CS 188 Spring 2024 — Introduction to Artificial Intelligence — Midterm

- You have 110 minutes.
- The exam is closed book, no calculator, and closed notes, other than one double-sided cheat sheet that you may reference.
- Anything you write outside the answer boxes or you ~~cross out~~ will not be graded. If you write multiple answers, your answer is ambiguous, or the bubble/checkbox is not entirely filled in, we will grade the worst interpretation.

For questions with **circular bubbles**, you may select only one choice.

○ Unselected option (completely unfilled)

● Only one selected option (completely filled)

○ Don't do this (it will be graded as incorrect)

For questions with **square checkboxes**, you may select one or more choices.

■ You can select

■ multiple squares (completely filled)

First name	
Last name	
SID	
Name of person to the right	
Name of person to the left	
Discussion TAs (or None)	

Honor code: "As a member of the UC Berkeley community, I act with honesty, integrity, and respect for others."

By signing below, I affirm that all work on this exam is my own work, and honestly reflects my own understanding of the course material. I have not referenced any outside materials (other than my cheat sheets), nor collaborated with any other human being on this exam. I understand that if the exam proctor catches me cheating on the exam, that I may face the penalty of an automatic "F" grade in this class and a referral to the Center for Student Conduct.

Signature: ______________________________

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It's testing time for our CS188 robots!
Circle your favorite robot below.
(ungraded, just for fun)

Q1. [12 pts] Potpourri

In the next two subparts, consider a search problem with maximum branching factor of b, and maximum search tree depth of m (i.e. the search tree is finite).

(a) [1 pt] What is the **space complexity** (maximum number of nodes on the fringe at any given time) for **breadth-first** tree search?

○ $O(b^m)$ ○ $O(bm)$ ○ $O(m)$ ○ $O(b)$

(b) [1 pt] What is the **time complexity** (maximum number of nodes explored in the worst case) for **depth-first** tree search?

○ $O(b^m)$ ○ $O(bm)$ ○ $O(m)$ ○ $O(b)$

In the next three subparts, consider a search problem with a finite state space. Suppose we have an admissible heuristic function $h_1(n)$, a consistent heuristic function $h_2(n)$, and a heuristic function $h_3(n) = \max(h_1(n), h_2(n))$.

(c) [2 pts] Select all heuristics that will guarantee that A* **graph** search (used with that heuristic) will return the optimal solution.

☐ $h_1(n)$ ☐ $h_2(n)$ ☐ $h_3(n)$ ○ None of the above

(d) [2 pts] Select all heuristics that will guarantee that A* **tree** search (used with that heuristic) will return the optimal solution.

☐ $h_1(n)$ ☐ $h_2(n)$ ☐ $h_3(n)$ ○ None of the above

(e) [2 pts] Select all true statements.

☐ A^* tree search is always optimal.
☐ A^* graph search is optimal if the heuristic function used is admissible.
☐ A^* graph search is optimal if the heuristic function used is consistent.
○ None of the above

(f) [2 pts] In the context of Monte Carlo Tree Search (MCTS), when are nodes likely to be visited more frequently during the search process? Select all that apply.

☐ Nodes that have a lower win rate, as the algorithm seeks to explore less successful paths more thoroughly.
☐ Nodes that have a higher win rate, as the algorithm prioritizes paths with a higher probability of success.
☐ Nodes that have fewer rollouts, as the algorithm prioritizes exploration.
☐ Nodes at the deepest level of the tree, as the algorithm focuses on fully exploring the end.
○ None of the above

(g) [2 pts] Which of these scenarios would be most appropriate for a Hidden Markov Model (HMM) setup?

○ You receive daily reports of "sun" or "no sun." You know the probability of sun only depends on whether there was sun the previous day. You want to estimate the probability of sun on future days.

○ You receive daily reports of a patient's symptoms, but cannot directly observe the state of the patient's disease. You know how the disease causes the symptoms, and you know that the state of the disease on a given day only depends on the state of the disease on the previous day. You want to estimate the probability of disease on each day.

○ You receive the exact location of a vehicle every minute. You control the vehicle, and you want to guide the vehicle to its destination.

Q2. [17 pts] Search: Half the Dots

Recall the "All-the-Dots" problem from Project 1. Here are some reminders of Pacman rules: Pacman lives in an M by N grid. He can move up, down, left, or right, but he is not allowed to take actions that move into a wall. Walls may exist throughout the grid, but the locations of the walls do not change for the entire problem. In the starting state, there are K dots throughout the grid. Pacman's goal in Project 1 was to eat all K dots.

In this question, Pacman has built a spaceship and has landed on a new world, Earth Prime (also an M by N grid), with K dots. For this entire question, you can assume that M, N, and K are fixed, and you can **assume that K is even**. Pacman's new goal is to solve the "Half-the-Dots" search problem and eat **any** $K/2$ dots!

(a) [2 pts] Select all pieces of information that should be part of a **minimal state representation**.

Note: In other words, all the options you select should, together, form the smallest valid state representation. Consider only space complexity (do not consider time complexity).

- ☐ Coordinates of Pacman's starting position.
- ☐ Coordinates of Pacman's current position.
- ☐ A boolean matrix with the dots' starting positions.
- ☐ A boolean matrix indicating which dots have not been eaten.
- ☐ A boolean matrix indicating where Pacman has visited.

For the rest of the question, assume that Pacman's state representation is an M by N matrix of integers, where the integers are interpreted as follows: 0 indicates an empty square, 1 indicates a wall is present, 2 indicates that Pacman is present, and 3 indicates that a dot is present.

(b) [2 pts] Suppose Pacman implements a goal test, $G(s)$. This function takes in a state (and no other information about the problem), and returns whether this state passes the goal test.

