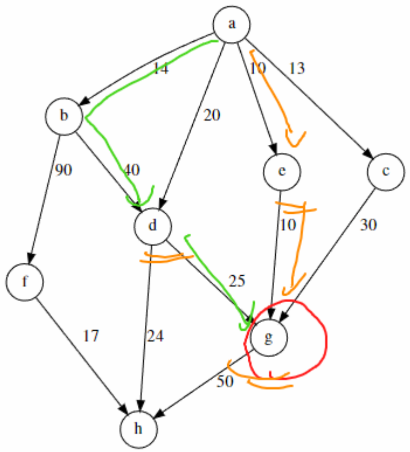
Problem 5 (Written; 10 pts): Consider iterative deepening search. When the goal is (g), how many nodes are visited before reaching that node?

2 Informed Search



Node	h(n)
a	22
b	22
c	10
d	23
e	14
f	16
g	10
h	0

$f(g)$?

$= g(g) + h(g)$

$= g(g) + 10$

$\parallel$

$14+40+25$

$10+10$

Figure 2: **Informed Search.**

Problem 6 (Written; 10 pts): For the problem shown in Fig. 2, show that the heuristic is admissible ($h(n) \le h^*(n)$ for all n). Note: You have to compute $h^*(n)$ for each n and compare to the $h(n)$ table.

Hint: It is best to work backwards from the goal, where $h^*(h) = 0$ (already at goal), $h^*(f) = 17$ (true minimum cost from (f) to (h)), $h^*(b) = 40 + 24 = 64$ (true minimum cost from (b) to (h): note that there are multiple paths and t[...]

Problem 7 (Written; 2[...] the graph below (Fig. 2), with initial node (a) and goal node (h). Actual cost from node to node are shown as edge la[...]

So depending on which pass you follow. So when when this was expanded, from which parents, this F value would be different.

Horn Clauses

(Q)

$\neg G$

pos literal =1

Horn clause ?

① Yes

② No

Horn clauses

- clauses that contain ≤ 1 **positive** literal:
  $F \vee \neg G \vee \neg H, \quad \neg F \vee G$

Horn Normal Form: conjunction of horn clauses

- for example, $(F \vee \neg G \vee \neg H) \wedge (\neg F \vee G)$
- it is the same as: $((G \wedge H) \rightarrow F) \wedge (F \rightarrow G)$
- Easier to do inference (computationally less intensive) than other normal forms.
- Restrictive, so not all formulas can be represented in horn normal form.

Horn Clauses

pos

G

P

H

$P \wedge Q \to R$

$P \wedge Q \wedge S \to R$

Horn clauses

- clauses that contain ≤ 1 **positive** literal:
  $F \vee \neg G \vee \neg H, \qquad \neg F \vee G$

(Q)

$\neg F \vee G \vee P$ 2 pos. lit.

Is this a Horn clause?

① Yes

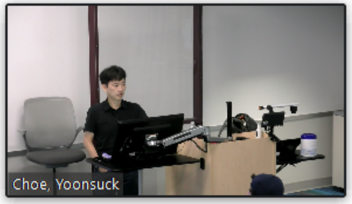
② No

Horn Normal Form: conjunction of horn clauses

- for example, $(F \vee \neg G \vee \neg H) \wedge (\neg F \vee G)$
- it is the same as: $((G \wedge H) \to F) \wedge (F \to G)$
- Easier to do inference (computationally less intensive) than other normal forms.
- Restrictive, so not all formulas can be represented in horn normal form.

$\neg(F \wedge \neg G) \vee P$

$F \wedge \neg G \to P$



Converting to Normal Forms

You can transform any formula into a normal form by applying the following rules:

1. Use the definitions:

   $F \leftrightarrow G = (F \rightarrow G) \wedge (G \rightarrow F)$

   $F \rightarrow G = \neg F \vee G$

   to eliminate $\rightarrow$ and $\leftrightarrow$

2. Repeatedly use the double negation law:

   $\neg(\neg F) = F$

   and the De Morgan's laws:

   $\neg(F \vee G) = \neg F \wedge \neg G$

   $\neg(F \wedge G) = \neg F \vee \neg G$

   to bring negation signs immediately before atoms.

3. Repeatedly use the distributive laws (forward and/or backward):

   $F \vee (G \wedge H) = (F \vee G) \wedge (F \vee H)$,

   $F \wedge (G \vee H) = (F \wedge G) \vee (F \wedge H)$

   and the other laws as necessary.

((2))

conj $\wedge$

① CNF?

② DNF ?

main connective!

Converting to Normal Forms

You can transform any formula into a normal form by applying the following rules:

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(Q)

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$\wedge$

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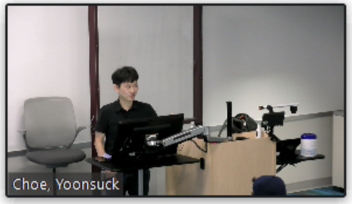

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   $F \wedge (G \vee H) = (F \wedge G) \vee (F \wedge H)$
   and the other laws as necessary.

$(F \vee G) \wedge (F \vee H) \xrightarrow{(Q)} \text{DNF}$?

$\equiv [(F \vee G) \wedge F] \vee [(F \vee G) \wedge H]$

$\equiv (F \wedge F) \vee (F \wedge G) \vee (F \wedge H) \vee (G \wedge H)$

Is that DNF?
(1) Yes
(2) No

(Q) Is $F \vee (G \wedge H)$ in DNF?
(1) Yes
(2) No

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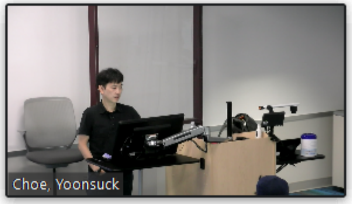

Exercise: Converting to Normal Forms

Convert the following into CNF and DNF:

$(P \vee \neg Q) \rightarrow R$

- DNF :

$$
\begin{aligned}
(P \vee \neg Q) \rightarrow R &= \neg(P \vee \neg Q) \vee R \text{ :remove } \rightarrow \\
&= (\neg P \wedge \neg(\neg Q)) \vee R \text{ :by De Morgan's Law} \\
&= (\neg P \wedge Q) \vee R \text{ :remove double negation}
\end{aligned}
$$

dnf → CNF.

- CNF : try it yourself (hint: use the distributive law on the result above)

Another exercise: find the CNF of $(P \wedge (Q \rightarrow R)) \rightarrow S)$

(Q)

$P \vee Q$

Is this

① DNF (∨)

② CNF (∨)

$(P \vee Q)$

single clause

But if you think of it as P or q as a unit then it's a single close, so it's also Cnf

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Choe, Yoonsuck

(Q)

$P \vee Q$

Is this

① DNF (V)

② CNF (V)

$(P \vee Q)$

single clause

Exercise: Converting to Normal Forms

Convert the following into CNF and DNF:

$(P \vee \neg Q) \to R$

- DNF :

$$(P \vee \neg Q) \to R \quad = \quad \neg(P \vee \neg Q) \vee R \text{ :remove } \to$$
$$= \quad (\neg P \wedge \neg(\neg Q)) \vee R \text{ :by De Morgan's Law}$$
$$= \quad (\neg P \wedge Q) \vee R \text{ :remove double negation}$$

DNF → CNF.

