisfied clauses:

$$\text{maximize} \sum_{c \in \Delta_{\text{sat}}} w(c)$$

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Weight is 24 and **cost** is 1.

# MAXSAT example

```
1 ## pip install python-sat
2 from pysat.examples.rc2 import RC2
3 from pysat.formula import WCNF
4
5 wcnf = WCNF()
6 ### variables
7 P0,P1 = [1,2]
8 ### formula clauses
9 wcnf.extend(
10     [[P0,P1],[P0,-P1],[-P0,P1],[-P0,-P1]],
11     weights=[9,12,3,1],
12 )
13 with RC2(wcnf) as rc2:
14     for m in rc2.enumerate():
15         print(f"model {m} has cost {rc2.cost}")
16 # model [1, 2] has cost 1
17 # model [1, -2] has cost 3
18 # model [-1, -2] has cost 9
19 # model [-1, 2] has cost 12
```

# MPE to MaxSAT

# The MPE to MAXSAT reduction

For  $p(\mathbf{A}, \mathbf{B})$  we have the CPTs:

| $\mathbf{A}$ | $p(\mathbf{A})$ | $\mathbf{A}$ | $\mathbf{B}$ | $p(\mathbf{B}   \mathbf{A})$ |
|--------------|-----------------|--------------|--------------|------------------------------|
| $a_1$        | .3              | $a_1$        | $b_1$        | .2                           |
| $a_2$        | .5              | $a_1$        | $b_2$        | .8                           |
| $a_3$        | .2              | $a_2$        | $b_1$        | .7                           |
|              |                 | $a_2$        | $b_2$        | .3                           |
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|--------------|-----------------|------------------------------|
| $\mathbf{A}$ | $p(\mathbf{A})$ |                              |
| $a_1$        | $b_1$           | .2                           |
| $a_1$        | $b_2$           | .8                           |
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for  $\mathbf{A}$ :  $(I_{a_1} \vee I_{a_2} \vee I_{a_3}) \wedge (\neg I_{a_1} \vee \neg I_{a_2}) \wedge (\neg I_{a_2} \vee \neg I_{a_3}) \wedge (\neg I_{a_1} \vee \neg I_{a_3})$

for  $\mathbf{B}$ :  $(I_{b_1} \vee I_{b_2}) \wedge (\neg I_{b_1} \vee \neg I_{b_2})$

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for  $\mathbf{B}$ :  $(I_{b_1} \vee I_{b_2}) \wedge (\neg I_{b_1} \vee \neg I_{b_2})$

2. **Parameter clauses (units):** Negate and make clause weight  $-\log p$ :

$$(\neg I_{a_1})^{-\log(.3)} \wedge (\neg I_{a_2})^{-\log(.5)} \wedge (\neg I_{a_3})^{-\log(.2)}$$

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| $a_2$        | $b_2$           | .3                           |
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| $a_3$        | $b_2$           | .4                           |

1. **Indicator clauses:** uniqueness constraints for  $\mathbf{A}$  and  $\mathbf{B}$ :

for  $\mathbf{A}$ :  $(I_{a_1} \vee I_{a_2} \vee I_{a_3}) \wedge (\neg I_{a_1} \vee \neg I_{a_2}) \wedge (\neg I_{a_2} \vee \neg I_{a_3}) \wedge (\neg I_{a_1} \vee \neg I_{a_3})$

for  $\mathbf{B}$ :  $(I_{b_1} \vee I_{b_2}) \wedge (\neg I_{b_1} \vee \neg I_{b_2})$

2. **Parameter clauses (units):** Negate and make clause weight  $-\log p$ :

$$(\neg I_{a_1})^{-\log(.3)} \wedge (\neg I_{a_2})^{-\log(.5)} \wedge (\neg I_{a_3})^{-\log(.2)}$$

3. **Parameter clauses (non-units):** Negate each part in clause:

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# The MPE to MAXSAT reduction: why this makes sense

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**Example:** if we make  $I_{a_2}$  true, which has probability 0.5, then we violate  $(\neg I_{a_2})^{-\log(.5)}$  with a (relatively low) cost of 0.693

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for **B**:  $(I_{b_1} \vee I_{b_2})^\infty \wedge (\neg I_{b_1} \vee \neg I_{b_2})^\infty$

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**Infinite weight:** To enforce clauses that should always be true, we can add a weight  $\infty$  (operationally, make the weight of all clauses  $+ 1$ )

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**Evidence:** Do the same thing: add the evidence to the formula and weight with infinity.