What is the time complexity (in big O notation) of $G(s)$, in terms of M, N, and K? Assume the function is optimal (written to be as fast as possible).

$O($ $)$

(c) [2 pts] Blinky thinks that Pacman's state representation is inefficient, and suggests adding this variable to the state space: $R =$ the number of remaining dots Pacman needs to eat to solve the problem.

Select all true statements about Blinky's modified problem.

- ☐ The original successor function, with no modifications, can output successor states for the modified problem.
- ☐ The logic of the original goal test can still be used for the modified problem.
- ☐ Running BFS (with all necessary modifications made) will explore fewer search nodes, compared to the unmodified problem.
- ☐ If we only count valid, reachable states, the size of the state space will increase by a factor of R.
- ○ None of the above

(d) [2 pts] With Blinky's modification, what is the time complexity of the goal test function? Assume the function is optimal (written to be as fast as possible).

$O($ $)$

(e) [3 pts] Suppose we have an arbitrary admissible heuristic $h(s)$ for the All-the-Dots problem. Select all heuristics that are guaranteed to be admissible for the Half-the-Dots problem.

- ☐ $h(s)$
- ☐ $\frac{1}{2}h(s)$
- ☐ $\frac{1}{2}cost(s)$, where $cost(s)$ is the cost of the optimal solution to the All-the-Dots problem from state s.
- ☐ Half of the currently remaining number of dots.
- ☐ The number of remaining dots that need to be eaten for $K/2$ dots to be eaten in total.
- ○ None of the above

(f) [2 pts] Consider the following heuristic:

First, order the remaining dots in **descending** order of Manhattan distance. Examples: The 1st dot is the furthest dot from Pacman. The 2nd dot is the second-furthest dot from Pacman. In the start state, the Kth dot is the closest dot to Pacman.

If there are X or fewer dots remaining, return 0. Else, return the Manhattan distance to the Yth dot in the list.

Do there exist any values of X and Y that make this heuristic admissible? If yes, write down the smallest values of X and Y that make it admissible. Otherwise, write N/A in both squares. You may answer in terms of K, the number of dots the problem begins with. *Remember K is even.*

X: ☐ Y: ☐

For the following subparts, Pacman has a supercomputer, ORACLE, that can instantly compute the optimal solution to a given "All-the-Dots" search problem. Pacman is still attempting to find an optimal solution to the "Half-the-Dots" problem.

(g) [2 pts] Consider this strategy: At the beginning of the problem, Pacman selects the $K/2$ closest dots by Manhattan distance and runs ORACLE to find the optimal solution for an "All-the-Dots" problem with only the $K/2$ selected dots (effectively ignoring the existence of the farther dots).

Will this strategy return an optimal solution to the "Half-the-Dots" problem?

- ○ Yes, because the optimal solution always uses the closest dots to the starting position.
- ○ Yes, because planning the complete path ahead of time is always optimal.
- ○ No, because planning the complete path from the starting position can never be optimal for this problem.
- ○ No, because the optimal solution does not always use the closest dots to the starting position.

(h) [2 pts] Suppose Pacman uses the method in part (g), but instead as a heuristic to A^* search. For a given state, Pacman calculates R, the remaining number of dots he needs to eat to reach $K/2$ dots eaten. Then, Pacman runs ORACLE on the R closest dots by Manhattan distance. The length of the optimal path returned by ORACLE is used as the heuristic value.

This heuristic is not admissible. Select the counterexample that shows this.

In the grids below, $K = 4$ and $R = 2$. Assume that Pacman breaks ties arbitrarily. P marks Pacman's position.

○

P		●		
	●			
			●	●

○

P				●
				●
●			●	

○

P		●		
		●		
		●	●	

○

P			●	
				●
			●	●

Q3. [15 pts] Logic: Pacdrone

Pacman needs your help predicting what his drone will do on Mars! Let's do some first order logic warmup.

Suppose there are many sensors: $S_0,\ S_1,\ S_2,\ \ldots$. Each sensor is located either on Mars, on Earth, or on the Drone.

If sensor S_i is present on Mars, on Earth, or on the Drone, then OnMars(S_i), OnEarth(S_i), or OnDrone(S_i) returns True, respectively. Otherwise, the predicate returns False.

A sensor can *disrupt* another sensor. Disrupts(S_i, S_j) is True if S_i disrupts S_j. Note that if S_i disrupts S_j, that does not necessarily mean that S_j disrupts S_i.

Choose all statements that are equivalent to the given statement.

(a) [2 pts] All sensors on Mars disrupt some sensor that is either on Earth or on the Drone.

- ☐ $\exists s_a, \text{OnMars}(s_a) \implies \forall s_b, \text{Disrupts}(s_a, s_b) \vee \text{OnMars}(s_b)$
- ☐ $\forall s_a, \text{OnMars}(s_a) \implies \forall s_b, \text{Disrupts}(s_a, s_b) \wedge \text{OnMars}(s_b)$
- ☐ $\exists s_a, \text{OnMars}(s_a) \implies \exists s_b, \text{Disrupts}(s_a, s_b) \vee \big(\text{OnEarth}(s_b) \vee \text{OnDrone}(s_b)\big)$
- ☐ $\forall s_a, \text{OnMars}(s_a) \implies \exists s_b, \text{Disrupts}(s_a, s_b) \wedge \big(\text{OnEarth}(s_b) \vee \text{OnDrone}(s_b)\big)$
- ○ None of the above

(b) [3 pts] $\forall (s_a, s_b) \left[(s_a \neq s_b) \implies \Big(\neg\text{Disrupts}(s_a, s_b) \vee \big(\text{OnEarth}(s_a) \wedge \text{OnDrone}(s_b)\big)\Big)\right]$

- ☐ If sensor A disrupts different sensor B, then A is on Earth and B is on the Drone.
- ☐ Given different sensors A and B, either: A does not disrupt B, or: A is on Earth and B is on the Drone.
- ☐ If sensor A disrupts sensor B, one of them is on Earth and one of them is on the Drone.
- ☐ All sensors that disrupt another sensor are either on Earth or on the Drone.
- ☐ For every distinct pair (s_a, s_b), $\text{Disrupts}(s_a, s_b) \implies \big[\text{OnEarth}(s_a) \wedge \text{OnDrone}(s_b)\big]$
- ☐ $\exists (s_a, s_b), \text{Disrupts}(s_a, s_b) \implies \neg\text{OnEarth}(s_a) \vee \neg\text{OnDrone}(s_b)$
- ○ None of the above

The rest of the problem is independent of the previous subparts.