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But if you think of it as P or q as a unit then it's a single close, so it's also Cnf it's a it's both in dnf and cnn

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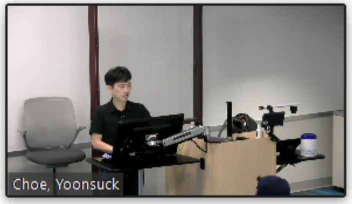

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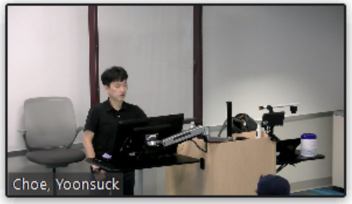
Another exercise: find the CNF of $(P \wedge (Q \rightarrow R)) \rightarrow S)$



Logical Consequence

$P \vee Q$

$\neg P \vee R$

$\neg P \to (Q \vee R)$

G is a **logical consequence** of formulas $F_1, F_2, \ldots, F_n$ iff for any interpretation I for which $F_1 \wedge F_2 \wedge \ldots \wedge F_n$ is true, G is also true (i.e. $(F_1 \wedge F_2 \wedge \ldots \wedge F_n) \to G$ is **valid**).

premises

c.f. Modus Ponens $\dfrac{F, F \to G}{G}$

- $(F_1 \wedge F_2 \wedge \ldots \wedge F_n) \to G$ is called a **theorem**.
- $F_1, F_2, \ldots, F_n$ are called **axioms (postulates, premises)** of G
- G is called the **conclusion**.

$\neg P \vee (R \to Q)$

P	Q	R	$(F_1 \wedge F_2 \wedge \cdots \wedge F_n) \to G$
T	T	T	T
T	T	F	T
T	F	T	T
T	F	F	T
⋮	⋮	⋮	

"a" is the first element of this list that gets taken out for inspection, and the rest are ordered from left to right.
That is, `Get-First-Node([a, b, c, d ...])  = a`.

* Note: Depth is 0 at the root, and increases by 1 as you follow the edge downward. That is, depth equals the number of operator you executed to reach the current level.

1 Uninformed Search

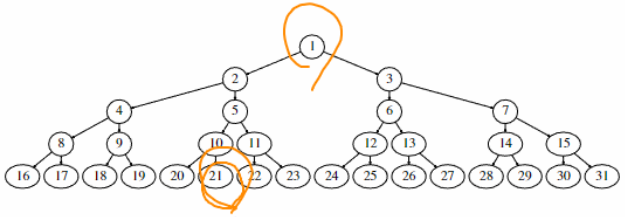


Figure 1: **Search Trees.**

Consider the search tree in Fig. 1. Assume that the exploration of the children of a particular node proceeds from the left to the right for all search methods in this section.

Problem 1 (Written; 5 pts): Consider depth first search. When the goal is 21 and the node is reached (taken out of node list), (1) what are the nodes that remain in the node list? (list them in the correct order). Also (2) which nodes have been visited until then, in what order?

Problem 2 (Written; 5 pts): Consider breadth first search. When the goal is 13 and the node is reached (taken out of node list), (1) what are the nodes that remain in the node list? (list them in the correct order). Also (2) which nodes have been visited until then, in what order?

Problem 3 (Written; 5 pts): Why is the space complexity of BFS $O(b^{d+1})$, not $O(b^d)$, where b is the branching factor and d is the goal depth?

Problem 4 (Written; 5 pts): Can depth limited search become incomplete in the case of the finite search tree above? If so, give an example (use Figure 1). If not, explain why not (use Figure 1).

Logical Consequence

$P \vee Q$

$\neg P \vee R$

$\therefore \neg P \to (Q \vee R)$

G is a **logical consequence** of formulas $F_1, F_2, \ldots, F_n$ iff for any interpretation I for which $F_1 \wedge F_2 \wedge \ldots \wedge F_n$ is true, G is also true (i.e. $(F_1 \wedge F_2 \wedge \ldots \wedge F_n) \to G$ is **valid**).

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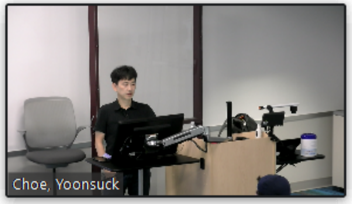
$\neg P \vee (R \to Q)$

P	Q	R	$(F_1 \wedge F_2 \wedge \cdots \wedge F_n) \to G$
T	T	T	T
T	T	F	T
T	F	T	T
T	F	F	T
⋮	⋮	⋮	



Logical Consequence

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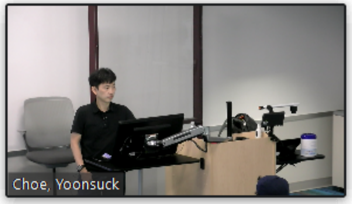
- G is called the **conclusion**.

KB

facts

P

Logical Consequence



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- $F_1, F_2, ..., F_n$ are called **axioms (postulates, premises)** of G
- G is called the **conclusion**.

KB

F_1

F_2

F_n

$\neg\alpha$

$\neg P \rightarrow R$

Goal

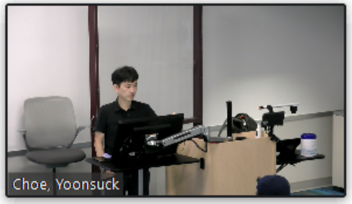
Query: G

rules

Inference engine

True / False

And then this conclusion, or sometimes called the goal and then say yeah, it's true or false



KB

P

facts

Logical Consequence

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c.f. Modus Ponens $\dfrac{F, F \rightarrow G}{G}$

KB

F_1

F_2

$\neg\alpha$

F_n

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- $F_1, F_2, \ldots, F_n$ are called **axioms (postulates, premises)** of G
- G is called the **conclusion**.

Goal

$\neg P \rightarrow R$

Query: G

rules

Inference engine

True / False

Any questions? Okay.

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Choe, Yoonsuck

Valid vs. Inconsistent

Theorem: G is a logical consequence of $F_1, F_2, ..., F_n$ iff the formula $F_1 \wedge F_2 \wedge ... \wedge F_n \wedge \neg G$ is **inconsistent**

Proof: G is a logical consequence of $F_1, F_2, ..., F_n$ iff $(F_1 \wedge F_2 \wedge ... \wedge F_n) \rightarrow G$ (lets call this H) is valid. Since H is valid iff $\neg H$ is inconsistent, H is valid iff $\neg((F_1 \wedge F_2 \wedge ... \wedge F_n) \rightarrow G)$ is inconsistent. Because

want this to be valid ?

$$
\begin{aligned}
& \neg((F_1 \wedge F_2 \wedge ... \wedge F_n) \rightarrow G) \\
= \quad & \neg(\neg(F_1 \wedge F_2 \wedge ... \wedge F_n) \vee G) \\
= \quad & (\neg(\neg(F_1 \wedge F_2 \wedge ... \wedge F_n))) \wedge \neg G \\
= \quad & (F_1 \wedge F_2 \wedge ... \wedge F_n) \wedge \neg G,
\end{aligned}
$$

P Q R	$F_1 \wedge F_2 \cdots F_n \rightarrow G$
	T
	T
	T
	T
	T

P Q R	$\neg(F_1 \wedge F_2 \wedge \cdots F_n \rightarrow G)$
	F
	F
	F
	⋮
	F

H is valid iff $F_1 \wedge F_2 \wedge ... \wedge F_n \wedge \neg G$ is **inconsistent**.

VALID

INCONSISTENT.