## A MAXSAT reduction for our initial problem

- We have some **predictions**:  $C1(c1, c2)$ ,  $C2(c1, c2)$ ,  $Y(c2, c1)$ ,  $N(c2, c1)$ ,  
**probabilities**:  $\mathbf{p} = [p_{c1}, p_{c2}, p_Y, p_N]$

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**probabilities**:  $\mathbf{p} = [p_{c1}, p_{c2}, p_Y, p_N]$
1. **Hard constraints**: Translate all constraints into infinite weighted CNF clauses, i.e., constraints of the kind (translated to CNF):

$\forall(c_1, c_2).$

$$((\mathbf{C2}(c_1, c_2) \leftrightarrow \mathbf{Y}(c_2, c_1)) \wedge \\ (\mathbf{C1}(c_1, c_2) \leftrightarrow \mathbf{N}(c_2, c_1)))$$

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2. **Prediction units**: negate predictions and add  $-\log p$  weight, for example:

$$\neg \mathbf{C1}(c1, c2)^{-\log(p_{c1})} \wedge \neg \mathbf{C2}(c1, c2)^{-\log(p_{c2})} \wedge \neg \mathbf{Y}(c2, c1)^{-\log(p_Y)} \wedge \neg \mathbf{N}(c2, c1)^{\cdot\cdot}$$

## Hard vs. Soft clauses and constraints

```
1 from pysat.formula import WCNF
2
3 wcnf = WCNF()
4 ### variables
5 P0,P1 = [1,2]
6 ### formula clauses
7 wcnf.extend(
8     [[P0,P1],[P0,-P1],[-P0,P1],[-P0,-P1]],
9     weights=[9,12,3,1],
10 )
11
12 ### hard clause, evidence
13 wcnf.append([P1])
14 print(wcnf.hard)
```

# Related work in NLP

## Language Models with Rationality

Nora Kassner<sup>1,2</sup> Oyvind Tafjord<sup>1</sup> Ashish Sabharwal<sup>1</sup> Kyle Richardson<sup>1</sup>  
Hinrich Schütze<sup>2</sup> Peter Clark<sup>1</sup>

### Enhancing Self-Consistency and Performance of Pre-Trained Language Models through Natural Language Inference

Eric Mitchell, Joseph J. Noh, Siyan Li, William S. Armstrong,  
Ananth Agarwal, Patrick Liu, Chelsea Finn, Christopher D. Manning  
Stanford University  
[eric.mitchell@cs.stanford.edu](mailto:eric.mitchell@cs.stanford.edu)

### Ἁ Maieutic Prompting: Logically Consistent Reasoning with Recursive Explanations

Jaehun Jung<sup>†</sup> Lianhui Qin<sup>†</sup> Sean Welleck<sup>†‡</sup>  
Faeze Brahman<sup>†</sup> Chandra Bhagavatula<sup>†</sup> Ronan Le Bras<sup>‡</sup> Yejin Choi<sup>†‡</sup>

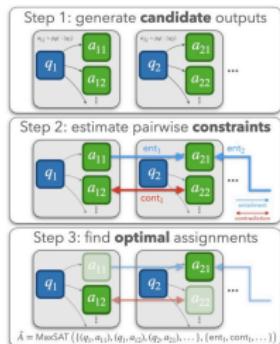
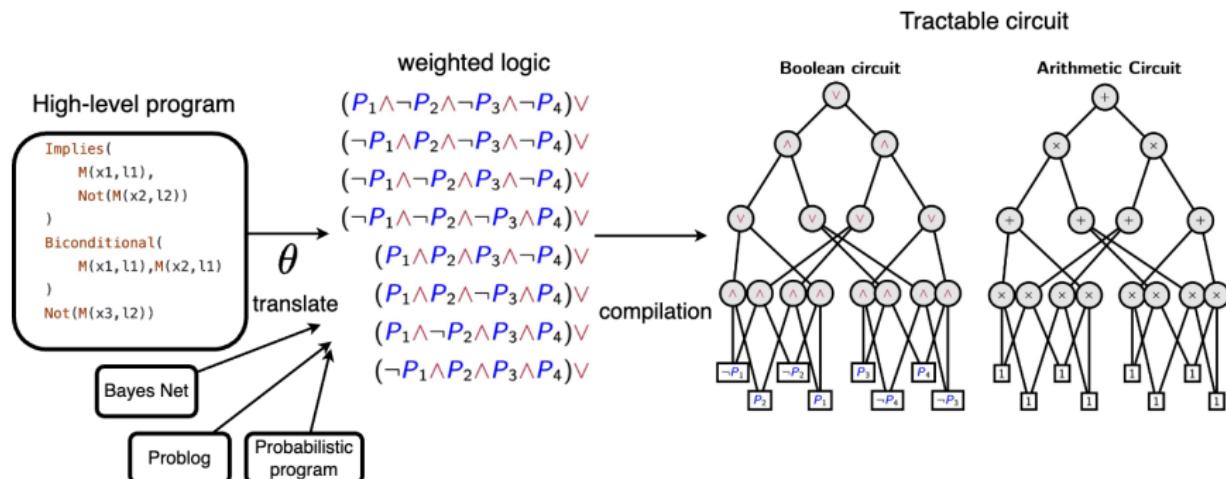