Pacman tells you that there are four binary environment variables on Mars: Dusty (D), Cloudy (C), Windy (W), Sunny (S). However, we have no access to these values directly. Instead, we observe the truth values of the drone's logical sensors, which are logical expressions that consist of the environment variables. For example, if D and C are true, then the sensor $D \implies C$ returns True. For the next three subparts, select the logical sentence that matches the given sensor description.

(c) [1 pt] Mars is either dusty or sunny.

○ $D \implies S$ ○ $S \implies D$ ○ $D \wedge S$ ○ $D \vee S$

(d) [1 pt] If Mars is windy, then it must be dusty or cloudy.

○ $W \vee D \vee C$ ○ $W \wedge (D \vee C)$ ○ $W \implies (D \vee C)$ ○ $(D \vee C) \implies W$

(e) [1 pt] Whenever it is not sunny, if it is windy, then it is dusty.

○ $\neg S \wedge W \wedge D$ ○ $\neg S \vee W \vee D$ ○ $S \vee \neg W \vee D$ ○ $\neg S \implies (W \wedge D)$

Now we can help Pacman understand what his Drone will do on Mars. Pacman tells you he outfitted the Drone with three sensors:

Solar Panel: $S \wedge \neg D$ Window: $(C \wedge W) \vee D$ Storm: $(D \vee W) \implies (C \wedge \neg S)$

We also have our own, high tech sensors on Earth:

α: $\neg S \implies W$ β: $W \implies C$ γ: $(D \wedge C) \vee W$

Suppose that our sensors currently detect the following: α = False, β = True, γ = True.

What are the truth values of the Drone's sensors?

(f) [1 pt] Solar Panel:

○ True
○ False

(g) [1 pt] Window:

○ True
○ False

(h) [1 pt] Storm:

○ True
○ False

(i) [2 pts] The Pacdrone decides to land and go into hibernation whenever the following Prime Directive evaluates as True:

$$(\neg\text{Window} \vee \text{Storm}) \implies \neg\text{Solar Panel}$$

Which of the following is the correct Conjunctive Normal Form (CNF) of the Prime Directive?

○ (Window ∨ Storm) $\implies$ Solar Panel
○ Window ∧¬Storm ∧ Solar Panel
○ (Window ∧¬Storm) ∨ ¬Solar Panel
○ (Window ∨ ¬Solar Panel) ∧ (¬Storm ∨ ¬Solar Panel)

(j) [2 pts] Pacman has learned some of the environment variables: S = False, D = False, C = unknown, W = True. The Prime Directive evaluates as True. What is the value of C?

○ True ○ False ○ Can't calculate

Q4. [21 pts] Logic: Transactions

A database system has 3 disks, A, B, and C.

A transaction is a database operation (e.g. reading a file), which requires using one or more disks for one or more consecutive time steps. At a given time step, a transaction is either running, or not running.

A disk cannot be used by two transactions at the same time. One way to enforce this is to introduce a **lock** for each disk. You can think of a lock as an object that can be acquired by a transaction. When a transaction is holding a lock, all other transactions are unable to acquire that lock (and use the lock's corresponding disk). The transaction can hold on to the lock for as long as needed. Once the transaction is finished using the disk, the transaction can release the corresponding lock for other transactions to acquire.

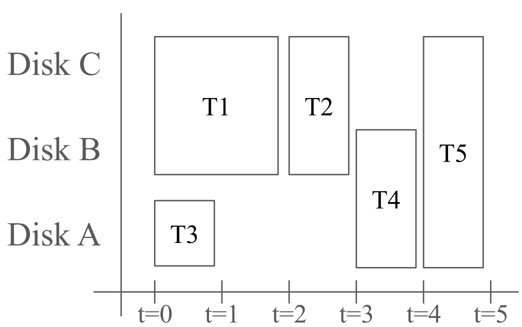
Up to 2 transactions can run at the same time, as long as they are using different disks.

There are 5 transactions we need to run, each needing to run for a certain amount of time steps and needing to use a certain set of disks. (See an example below.)

Note: You can every transaction uses all the needed disks and holds all the needed locks for the transaction's entire duration.

We would like to write logical statements to find a time for each of the 5 transactions to run, while avoiding any scheduling conflicts (e.g. ensuring transactions don't access the same disk at the same time).

Here is an example of a set of transactions, their requirements, and an example of a valid schedule. This is just an example, and is not needed to solve the problem. (Note: The height of the transaction boxes is just for indicating which disks are being used, and has no other meaning.)



Transaction	Disks Used	Time Steps Needed
T1	B, C	2
T2	B, C	1
T3	A	1
T4	A, B	1
T5	A, B, C	1

Let's define the following propositional logic symbols:

- A_1 is True if and only if Transaction 1 needs to access disk A.

  $A_2,\ A_3,\ A_4,\ A_5,\ B_1,\ B_2,\ \dots,\ C_4,\ C_5$ are defined similarly.

- $a_1^{t=0}$ is True if and only if Transaction 1, at time $t = 0$, is holding the lock a corresponding to disk A.