Hey? So now we establish that that possible

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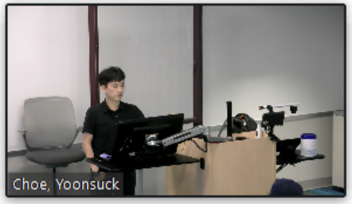

$\neg(F_1 \wedge F_2 \wedge \cdots F_n \to G)$

Valid vs. Inconsistent

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= \quad & (F_1 \wedge F_2 \wedge \ldots \wedge F_n) \wedge \neg G,
\end{aligned}
$$

P Q R	$F_1 \wedge F_2 \cdots F_n \to G$
	T
	T
	T
	T
	T

VALID

P Q R	$\neg(F_1 \wedge F_2 \wedge \cdot F_n \to G)$
	F
	F
	F
	⋮
	F

INCONSISTENT.

H is valid iff $F_1 \wedge F_2 \wedge \ldots \wedge F_n \wedge \neg G$ is **inconsistent**.

So you just what what you do is you just find you just use the demons no, and so on to reduce this so simple

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Valid vs. Inconsistent

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Theorem.

$$
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= \quad & (F_1 \wedge F_2 \wedge \ldots \wedge F_n) \wedge \neg G,
\end{aligned}
$$

implication

H is valid iff $F_1 \wedge F_2 \wedge \ldots \wedge F_n \wedge \neg G$ is **inconsistent**.

Valid vs. Inconsistent

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valid

Theorem.

$$
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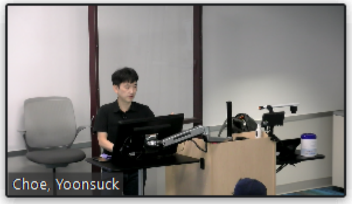
= \quad & (F_1 \wedge F_2 \wedge \ldots \wedge F_n) \wedge \neg G,
\end{aligned}
$$

implication

De Morgan's

H is valid iff $F_1 \wedge F_2 \wedge \ldots \wedge F_n \wedge \neg G$ is **inconsistent**.

And when this file result is inconsistent, then you are proven that the original formula here is valid



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valid

Theorem.

$$
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implication

De Morgan's

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Caveats

KB

$F_1 \cdots p$

$F \cdots \neg p$

F_n

Anything is a logical consequence of $\textbf{False}$ (recall that G is a logical consequence of F iff $F \rightarrow G$ is valid).

False

KB

False

$F_1 \wedge F_2 \wedge F_3 \wedge \cdots F_n \wedge \neg G$

False

False

$$
\begin{aligned}
F \rightarrow G &= \textbf{False} \rightarrow G \\
&= \neg\textbf{False} \vee G \\
&= \boxed{\textbf{True} \vee G} \\
&= \textbf{True}
\end{aligned}
\qquad (1)
$$

VALID

Thus, for a result of a theorem to be meaningful, the premises should be **consistent**.

Well, so this way, you showed that Oops that did this is valid, or you can show, that is, the negation of this is invalid

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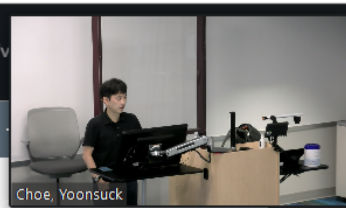


1 Uninformed Search

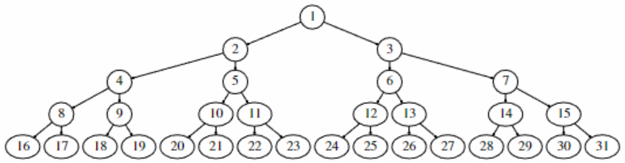


Figure 1: **Search Trees.**

Consider the search tree in Fig. 1. Assume that the exploration of the children of a particular node proceeds from the left to the right for all search methods in this section.

Problem 1 (Written; 5 pts): Consider depth first search. When the goal is 21 and the node is reached (taken out of node list), (1) what are the nodes that remain in the node list? (list them in the correct order). Also (2) which nodes have been visited until then, in what order?

Problem 2 (Written; 5 pts): Consider breadth first search. When the goal is 13 and the node is reached (taken out of node list), (1) what are the nodes that remain in the node list? (list them in the correct order). Also (2) which nodes have been visited until then, in what order?

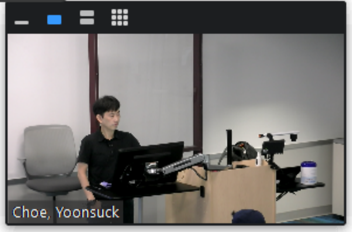
Problem 3 (Written; 5 pts): Why is the space complexity of BFS $O(b^{d+1})$, not $O(b^d)$, where b is the branching factor and d is the goal depth?

Problem 4 (Written; 5 pts): Can depth limited search become incomplete in the case of the finite search tree above? If so, give an example (use Figure 1). If not, explain why not (use Figure 1).

Logical Consequence: Proving

Model checking (truth table, search), or algebraic application of inference rules:

1. Truth table: the conclusion G must be true whenever the premises $F_1 \wedge F_2 \wedge \ldots \wedge F_n$ is true.
2. Prove that $(F_1 \wedge F_2 \wedge \ldots \wedge F_n) \rightarrow G$ is **valid**:
   - truth table, or
   - algebraically reduce the formula to $\mathbf{True}$
3. Prove that $F_1 \wedge F_2 \wedge \ldots \wedge F_n \wedge \neg G$ is **inconsistent**:
   - truth table, or
   - algebraically reduce the formula to $\mathbf{False}$



Logical Consequence: Proving

Model checking (truth table, search), or algebraic application of inference rules:

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2. Prove that $(F_1 \wedge F_2 \wedge \ldots \wedge F_n) \rightarrow G$ is **valid**:
   - truth table, or
   - algebraically reduce the formula to $\mathbf{True}$
3. Prove that $F_1 \wedge F_2 \wedge \ldots \wedge F_n \wedge \neg G$ is **inconsistent**:
   - truth table, or
   - algebraically reduce the formula to $\mathbf{False}$

easier

Logical Consequence: Proving

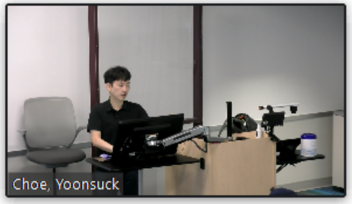
Model checking (truth table, search), or algebraic application of inference rules:

1. Truth table: the conclusion G must be true whenever the premises $F_1 \wedge F_2 \wedge \ldots \wedge F_n$ is true.
2. Prove that $(F_1 \wedge F_2 \wedge \ldots \wedge F_n) \rightarrow G$ is **valid**:
   ¬
   - truth table, or
   - algebraically reduce the formula to **True**

easier

3. Prove that $F_1 \wedge F_2 \wedge \ldots \wedge F_n \wedge \neg G$ is **inconsistent**:
   False
   - truth table, or
   - algebraically reduce the formula to **False**

Then something transfers. Then the interesting collapse is the false



Theorem Proving

Given a set of facts (*ground literals*) and a set of rules, a desired theorem can be proved in several different ways:

- **Forward Chaining**: use known facts and rules to discover (or deduce) new facts. When the desired theorem is deduced, stop.
- **Backward Chaining**: work backward from the theorem by finding rules that could deduce it; then try to deduce the premises of those rules.
- **Resolution**: proof by contradiction. Using ground facts, rules, and the **negation** of the theorem, try to derive $\mathbf{False}$ by resolution steps. To prove $F \rightarrow G$ is valid, prove $F \wedge \neg G$ (i.e. $\neg(F \rightarrow G)$) is inconsistent.