Figure 1: ConCoRD first generates candidate outputs from the base pre-trained model, then estimates soft pairwise constraints between output choices, and finally finds the most satisfactory choices of answers accounting for both the base model and NLI model's beliefs.

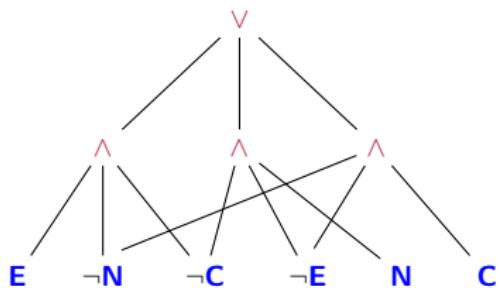
# Zooming out again: building high-level modeling languages



# Creating tractable representations: extending to MAXSAT

Uniqueness constraint again

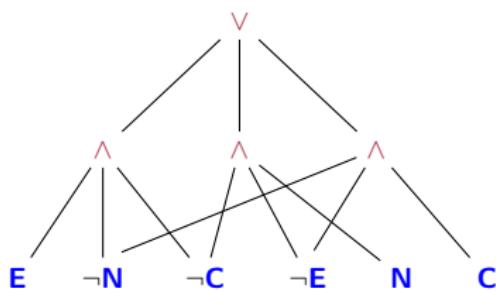
$$(\text{E} \wedge \neg \text{N} \wedge \neg \text{C}) \vee (\neg \text{E} \wedge \text{C} \wedge \neg \text{N}) \vee (\neg \text{E} \wedge \neg \text{C} \wedge \text{N})$$



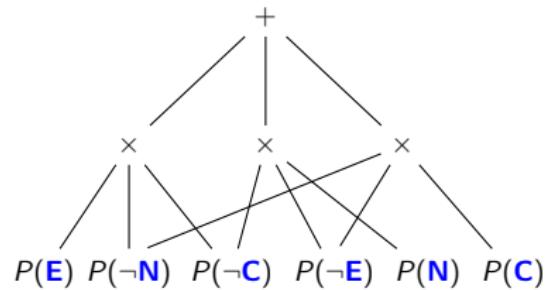
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Boolean circuit

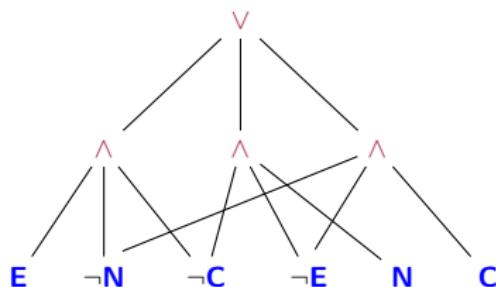


Arithmetic circuit

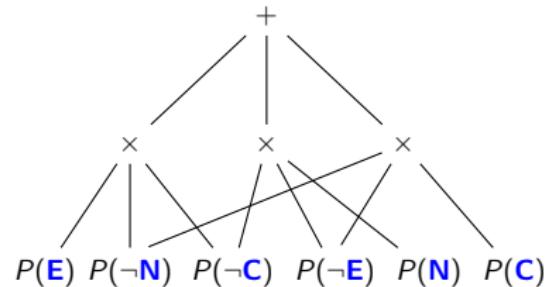
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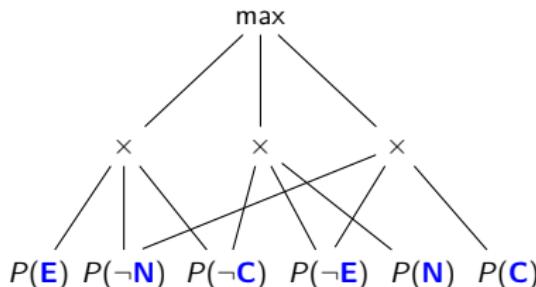
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**Boolean circuit**