  Note that we use lowercase letters to represent the locks.

  $a_2^{t=0},\ a_3^{t=0},\ a_4^{t=0},\ a_5^{t=0},\ b_1^{t=0},\ b_2^{t=0},\ \dots,\ c_4^{t=0},\ c_5^{t=0}$ are defined similarly.

  Another similar set of variables is defined for $t = 1$, $t = 2$, etc.

- $T_1^{t=0}$ is True if and only if Transaction 1 is running at time $t = 0$.

  $T_2^{t=0},\ T_3^{t=0},\ T_4^{t=0},\ T_5^{t=0}$ are defined similarly.

  Another similar set of variables is defined for $t = 1$, $t = 2$, etc.

The symbol definitions, repeated for your convenience:

- A_1 is True if and only if Transaction 1 needs to access disk A.
- $a_1^{t=0}$ is True if and only if Transaction 1, at time $t = 0$, is holding the lock a corresponding to disk A.
- $T_1^{t=0}$ is True if and only if Transaction 1 is running at time $t = 0$.

In the next few subparts, select the logical sentence that matches the English statement.

(a) [2 pts] If Transaction 1 is holding a lock at time $t = 0$, then Transaction 1 is running at that time, and needs to access the disk corresponding to the lock.

○ $a_1^{t=0} \vee b_1^{t=0} \vee c_1^{t=0}$

○ $a_1^{t=0} \implies \left(\neg a_2^{t=0} \wedge \neg a_3^{t=0} \wedge \neg a_4^{t=0} \wedge \neg a_5^{t=0}\right)$

○ $\left((A_1 \wedge T_1^{t=0}) \implies a_1^{t=0}\right) \wedge \left((B_1 \wedge T_1^{t=0}) \implies b_1^{t=0}\right) \wedge \left((C_1 \wedge T_1^{t=0}) \implies c_1^{t=0}\right)$

○ $\left(a_1^{t=0} \implies (A_1 \wedge T_1^{t=0})\right) \wedge \left(b_1^{t=0} \implies (B_1 \wedge T_1^{t=0})\right) \wedge \left(c_1^{t=0} \implies (C_1 \wedge T_1^{t=0})\right)$

(b) [1 pt] Is the logical sentence in the previous subpart an axiom that is true of the problem we described?

In other words: Select "Yes" if the logical sentence above should be included for any possible set of 5 transactions we want to schedule.

Note: In the problem, a transaction could possibly hold a lock without using the corresponding disk.

○ Yes ○ No

(c) [2 pts] If Transaction 3 needs to use Disk A and is running at time $t = 2$, then no other transaction that uses Disk A should be running at the same time step.

○ $\left(A_3 \wedge T_3^{t=2}\right) \implies \left(\left(\neg A_1 \vee \neg T_1^{t=2}\right) \wedge \left(\neg A_2 \vee \neg T_2^{t=2}\right) \wedge \left(\neg A_4 \vee \neg T_4^{t=2}\right) \wedge \left(\neg A_5 \vee \neg T_5^{t=2}\right)\right)$

○ $a_3^{t=2} \implies \left(\neg a_1^{t=2} \vee \neg a_3^{t=2} \vee \neg a_4^{t=2} \vee \neg a_5^{t=2}\right)$

○ $\left(A_3 \wedge T_3^{t=2}\right) \implies a_3^{t=2}$

○ $a_3^{t=2} \implies \left(A_3 \wedge T_3^{t=2}\right)$

(d) [1 pt] Is the logical sentence in the previous subpart an axiom that is true of the problem we described?

○ Yes ○ No

(e) [2 pts] We never want the database system to idle (do nothing). Select the logical sentence that matches the statement below:

"At least one transaction is running at $t = 4$."

○ $T_1^{t=4} \vee T_2^{t=4} \vee T_3^{t=4} \vee T_4^{t=4} \vee T_5^{t=4}$

○ $T_1^{t=4} \wedge T_2^{t=4} \wedge T_3^{t=4} \wedge T_4^{t=4} \wedge T_5^{t=4}$

○ $\left(a_1^{t=4} \vee a_2^{t=4} \vee \ldots \vee a_5^{t=4}\right) \wedge \left(b_1^{t=4} \vee b_2^{t=4} \vee \ldots \vee b_5^{t=4}\right) \wedge \left(c_1^{t=4} \vee c_2^{t=4} \vee \ldots \vee c_5^{t=4}\right)$

○ $\left(T_1^{t=0} \implies T_1^{t=1}\right) \vee \left(T_1^{t=1} \implies T_1^{t=2}\right) \vee \ldots \vee \left(T_1^{t=3} \implies T_1^{t=4}\right)$

The symbol definitions, repeated for your convenience:

- A_1 is True if and only if Transaction 1 needs to access disk A.
- $a_1^{t=0}$ is True if and only if Transaction 1, at time $t = 0$, is holding the lock a corresponding to disk A.
- $T_1^{t=0}$ is True if and only if Transaction 1 is running at time $t = 0$.