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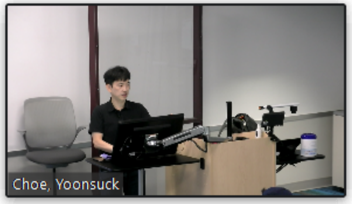

Theorem Proving: Example

Given that the following are all **True**, KB

$$A \quad (1)$$

$$B \quad (2)$$

$$D \quad (3)$$

Facts

$$A \wedge B \rightarrow C \quad (4)$$

$$C \wedge D \rightarrow E \quad (5)$$

Rules

Prove that E is valid. Let's consider forward chaining and backward chaining.

So let's just try looking at 4 change

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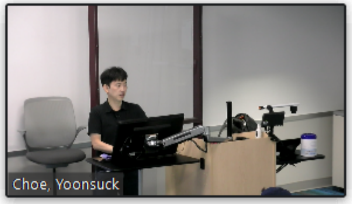


Forward Chaining

Given that the following are all $\mathbf{True}$,

$$\begin{array}{lr} A & (1) \\ B & (2) \\ D & (3) \\ A \wedge B \rightarrow C & (4) \\ C \wedge D \rightarrow E & (5) \end{array}$$

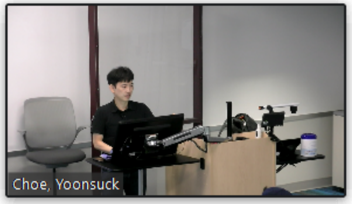
$(4) \rightarrow C$

$(5) \rightarrow E$

add $\rightarrow C$

add E

Since we know that A and B are true (1 and 2), C is also true (from 4). Let's call this (6), i.e. $C = \mathbf{True}$. From this, and the fact that D is true, we come to the conclusion that E is true (3, 5, and 6).



Forward Chaining

Given that the following are all $\mathbf{True}$,

$$
\begin{array}{lr}
A & (1) \\
B & (2) \\
D & (3) \\
A \land B \rightarrow C & (4) \\
C \land D \rightarrow E & (5)
\end{array}
$$

C

E

add C

add E

Since we know that A and B are true (1 and 2), C is also true (from 4). Let's call this (6), i.e. $C = \mathbf{True}$. From this, and the fact that D is true, we come to the conclusion that E is true (3, 5, and 6).

Backward Chaining

Given that the following are all $\mathbf{True}$,

$$A \quad (1)$$

$$B \quad (2)$$

$$D \quad (3)$$

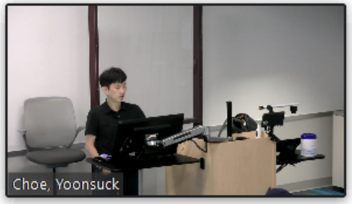
$$A \wedge B \rightarrow C \quad (4)$$

$$C \wedge D \rightarrow E \quad (5)$$

need C
need D

Find a rule where E is deduced (5). For this rule to be true when E is true, C and D must be true. Since $D = \mathbf{True}$ is given (3), we only need to show that C is true. Find a rule where C is deduced (4), and repeat the same process until all premises are deduced.

*** this strategy is ideal for Horn Normal Form.**



Backward Chaining

Given that the following are all $\mathbf{True}$,

$$A \qquad (1)$$

$$B \qquad (2)$$

$$D \qquad (3)$$

$$A \wedge B \rightarrow C \qquad (4)$$

$$C \wedge D \rightarrow E \qquad (5)$$

need C

need D

Find a rule where E is deduced (5). For this rule to be true when E is true, C and D must be true. Since $D = \mathbf{True}$ is given (3), we only need to show that C is true. Find a rule where C is deduced (4), and repeat the same process until all premises are deduced.

*** this strategy is ideal for Horn Normal Form.**

Backward Chaining

Given that the following are all $\mathbf{True}$,

? Fact

$$\begin{aligned} &A && (1) \\ &B && (2) \\ &D && (3) \\ A \wedge B &\rightarrow C && (4) \\ C \wedge D &\rightarrow E && (5) \end{aligned}$$

? Rule E

Find a rule where E is deduced (5). For this rule to be true when E is true, C and D must be true. Since $D = \mathbf{True}$ is given (3), we only need to show that C is true. Find a rule where C is deduced (4), and repeat the same process until all premises are deduced.

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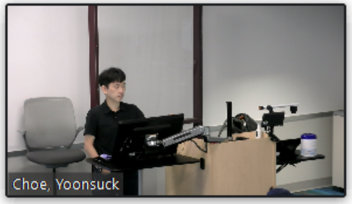
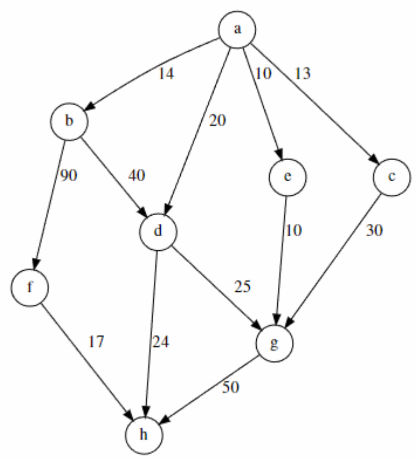


Problem 5 (Written; 10 pts): Consider iterative deepening search. When the goal is 9, how many nodes are visited before reaching that node?

Visit

G?

2 Informed Search



Node	h(n)
a	22
b	22
c	10
d	23
e	14
f	16
g	10
h	0

Figure 2: **Informed Search.**

Problem 6 (Written; 10 pts): For the problem shown in Fig. 2, show that the heuristic is admissible ($h(n) \le h^*(n)$ for all n). Note: You have to compute $h^*(n)$ for each n and compare to the $h(n)$ table.

Hint: It is best to work backwards from the goal, where $h^*(h) = 0$ (already at goal).

So how many times did you take take something out so that counts as

Backward Chaining

Given that the following are all $\mathbf{True}$,

$$A \qquad (1)$$

$$B \qquad (2)$$

$$D \qquad (3)$$

$$A \land B \rightarrow C \qquad (4)$$

$$C \land D \rightarrow E \qquad (5)$$

$\neg (C \land D) \lor E$

$\neg C \lor \neg D \lor E$

Horn Clause.

Find a rule where E is deduced (5). For this rule to be true when E is true, C and D must be true. Since $D = \mathbf{True}$ is given (3), we only need to show that C is true. Find a rule where C is deduced (4), and repeat the same process until all premises are deduced.

*** this strategy is ideal for Horn Normal Form.**

Modus Ponens

$$\frac{P \to Q, \quad P}{Q}$$

Unit Resolution

$$\frac{P \vee \neg Q, \quad Q}{P}$$

Resolution

$$\frac{P \vee \neg Q \quad Q \vee R}{P \vee R}$$

Resolution: An Overview

Given formulas in conjunctive normal form $F = F_1 \wedge F_2 \wedge \ldots \wedge F_n$, where each F_i is a **clause (i.e. disjunctions of literals)**, and the desired conclusion G, to show G is a logical consequence of F, follow these steps:

1. negate G and add it to the list of clauses (make it into CNF if necessary):
   $F_1, F_2, \ldots, F_n, \neg G$
2. choose two clauses that have **exactly one** pair of literals that are complementary, e.g.:
   $F_n : \underline{\neg P} \vee Q \vee R$ and $F_m : S \vee \underline{P}$
3. Produce a new clause by deleting the complimentary pair and producing a new formula, e.g.:
   $Q \vee R \vee S$
4. repeat until the new clause generated is **False**

This assumes that the premises are consistent.