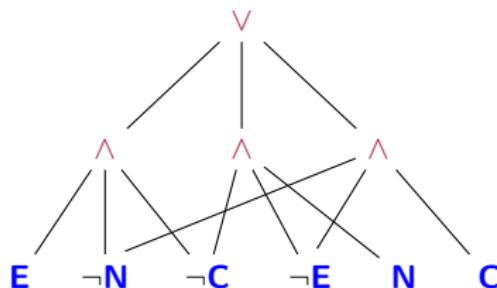
**Arithmetic circuit**



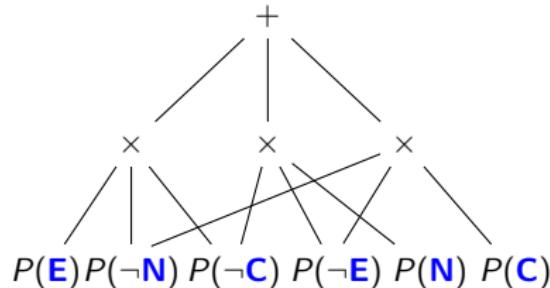
**Maximizer circuit**

| Task      | $A$                   | $\oplus$ | $\otimes$ |
|-----------|-----------------------|----------|-----------|
| SAT       | {true, false}         | $\vee$   | $\wedge$  |
| #SAT (MC) | N                     | +        | $\times$  |
| MAXSAT    | N                     | max      | $\times$  |
| WMC       | $\mathbb{R}_{\geq 0}$ | +        | $\times$  |
| WMAXSAT   | $\mathbb{R}_{\geq 0}$ | max      | $\times$  |
| PROB      | $\mathbb{R}_{\geq 0}$ | +        | $\times$  |
| MPE       | $\mathbb{R}_{\geq 0}$ | max      | $\times$  |
| FUZZY     | [0,1]                 | max      | min       |

## Creating tractable representations (reminder)



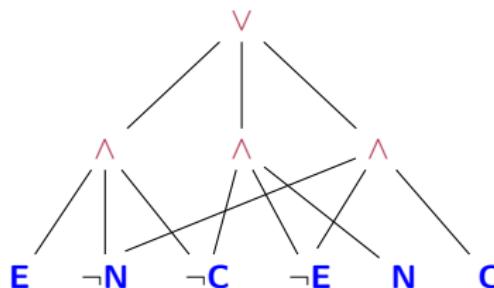
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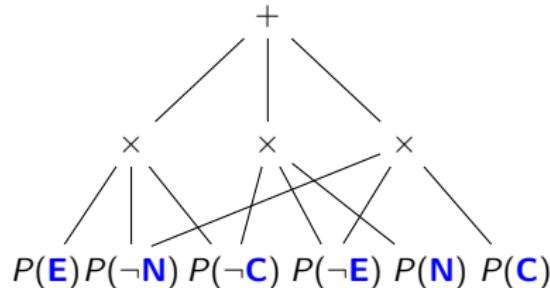
Arithmetic circuit

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## Creating tractable representations (reminder)



Boolean circuit



Arithmetic circuit

- ▶ Facilitates solving these algorithmic problems (SAT, WMC, MAXSAT) efficiently. Two key properties:

**decomposability:** For conjunction nodes  $\wedge$ , children never share the same variables.

**determinism:** For each disjunction node  $\vee$ , the children are logically inconsistent.

# Compilation Software: example

```
1 from pysdd.sdd import SddManager
2
3 sdd = SddManager(var_count=3)
4 p1, p2, p3 = sdd.vars
5 uniqueness = (p1 & -p2 & -p3) | (-p1 & p2 & -p3) \
6             | (-p1 & -p2 & p3)
7
8 count = uniqueness.wmc(log_mode=False)
9 print(f"model count: {count.propagate()}")
```

<https://github.com/wannesm/PySDD>, see Darwiche (2011)

- ▶ Can extract underlying circuit, mix with Pytorch.