(f) [2 pts] Select the English sentence that matches the sentence below:

$$
\begin{aligned}
&\left((T_1^{t=0} \wedge T_2^{t=0}) \implies (\neg T_3^{t=0} \wedge \neg T_4^{t=0} \wedge \neg T_5^{t=0})\right) \wedge \\
&\left((T_1^{t=0} \wedge T_3^{t=0}) \implies (\neg T_2^{t=0} \wedge \neg T_4^{t=0} \wedge \neg T_5^{t=0})\right) \wedge \\
&\left((T_1^{t=0} \wedge T_4^{t=0}) \implies (\neg T_2^{t=0} \wedge \neg T_3^{t=0} \wedge \neg T_5^{t=0})\right) \wedge \\
&\left((T_1^{t=0} \wedge T_5^{t=0}) \implies (\neg T_2^{t=0} \wedge \neg T_3^{t=0} \wedge \neg T_4^{t=0})\right) \wedge \\
&\left((T_2^{t=0} \wedge T_3^{t=0}) \implies (\neg T_1^{t=0} \wedge \neg T_4^{t=0} \wedge \neg T_5^{t=0})\right) \wedge \\
&\ldots \\
&\left((T_4^{t=0} \wedge T_5^{t=0}) \implies (\neg T_1^{t=0} \wedge \neg T_2^{t=0} \wedge \neg T_3^{t=0})\right)
\end{aligned}
$$

◯ We can run at most 2 transactions at time $t = 0$.
◯ We can run at most 2 transactions consecutively (without a time step in between transactions).
◯ We can run any 2 transactions consecutively (without a time step in between transactions).
◯ None of the above.

(g) [3 pts] For this subpart only, suppose there are X transactions, each accessing exactly K disks each, D total disks, and T time steps. How many different propositional logic symbols are used to specify this problem?

You can answer in big-O notation, i.e. you can drop lower-order terms in the summation.
Unrelated example: $O(MN + 3N)$ can be simplified to $O(MN)$.

$O(\qquad\qquad)$

(h) [2 pts] Is it possible to represent the same problem using propositional logic, without using the lock symbols like $a_1^{t=0}$?

In other words, can you write a logical problem that always outputs a solution (a set of satisfying assignments for all other symbols) if one exists, without using the lock symbols?

◯ Yes, because different transactions can access different items.
◯ Yes, because we can write a goal test that ensures that transactions running at the same time do not access the same disk.
◯ No, because it is no longer possible for a transaction to acquire a lock it does not need.
◯ No, because the symbols encoding which transactions need which disks (e.g. A_1) cannot specify a time when the transaction needs the disk.

The relevant symbol definitions, repeated for your convenience:

- A_1 is True if and only if Transaction 1 needs to access disk A.

In the rest of the question, we want to express the same problem in first-order logic. Let's add the following constants:

- Transactions: T1, T2, T3, T4, T5
- Locks: LA, LB, LC
- Disks: A, B, C
- Time steps: 0, 1, 2, 3, 4, ...

(i) [2 pts] Suppose we want to convert the symbol B_3 into first-order logic.

We define a new predicate named Accesses to help represent this symbol. What is the minimum set of constants that Accesses needs in order to compute a true/false value corresponding to B_3?

Your answer may only use constants from the list above and commas.

Accesses( )

In addition to Accesses, let's add the following predicates:

- Transaction(x), Lock(x), Disk(x), and Time(x) are True if and only if the constant x is a transaction, lock, disk, or time step, respectively.
- Locked(x, l, t) is True if and only if transaction x is holding lock l at time t.
- Running(x, t) is True if and only if transaction x is running at time t.

(j) [2 pts] Select the English sentence that matches the sentence below:

$$\Big(\forall x\ \big(\text{Transaction}(x) \implies \neg\text{Running}(x,t)\big)\Big) \implies \Big(\forall x, l\ \big(\text{Transaction}(x) \wedge \text{Lock}(l)\big) \implies \neg\text{Locked}(x,l,t)\Big)$$

- ◯ Every transaction at time t needs to use at least one disk.
- ◯ If no transaction is running at time t, then none of the locks are being held.
- ◯ If a transaction is holding all locks at time t, then no other transaction can be running.
- ◯ If a transaction is running at time t, that transaction must be holding at least one lock.

(k) [2 pts] Select the logical sentence that goes in the blank to match the statement below:

When a transaction is holding a lock, no other transaction can be holding the lock at that time.

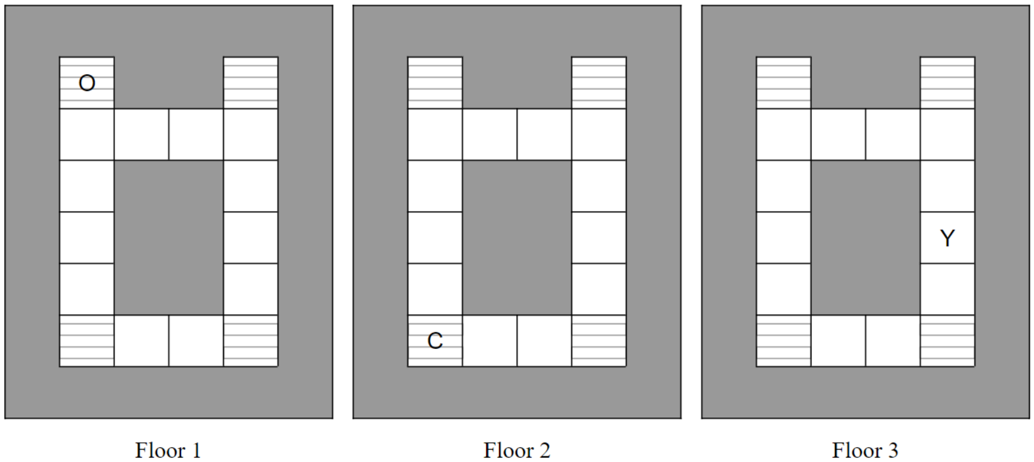
$$\forall x, l, t\ \Big(\big(\text{Transaction}(x) \wedge \text{Lock}(l) \wedge \text{Time}(t)\big) \implies (\_\_\_\_\_\_\_\_)\Big)$$

- ◯ $\text{Locked}(x,l,t) \implies \exists y\ \big(\text{Locked}(y,l,t) \implies (x \neq y)\big)$
- ◯ $\text{Locked}(x,l,t) \implies \forall y\ \big(\text{Locked}(y,l,t) \implies (x \neq y)\big)$
- ◯ $\text{Locked}(x,l,t) \implies \exists y\ \big(\text{Locked}(y,l,t) \implies (x = y)\big)$
- ◯ $\text{Locked}(x,l,t) \implies \forall y\ \big(\text{Locked}(y,l,t) \implies (x = y)\big)$

Q5. [17 pts] Games: Five Nights at Wheeler

You and your friend Cam are being chased by Oski, a homework-eating bear. Oski has chased you and Cam inside Wheeler Hall. You decide that your homework is more important than Cam's homework and intend on getting Oski to eat Cam's homework instead of yours.