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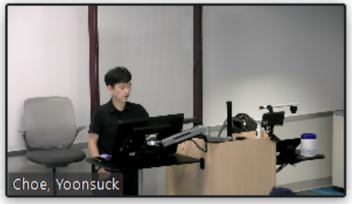

KB

$(P \vee \neg Q) \to (S \wedge R)$

F_1 C_1 C_2 F_2 F_j F_n

Resolution: An Overview

Given formulas in conjunctive normal form $F = F_1 \wedge F_2 \wedge \ldots \wedge F_n$, where each F_i is a **clause (i.e. disjunctions of literals)**, and the desired conclusion G, to show G is a logical consequence of F, follow these steps:

1. negate G and add it to the list of clauses (make it into CNF if necessary):
   $F_1, F_2, \ldots, F_n, \neg G$
2. choose two clauses that have **exactly one** pair of literals that are complementary, e.g.:
   $F_n : \underline{\neg P} \vee Q \vee R$ and $F_m : S \vee \underline{P}$
3. Produce a new clause by deleting the complimentary pair and producing a new formula, e.g.:
   $Q \vee R \vee S$
4. repeat until the new clause generated is **False**

This assumes that the premises are consistent.

KB in CNF

$\neg G$

KB

F_1 C_1 C_2 F_n C_3 F_j C_4 C_5 C_6

And the added here, But you also have to turn this into Cnf

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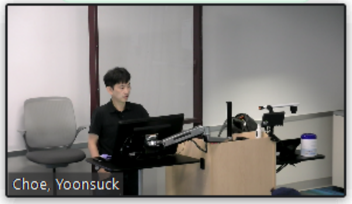

KB

$(P \vee \neg Q) \to (S \wedge R)$

Resolution: An Overview

Given formulas in conjunctive normal form $F = F_1 \wedge F_2 \wedge \ldots \wedge F_n$, where each F_i is a **clause (i.e. disjunctions of literals)**, and the desired conclusion G, to show G is a logical consequence of F, follow these steps:

1. negate G and add it to the list of clauses (make it into CNF if necessary):
   $F_1, F_2, \ldots, F_n, \neg G$
2. choose two clauses that have **exactly one** pair of literals that are complementary, e.g.:
   $F_n : \underline{\neg P} \vee Q \vee R$ and $F_m : S \vee \underline{P}$
3. Produce a new clause by deleting the complimentary pair and producing a new formula, e.g.:
   $Q \vee R \vee S$
4. repeat until the new clause generated is **False**

This assumes that the premises are consistent.

F_1 C_1 F_2 C_2 F_n

KB

F_1 C_1 C_2 F_n C_3 F_j C_4 C_5 C_6

KB in CNF

$\neg G$

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Resolution: An Overview

$(P \vee \neg Q) \rightarrow (S \wedge R)$

Given formulas in conjunctive normal form $F = F_1 \wedge F_2 \wedge \ldots \wedge F_n$, where each F_i is a **clause (i.e. disjunctions of literals)**, and the desired conclusion G, to show G is a logical consequence of F, follow these steps:

KB in CNF

1. negate G and add it to the list of clauses (make it into CNF if necessary):

   $F_1, F_2, \ldots, F_n, \neg G$

2. choose two clauses that have **exactly one** pair of literals that are complementary, e.g.:

   $F_n : \underline{\neg P} \vee Q \vee R$ and $F_m : S \vee \underline{P}$

3. Produce a new clause by deleting the complimentary pair and producing a new formula, e.g.:

   $Q \vee R \vee S$

4. repeat until the new clause generated is **False**

This assumes that the premises are consistent.

$P \vee Q \vee \neg R$, $\neg P \vee S$

$Q \vee \neg R \vee S$

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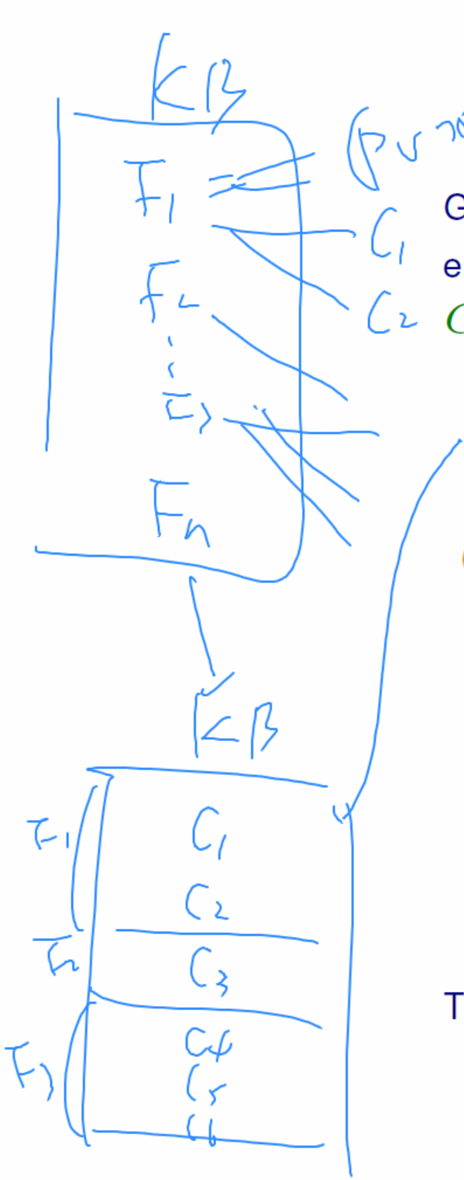
And then. Now you keep a repeat

Resolution: An Overview



Given formulas in conjunctive normal form $F = F_1 \wedge F_2 \wedge \ldots \wedge F_n$, where each F_i is a **clause (i.e. disjunctions of literals)**, and the desired conclusion G, to show G is a logical consequence of F, follow these steps:

1. negate G and add it to the list of clauses (make it into CNF if necessary):

   $F_1, F_2, \ldots, F_n, \neg G$

2. choose two clauses that have **exactly one** pair of literals that are complementary, e.g.:

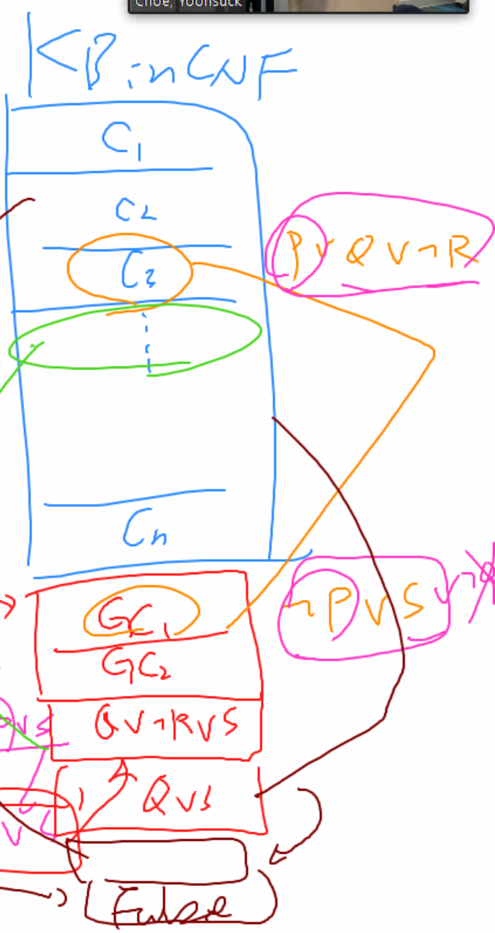
   $F_n : \underline{\neg P} \vee Q \vee R$ and $F_m : S \vee \underline{P}$

3. Produce a new clause by deleting the complimentary pair and producing a new formula, e.g.:

   $Q \vee R \vee S$

4. repeat until the new clause generated is **False**

This assumes that the premises are consistent.