## Interim summary

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- ▶ Can be reduced to MAXSAT, requires some reduction into weighted logic (see Park (2002), example follows [here](#)).

Model correction via compilation to MAXSAT has received recent attention in NLP ([Kassner et al., 2021, 2023](#); [Gu et al., 2022](#); [Mitchell et al., 2022](#)).

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Imperative Style

```
output = ''  
  
while M1(query,output):  
  
    if T1(query,output):  
        output,query = M2(query,output)  
        continue  
  
    for item in M3(query,output):  
        output += T2(query,output):  
  
return output
```

Declarative Style

```
Implies(  
    And(M1(query,output), T2(query,output)),  
    M2(query,output)  
)  
Biconditional(  
    M1(query,output),  
    Not(M3(query,output))  
)  
Or(T1(query,output), Not(M2(query,output)))
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| Paradigm    | Basic Units  | Applications   |
|-------------|--|--|
| imperative  | models as <b>subroutines</b> , for/while loops, recursion, if-then control | structure building, combining LLMs w/ tools, explanation.        |
| declarative | models predictions as <b>symbolic objects</b> , logical constraints        | probabilistic reasoning, learning, self-correction, consistency. |

# Logic programming

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*Best of both worlds?* keep properties of your original model (e.g., logical or probabilistic inference) improved estimation via neural methods. ([De Raedt et al., 2020](#))

# Directed Relational Models: DeepProblog

- An approach based on (probabilistic) logic programming ([Manhaeve et al., 2018](#)).

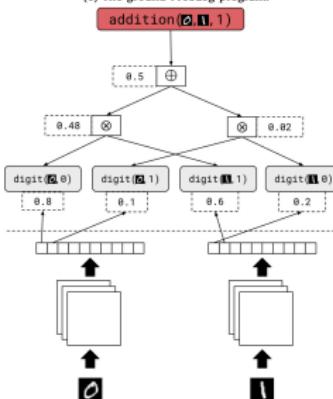
(a) The DeepProLog program.

```
nn(m_digit,[0],0)::digit(0,0);nn(m_digit,[0],1)::digit(0,1).  
nn(m_digit,[1],0)::digit(1,0);nn(m_digit,[1],1)::digit(1,1).  
addition([0][1],1) :- digit(0,0), digit(1,1).  
addition([0][1],1) :- digit(0,1), digit(1,0).
```

(b) The ground DeepProLog program.

```
0.8 :: digit(0,0); 0.1 :: digit(0,1).  
0.2 :: digit(1,0); 0.6 :: digit(1,1).  
addition([0][1],1) :- digit(0,0), digit(1,1).  
addition([0][1],1) :- digit(0,1), digit(1,0).
```

(c) The ground ProLog program.



(d) The AC for query  $\text{addition}([0][1], 1)$ .

## Semantic differences: logic programming and full logic

- Logic programming is based on clausal logic, of the form:

$$\underbrace{P_1}_{\text{head/conclusion}} \leftarrow \underbrace{P_2, P_3, \dots, P_n}_{\text{body}}$$

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Corresponding (in our terms) to a formula  $P_2 \wedge P_3 \wedge \dots \wedge P_n \rightarrow P_1$ , or a clause

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**Example:** from [Raedt et al. \(2016\)](#)

```
flies ← bird,normal  
bird ← tweety  
bird ← oliver  
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```

First case, can only make the conclusion (`flies`) if we know that the body is true; ordinary case: just an unordered clause:

$$(\text{flies} \vee \neg \text{bird} \vee \neg \text{normal})$$

## Semantic differences: logic programming and full logic

- ▶ Semantic assumes a kind of **closed world assumption**, *least Herbrand model*.

```
flies ← bird, normal  
bird ← tweety  
bird ← oliver  
normal ← tweety  
tweety
```

*Operationally:* we don't work with the above logic program, but a rewritten version via *Clark completion rules* ([Clark, 1977](#)):

```
flies↔bird∧normal  
bird↔tweety∨oliver  
normal↔tweety  
tweety  
oliver↔false
```

# Conclusion

- ▶ Covered methods for improving models at **inference time** (e.g., frozen LLMs) via logical-probabilistic reasoning.
- ▶ **MPE** inference, finding the most probably complete variable assignment, common from Bayes nets, can be used via reduction to **MAXSAT**
- ▶ **Directed** vs. **Undirected** approaches to PGMs and relational models, extra details about logic programming.

Thank you.

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