You choose to represent Wheeler Hall as a 3-dimensional $6 \times 4 \times 3$ grid, with stairs at each of the corners allowing agents to move up or down one floor (into the same corner on the new floor). Shaded squares represent walls, and squares with horizontal bars represent stairs. O is Oski, C is Cam, and Y is You.



At each time step, each agent can **either** move to any valid adjacent grid square **or** choose to stay in place. After choosing to stay in place, an agent can choose to continue moving on the next time step.

You choose to model the situation as a **depth-limited multi-agent game tree**. Similar to Project 2, each depth level corresponds to one action from You, followed by one action from Cam, followed by one action from Oski. The evaluation function is called on a state when the maximum depth is reached.

(a) [2 pts] Which of the following is a **valid and minimal** state representation for the specific grid shown above?

- ◯ Three boolean values for each grid square, representing whether that square has You, Cam, or Oski, respectively.
- ◯ An (x, y, z) integer tuple for each agent, representing the agent's position.
- ◯ An (x, y, z) integer tuple for Oski's position, and the Euclidean distance between You and Oski, and the Euclidean distance between Cam and Oski.
- ◯ An (x, y, z) integer tuple for your position only.
- ◯ None of the above.

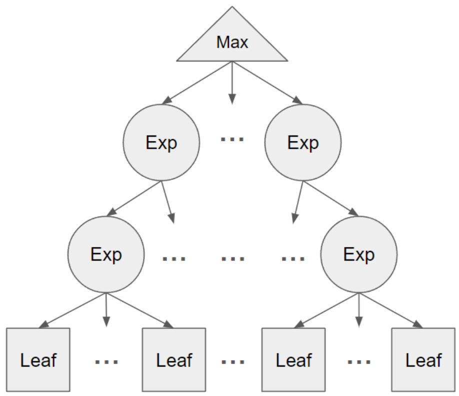
(b) [2 pts] For the specific grid shown above, what is the **maximum branching factor** of the game tree for **any** state (not necessarily the state shown)?

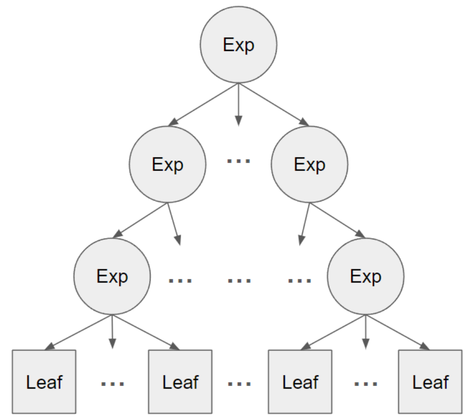
(c) [2 pts] Suppose your goal is to get Cam's homework eaten, Cam's goal is to avoid Oski, and Oski's goal is to eat either Cam's homework or your homework.

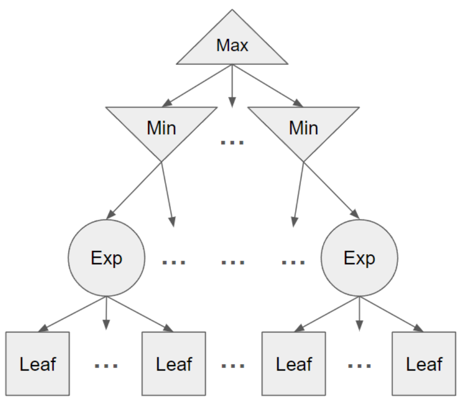
In this subpart, suppose all agents (You, Cam, and Oski) are playing optimally with respect to their own utility, and you know that Cam and Oski are playing optimally.

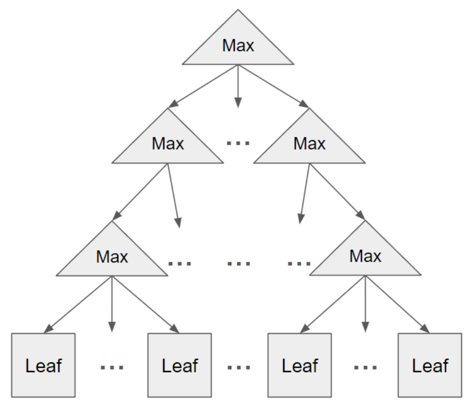
Which of the following game trees represents your model accurately with depth 1 and You as the root node?

Note: the ellipsis (...) represents omitted nodes in the tree.

○ 

○ 

○ 

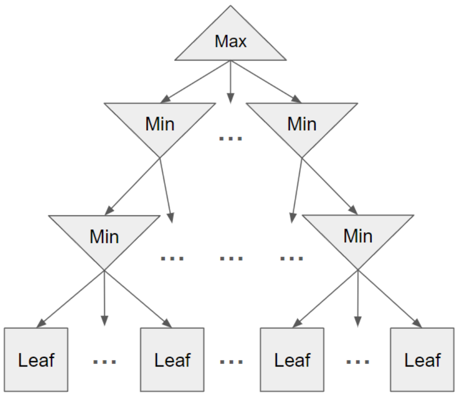
○ 

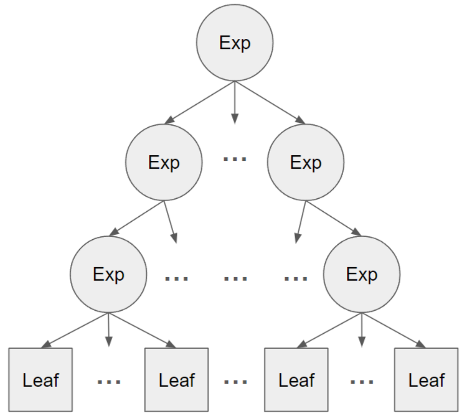
○ None of the above.