Resolution: An Overview

Given formulas in conjunctive normal form $F = F_1 \wedge F_2 \wedge \ldots \wedge F_n$, where each F_i is a **clause (i.e. disjunctions of literals)**, and the desired conclusion G, to show G is a logical consequence of F, follow these steps:

1. negate G and add it to the list of clauses (make it into CNF if necessary):

   $F_1, F_2, \ldots, F_n, \neg G$

2. choose two clauses that have **exactly one** pair of literals that are complementary, e.g.:

   $F_n : \underline{\neg P} \vee Q \vee R$ and $F_m : S \vee \underline{P}$

3. Produce a new clause by deleting the complimentary pair and producing a new formula, e.g.:

   $Q \vee R \vee S$

4. repeat until the new clause generated is **False**

This assumes that the premises are consistent.

KB

C_1
C_2
$\vdots$
C_n
GC_1
GC_2

$C_1 \wedge C_2 \wedge \cdots C_n \wedge GC_1 \wedge GC_2 \wedge C_{n+1} \cdots \wedge C_{n+m} \wedge$

False.

$= \text{False}$

$C_1 \wedge C_2 \wedge \cdots \wedge C_n \wedge GC_1 \wedge GC_2 \wedge C_{n+1} \wedge C_{n+2} \wedge C_{n+3}$

KB G

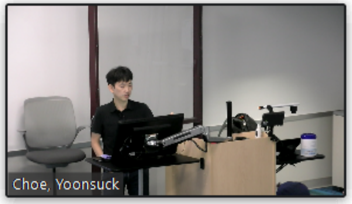
$\cdots \wedge C_{n+m} =$

based on resolution

False.

$C_1 \wedge C_2 \wedge \cdots \wedge C_n \wedge GC_1 \wedge GC_2 \wedge C_{n+1} = \wedge C_{n+2}$

False



Resolution: An Example

KB

$$
\begin{array}{llr}
C_1 & A & (1) \\
C_2 & B & (2) \\
C_3 & D & (3) \\
C_4 & \neg A \vee \neg B \vee C & (4) \\
C_5 & \neg C \vee \neg D \vee E & (5)
\end{array}
$$

Given the above, we want to prove that E is true. We simply add the negation of the desired conclusion, and try to draw a contradiction:

Gcl : E

$$G \quad \boxed{\neg E \quad (6)} \longrightarrow \neg G : \neg(\neg E) = E \qquad (2)$$

Resolution: An Example

KB

C_1	A	(1)
C_2	B	(2)
C_3	D	(3)
C_4	$\neg A \vee \neg B \vee C$	(4)
C_5	$\neg C \vee \neg D \vee E$	(5)

$\neg A \vee C$

Given the above, we want to prove that E is true. We simply add the negation of the desired conclusion, and try to draw a contradiction:

G_C: E

G $\boxed{\neg E \quad (6)}$ $\rightarrow$ $\neg G$: $\neg(\neg E) = E$

(2)

Resolution: Solution

KB

Given		
A		(1)
B		(2)
D		(3)
$\neg A \vee \neg B \vee C$		(4)
$\neg C \vee \neg D \vee E$		(5)
$\neg E$ (negated goal clause)		(6)

$\neg G$

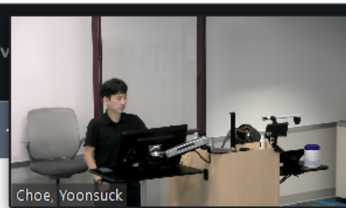
$\Longrightarrow$

Resolution		
(1,4)	$\neg B \vee C$	(7)
(2,7)	C	(8)
(5,6)	$\neg C \vee \neg D$	(9)
(8,9)	$\neg D$	(10)
(3,10)	**False**	(11)

B

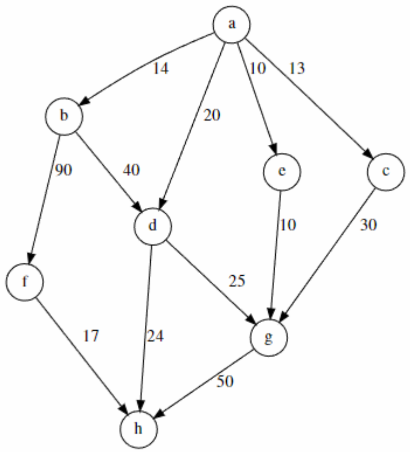
$\neg \cancel{B} \vee C$

$C_1 \wedge C_2 \wedge C_3 \wedge C_4 \wedge C_5 \wedge C_6 \wedge C_7 \wedge C_8$



Problem 5 (Written; 10 pts): Consider iterative deepening search. When the goal is 9, how many nodes are visited before reaching that node?

2 Informed Search



Node	h(n)
a	22
b	22
c	10
d	23
e	14
f	16
g	10
h	0

Figure 2: **Informed Search.**

Problem 6 (Written; ... heuristic is admissible ($h(n) \leq h^*(n)$ for all n) ... to the $h(n)$ table.

So the 3 visit just have to add all of these altogether because that's how many times you took the node out of the new list as part of that

1
1.
+
3
+

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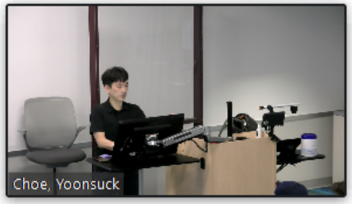

Resolution: Solution

Given	
A	(1)
B	(2)
D	(3)
$\neg A \vee \neg B \vee C$	(4)
$\neg C \vee \neg D \vee E$	(5)
$\neg E$ (negated goal clause)	(6)

Resolution		
(1,4)	$\neg B \vee C$	(7)
(2,7)	C	(8)
(5,6)	$\neg C \vee \neg D$	(9)
(8,9)	$\neg D$	(10)
(3,10)	**False**	(11)

$$\underbrace{\overbrace{C_1 \wedge C_2 \cdots \wedge C_6}^{1 \le B}}\ \Big|\ \underbrace{\wedge C_7 \wedge C_8 \wedge C_9 \wedge C_{10} \wedge \text{False}} = \text{False}$$

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...h is false, then this will formula here would now become false.

Resolution: Solution

Given	
A	(1)
B	(2)
D	(3)
$\neg A \vee \neg B \vee C$	(4)
$\neg C \vee \neg D \vee E$	(5)
$\neg E$ (negated goal clause)	(6)

Resolution		
(1,4)	$\neg B \vee C$	(7)
(2,7)	C	(8)
(5,6)	$\neg C \vee \neg D$	(9)
(8,9)	$\neg D$	(10)
(3,10)	**False**	(11)

$C_1 \wedge C_2 \cdots \wedge C_6 \wedge C_7 \wedge C_8 \wedge C_9 \wedge C_{10} \wedge False = False$

Resolution: Solution

Given	
A	(1)
B	(2)
D	(3)
$\neg A \vee \neg B \vee C$	(4)
$\neg C \vee \neg D \vee E$	(5)
$\neg E$ (negated goal clause)	(6)

Resolution		
(1,4)	$\neg B \vee C$	(7)
(2,7)	C	(8)
(5,6)	$\neg C \vee \neg D$	(9)
(8,9)	$\neg D$	(10)
(3,10)	**False**	(11)

that

This is a logical consequence of

KB

$C_1 \wedge C_2 \cdots \wedge C_6$ | $\wedge C_7 \wedge C_8 \wedge C_9 \wedge C_{10} \wedge \text{False} = \text{False}$

C_6

V

Resolution: Why Does It Work

The goal of resolution is to show that G is a logical consequence of $F_1 \wedge ... \wedge F_n$ is valid. This is equivalent to showing that $F_1 \wedge ... \wedge F_n \wedge \neg G$ is **inconsistent**.