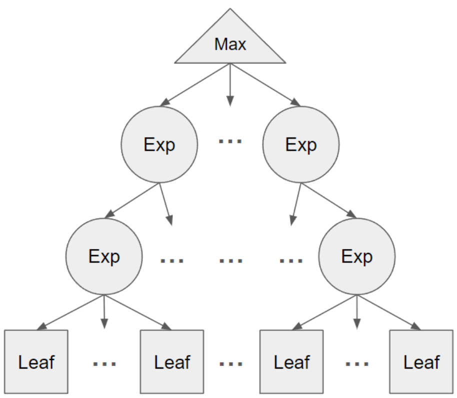
In the next two subparts, suppose Cam and Oski are selecting actions at random from some known distribution, and you know that Cam and Oski are doing this.

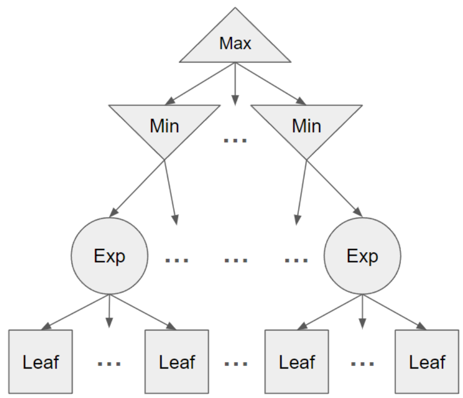
(d) [2 pts] Which of the following game trees represents your new model accurately with depth 1 and You as the root node?

Note: the ellipsis (...) represents omitted nodes in the tree.

○ 

○ 

○ 

○ 

○ None of the above.

(e) [4 pts] Write an expression representing what action you should take, according to the depth-1 game tree.

Notation:

- a_{oski}, a_{cam}, and a_{you} represent the actions available to Oski, Cam, and You, respectively.
- f_{oski}, f_{cam}, and f_{you} represent the evaluation functions used by Oski, Cam, and You, respectively.
- s' represents the successor state after taking action a from state s.

Fill in the blanks to write the expression:

$$\text{(i)}\left[\text{(ii)}\left[\text{(iii)}\left[\text{(iv)}\right]\right]\right]$$

Select one option from each column.

(i)	(ii)	(iii)	(iv)
○ $\text{argmax}_{a_{\text{you}}}$	○ $\mathbb{E}_{a_{\text{cam}}}$	○ $\mathbb{E}_{a_{\text{oski}}}$	○ $f_{\text{oski}}(s')$
○ $\max_{a_{\text{you}}}$	○ $\max_{a_{\text{cam}}}$	○ $\max_{a_{\text{oski}}}$	○ $f_{\text{you}}(s')$
○ $\mathbb{E}_{a_{\text{you}}}$	○ $\min_{a_{\text{cam}}}$	○ $\min_{a_{\text{oski}}}$	○ $f_{\text{cam}}(s')$
○ $\sum_{a_{\text{you}}}$	○ $\sum_{a_{\text{cam}}}$	○ $\sum_{a_{\text{oski}}}$	○ s'

The next two subparts are independent from the rest of the question.

(f) [3 pts] Consider a reflex agent who uses an evaluation function to compute a value for each successor state. However, instead of always moving to the successor state with the highest evaluation, we want the agent to probabilistically select a successor state to move to.

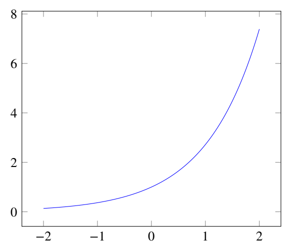
Notation:

- f is the evaluation function.
- s is the current state.
- s' is the successor state being considered.
- S' is the set of all successor states.

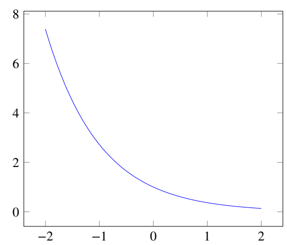
We want an expression for converting an evaluation score to a probability, satisfying the following two properties:

- The resulting probability distribution is **valid**, i.e. the probabilities of moving to the successor states must sum to 1.
- Successor states with **higher** evaluations must have a **higher** probability of being chosen.

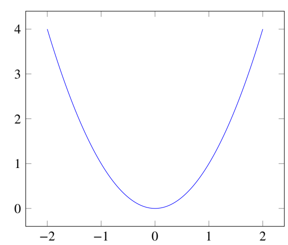
Here are some graphs to help you answer this question:



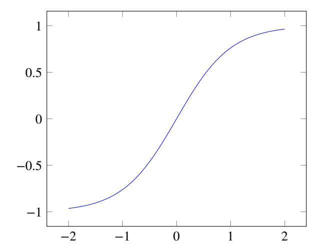
$y = \exp(x)$



$y = \exp(-x)$



$y = x^2$



$y = \tanh(x)$

Which of the following expressions satisfies the desired two properties? Select all that apply.

☐ $P(s'|s) = \dfrac{\exp(f(s'))}{\sum_{\tilde{s} \in S'} \exp(f(\tilde{s}))}$

☐ $P(s'|s) = \dfrac{\exp(-f(s'))}{\sum_{\tilde{s} \in S'} \exp(-f(\tilde{s}))}$

☐ $P(s'|s) = \dfrac{f(s')^2}{\sum_{\tilde{s} \in S'} f(\tilde{s})^2}$

☐ $P(s'|s) = \dfrac{\tanh(f(s'))+1}{\sum_{\tilde{s} \in S'} (\tanh(f(\tilde{s}))+1)}$

○ None of the above.

(g) [2 pts] Select all true statements about alpha-beta pruning in game trees.

☐ It is possible to prune an expectimax game tree with bounded utilities at the leaf nodes.

☐ It is possible to prune a game tree with three or more agents.

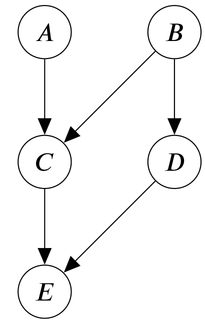
☐ It is always possible to prune a non-zero-sum game tree with three or more agents, all separately maximizing their own utility, as long as the tree contains both maximizer and minimizer nodes.

☐ It is only possible to prune a game tree if it contains both maximizer and minimizer nodes.

○ None of the above.

Q6. [18 pts] Bayes Nets: Easter Island Elections

Matei is an elf on Easter Island who is discontent with the current leadership of Pietru the Rotund. To model the island's politics in preparation for the Easter Elections, Matei has decided to use the following Bayes net.



Each letter represents a vote cast by members of the electoral college: Abby, Brad, Charles, Datsu, and Ershawn. For this question, $+v$ indicates that voter V votes in favor of Pietru the Rotund, while $-v$ indicates they have voted against. All voters must vote (in other words, A, B, C, D, E are binary variables).

Note (1): For the entire question, when computing the size of a factor or table, do not use the sum-to-one constraint to optimize rows out of the table. For example, if we had a table with the two values $P(+x) = 0.7$ and $P(-x) = 0.3$, this table has two rows (even though we could optimize and only store one of the rows, and derive the other row from the fact that both rows sum to 1).

Note (2): For the entire question, when computing the size of a factor or table, assume there is one row for each setting of the variables, i.e. one row for each probability value in the table. For example, if X and Y are binary variables, $P(X, Y)$ has four rows and $P(X|Y)$ also has four rows.

(a) [2 pts] Which of these probability tables can be found directly in the Bayes net, without performing any computation? Select all that apply.

☐ $P(A)$ ☐ $P(C \mid A, B)$ ☐ $P(E \mid C)$
☐ $P(B)$ ☐ $P(E)$

In the following subparts, Matei wants to compute the probability distribution $P(A \mid +e)$ using variable elimination.

(b) [2 pts] How many factors must Matei consider at the beginning of this process?

(c) [2 pts] Matei joins on B and eliminates B. Which variables are included in the new factor generated after eliminating B? Select all that apply.

For example, if you think the factor generated is $P(A, B, C)$ or $f(A, B, C)$, select options A, B, and C (and nothing else).

☐ A ☐ B ☐ C ☐ D ☐ $+e$

(d) [2 pts] Next, Matei joins on C and eliminates C. Which variables are included in the new factor generated after eliminating C? Select all that apply.

☐ A ☐ B ☐ C ☐ D ☐ $+e$

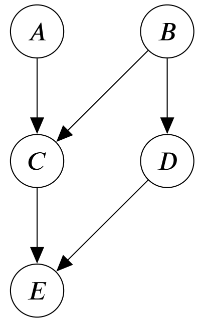
Following both of the above eliminations, we are left with 2 factors.

(e) [1 pt] Which variables are included in the **smaller** of the two remaining factors? Select all that apply.

☐ A ☐ B ☐ C ☐ D ☐ $+e$

(f) [1 pt] How many rows are in the **smaller** of the two remaining factors?

The Bayes Net, reproduced for your convenience:



(g) [1 pt] What is the **larger** of the two remaining factors?

- ◯ One of the original factors from subpart (b).
- ◯ The factor generated after eliminating B, in subpart (c).
- ◯ The factor generated after eliminating C, in subpart (d).
- ◯ None of the above.

(h) [1 pt] How many rows are in the **larger** of the two remaining factors?

(i) [2 pts] If Matei had instead decided to use inference by enumeration to compute $P(A|+e)$, how many rows would be in the joint probability table he generates?

Note: We are looking for the size of the table before any hidden variables are marginalized (eliminated).

Note: You can assume Matei deletes all rows inconsistent with the evidence. In other words, we are looking for the size of a table where all rows are consistent with the evidence.

◯ 2 ◯ 3 ◯ 16 ◯ 32

In the rest of the question, Matei now decides to use prior sampling to estimate the probability that Brad will vote in favor given that Ershawn has voted against, or $P(+b \mid -e)$. The samples he generates are in the table below:

Sample #	A	B	C	D	E
1	$+a$	$-b$	$+c$	$-d$	$-e$
2	$-a$	$+b$	$-c$	$+d$	$-e$
3	$+a$	$+b$	$+c$	$-d$	$+e$
4	$-a$	$-b$	$+c$	$-d$	$-e$
5	$+a$	$-b$	$-c$	$+d$	$+e$

(j) [2 pts] Using prior sampling, what is the estimated value of $P(+b \mid -e)$ that Matei computes?

◯ 1/3 ◯ 2/3 ◯ 1/4 ◯ 1/5

(k) [2 pts] Now, Matei generates two additional samples: $(+a, +b, -d, -c, +e)$ and $(-a, -b, +c, -d, -e)$

Using prior sampling, what is the new estimated value of $P(+b|-e)$ that Matei calculates?

◯ 2/7 ◯ 1/6 ◯ 3/5 ◯ 1/4