Note that if H is a logical consequence of $F_1 \wedge ... \wedge F_n$, then $F_1 \wedge ... \wedge F_n = F_1 \wedge ... \wedge F_n \wedge H$.

When $F_1 \wedge ... \wedge F_n$ is

1. $\mathbf{True}$: then H must also be true.
2. $\mathbf{False}$: both sides are false, thus H does not matter.

Thus, we can add any logical consequence of $F_1 \wedge ... \wedge F_n$ or of **any subset** of the F_i's without changing the value of the result. Recall that we **added** newly derived formulas to the list in the previous slide.

What Resolution Is Not

If $C_1 \wedge C_2 \rightarrow H$

- **then** $C_1 \wedge C_2 \wedge H = C_1 \wedge C_2$
- **but not** $C_1 \wedge C_2 = H$

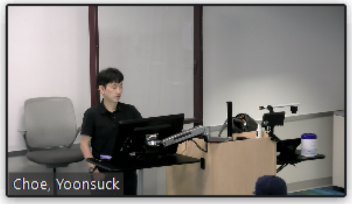
skip

In other words,

$(C_1 \wedge C_2 \rightarrow H) \rightarrow ((C_1 \wedge C_2 \wedge H) \leftrightarrow (C_1 \wedge C_2))$

$(C_1 \wedge C_2 \rightarrow H) \not\rightarrow ((C_1 \wedge C_2) \leftrightarrow H)$ **Exercise:** Verify the above with $C_1 = (A \vee B), C_2 = (\neg B \vee C)$, and $H = (A \vee C)$.

I'm not going to i'll i'll probably just skip this skip



KB

KB in CNF

CNF

Resolution Algorithm

1. Convert premises $F_1 \wedge \ldots \wedge F_n$ into **CNF**, and make a list of resulting clauses.
2. Negate the conclusion, convert to **CNF**, and add to the clause list.
3. **Resolution Step**: pick two clauses from the list with **exactly one** complementary literal; any other literals if they appear on both clauses **must** have the same sign. Form a new clause by disjunction w/o the complementary literals, and **add to the list**.

$$\underbrace{(P \vee C_i), (\neg P \vee C_j)}_{F_i \text{ and } F_j} \Rightarrow \underbrace{(C_i \vee C_j)}_{\text{Add to list}}$$

4. If **False** was added to the list of clauses, in step 3, stop; theorem proved. Otherwise, go to step 3.

$G \rightarrow \neg G$

And then you negate Conclusion, and then add it so that's t

KB

KB in CNF

CNF

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False

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False

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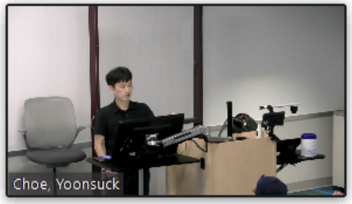


Tip: Negating Conclusion

If the conclusion is G: $P \vee R$, how many goal clauses are generated?

- Negate $P \vee R$
- then we get $\neg P \wedge \neg R$.
- We get **two** clauses, not one!:
  - negated goal clause 1: $\neg P$
  - negated goal clause 2: $\neg Q$
- That is, you need to add TWO lines.

$\neg G: \neg(P \vee R)$

$= \neg P \wedge \neg R$

(Q) Is this CNF?
① Yes
② No ?
③ maybe

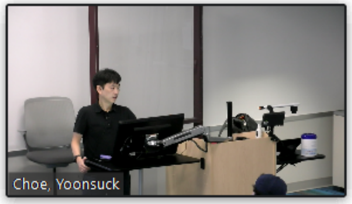
KB in CNF

$\wedge$
$\wedge$
$\wedge$
$\wedge$
$\neg P$
$\wedge$
$\neg R$

(Q) What are the clauses?

$\neg P$: C1
$\neg R$: C2

2 clauses



Tip: Negating Conclusion

① Negate G

If the conclusion is G: $P \vee R$, how many goal clauses are generated?

② Check if multiple clauses result

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KB in CNF

$\neg P$

$\neg R$

(Q) What are the clauses?

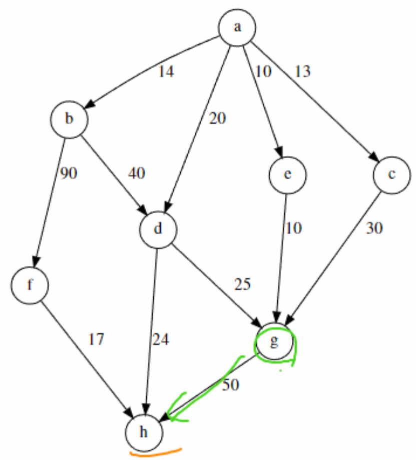
$\neg P$: C1

$\neg R$: C2

2 clauses

Problem 5 (Written; 10 pts): Consider iterative deepening search. When the goal is (g), how many nodes are visited before reaching that node?

2 Informed Search



Node	h(n)
a	22
b	22
c	10
d	23
e	14
f	16
g	10
h	0

$h(h) = 0$

$\wedge$|

$h^*(h) = 0$

$h(g) = 10$

$\wedge$|

$h^*(g) = 50$

Figure 2: **Informed Search.**

Problem 6 (Written; 10 pts): For the problem shown in Fig. 2, show that the heuristic is admissible ($h(n) \leq h^*(n)$ for all n). Note: You have to compute $h^*(n)$ for each n and compare to the $h(n)$ table.

Hint: It is best to work backwards from the goal, where $h^*(h) = 0$ (already at goal), $h^*(f) = 17$ (true minimum cost from (f) to (h)), $h^*(b) = 40 + 24 = 64$ (true minimum cost from (b) to (h): note that there are multiple paths and this path has the minimum cost!), etc.

Problem 7 (Written; 20 pts): Manually conduct greedy best-first search on the graph below (Fig. 2), with initial node (a) and goal node (h). Actual cost from node to node are shown as edge labels. The heuristic function value for each node is shown in a spearate table to the right. Show:

1. Node list content at each step
2. Node visit order

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$\neg$

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$= \neg P \wedge \neg R$

((1) Is this CNF?

① Yes

② No ?

③ maybe

(2) What are the clauses?

$\neg P$: C1

$\neg R$: C2

2 clauses

KB in CNF

$\wedge$

$\wedge$

$\wedge$

$\wedge$

$\neg P$

$\wedge$

$\neg R$

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And then to check if multiple closes results

Limitation of Propositional Logic

T/F

Limited expressive power:

property

- P: All men are mortal
- Q: Socrates is a man
- R: Socrates is mortal

property

Can you prove $(P \wedge Q) \rightarrow R$ using propositional logic?

$F_1: M \to I$

Exercise

Given:

If the unicorn is mythical, then it is immortal ($M \to I$), but if it is not mythical, then it is a mortal mammal ($\neg M \to (\neg I \wedge L)$). If the unicorn is either immortal or a mammal, then it is horned ($(I \vee L) \to H$). The unicorn is magical if it is horned ($H \to G$).

Prove or disprove:

1. The unicorn is mythical (M).
2. The unicorn is magical (G).
3. The unicorn is horned (H). $\longleftarrow$ Let's prove this.

https://aimacode.github.io/aima-exercises/knowledge-logic-exercises/ex_2/

Exercise

$M \to I$

$\neg M \to (\neg I \wedge L)$

$(I \vee L) \to H$

$H \to G$

$\neg H$

Given:

If the unicorn is mythical, then it is immortal($M \to I$), but if it is not mythical, then it is a mortal mammal ($\neg M \to (\neg I \wedge L)$). If the unicorn is either immortal or a mammal, then it is horned ($(I \vee L) \to H$). The unicorn is magical if it is horned ($H \to G$).

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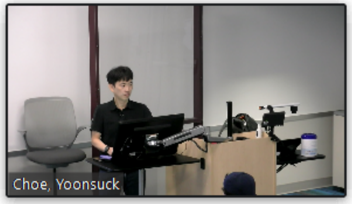


Exercise: Solution Using Resolution

$M \to I$

$\neg M \to (\neg I \wedge L)$

$(I \vee L) \to H$

$H \to G$

$\neg H$

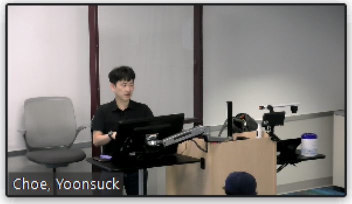
1. $\neg M \vee I$
2. (a) $M \vee \neg I$, (b) $M \vee L$
3. (a) $\neg I \vee H$, (b) $\neg L \vee H$
4. $\neg H \vee G$
5. $\neg H$ (negated conclusion)

3a,5	$\neg I$	(6)
3b,5	$\neg L$	(7)
2b,7	M	(8)
1,6	$\neg M$	(9)
8,9	**False**	(10)

$I \vee L$

$I \vee L$

You could follow different order, and then you can get



Exercise: Solution Using Resolution

1. $\neg M \vee I$ — Can you resolve?
2. (a) $M \vee \neg I$, (b) $M \vee L$
3. (a) $\neg I \vee H$, (b) $\neg L \vee H$
4. $\neg H \vee G$
5. $\neg H$ (negated conclusion)

No ✓

3a,5	$\neg I$	(6)
3b,5	$\neg L$	(7)
2b,7	M	(8)
1,6	$\neg M$	(9)
8,9	**False**	(10)

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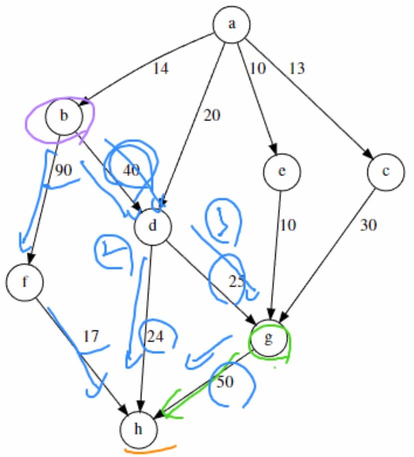
2 Informed Search



Node	h(n)
a	22
b	22
c	10
d	23
e	14
f	16
g	10
h	0

Figure 2: **Informed Search.**

$h(b) = 22$

$h^*(b) =$ min $50+17$, $40+24$, $40+25+50$

64

$h(h) = 0$

$h^*(h) = 0$

$h(g) = 10$

$h^*(g) = 50$

Problem 6 (Written; 10 pts): For the problem shown in Fig. 2, show that the heuristic is admissible ($h(n) \le h^*(n)$ for all n). Note: You have to compute $h^*(n)$ for each n and compare to the $h(n)$ table.

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1. Node list content at each step
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So this B is, also admissible

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Problem 5 (Written; 10 pts): Consider iterative deepening search. When the goal is (g), how many nodes are visited before reaching that node?

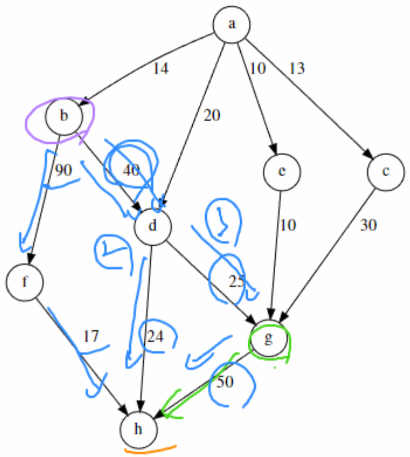
2 Informed Search

$h(b) = 22$

$\leq \min$

$h^*(b) = $ 50+17, 40+24, 40+25+50

64



Node	h(n)
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f	16
g	10
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$h(h) = 0$

$\leq$

$h^*(h) = 0$

$h(g) = 10$

$\leq$

$h^*(g) = 50$

Figure 2: **Informed Search.**

Problem 6 (Written; 10 pts): For the problem shown in Fig. 2, show that the heuristic is admissible ($h(n) \leq h^*(n)$ for all n). Note: You have to compute $h^*(n)$ for each n and compare to the $h(n)$ table.

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So this B is also admissible. You can repeat the the others

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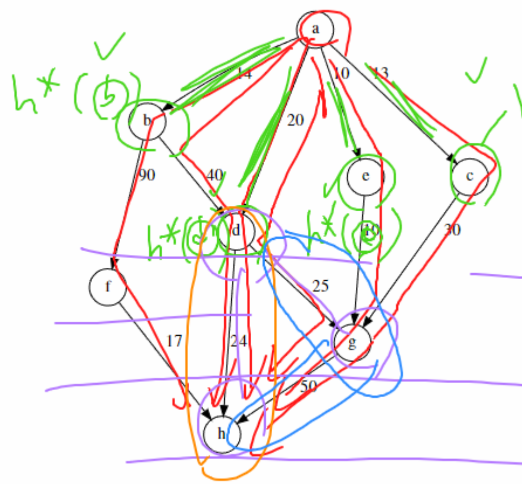
Problem 5 (Written; 10 pts): Consider iterative deepening search. When the goal is (g), how many nodes are visited before reaching that node?

2 Informed Search



Node	h(n)
a	22
b	22
c	10
d	23
e	14
f	16
g	10
h	0

$h^*(d) = \min(24 + h^*(h), 25 + h^*(g))$

$h^*(f)$

$h^*(g)$

$h^*(h)$

Figure 2: **Informed Search.**

Problem 6 (Written; 10 pts): For the problem shown in Fig. 2, show that the heuristic is admissible ($h(n) \leq h^*(n)$ for all n). Note: You have to compute $h^*(n)$ for each n and compare to the $h(n)$ table.

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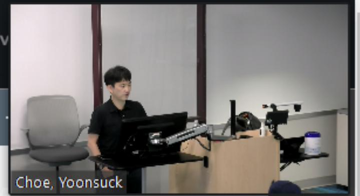

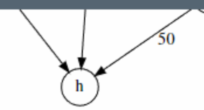

g	10
h	0

Figure 2: **Informed Search.**

Problem 6 (Written; 10 pts): For the problem shown in Fig. 2, show that the heuristic is admissible ($h(n) \leq h^*(n)$ for all n). Note: You have to compute $h^*(n)$ for each n and compare to the $h(n)$ table.

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Problem 7 (Written; 20 pts): Manually conduct greedy best-first search on the graph below (Fig. 2), with initial node a and goal node h. Actual cost from node to node are shown as edge labels. The heuristic function value for each node is shown in a spearate table to the right. Show:

1. Node list content at each step
2. Node visit order
3. Solution path
4. Cost of the final solution.

Problem 8 (Written; 20 pts): (1) Repeat the problem right above with A* search. (2) In addition, show the $f(n)$ value for all nodes expanded (you need this to sort them in the node list). (3)Which one gives a lower cost solution: Greedy best-first or A*?