University of Washington
Department of Computer Science and Engineering
CSE 311, Autumn 2013

October 31, 2013

Sample midterm questions

Instructions:

- Exam will consist of 5 to 8 questions.
- Closed book, closed notes, no cell phones, no calculators.
- Time limit: 50 minutes.
- Answer the problems on the exam paper.
- If you need extra space use the back of a page.
- Lists of equivalences and inference rules for your use are given on the final two pages.

Problem 1:

a) Show that the expression $(p \to q) \to (p \to r)$ is a contingency.

b) Give an expression that is logically equivalent to $(p \to q) \to (p \to r)$ using the logical operators $\neg$, $\vee$, and $\wedge$ (but not $\to$).

Solution:

a) Under the assignment $p = \mathbf{T}, q = \mathbf{T}, r = \mathbf{T}$, $(p \to q) \to (p \to r)$ evaluates to $\mathbf{T}$. but under the assignment $p = \mathbf{T}, q = \mathbf{T}, r = \mathbf{F}$, it evaluates to $\mathbf{F}$ (since $p \to q$ evaluates to $\mathbf{T}$ and $p \to r$ evaluates to $\mathbf{F}$). Therefore it is a contingency.
b) $\neg(\neg p \vee q) \vee (\neg p \vee r)$ and $(p \wedge \neg q) \vee \neg p \vee r$ are two natural choices here.

Problem 2:

Using the predicates:

$Likes(p, f)$: "Person p likes to eat the food f."
$Serves(r, f)$: "Restaurant r serves the food f."

translate the following statements into logical expressions.

a) Every restaurant serves a food that no one likes.

b) Every restaurant that serves TOFU also serves a food which RANDY does not like.

Solution:

a) $\forall r \exists f(Serves(r, f) \wedge \forall p \neg Likes(p, f))$ or
$\forall r \exists f \forall p(Serves(r, f) \wedge \neg Likes(p, f))$.

b) $\forall r(Serves(r, \text{TOFU}) \rightarrow \exists f(Serves(r, f) \wedge \neg Likes(\text{RANDY}, f))$ or
$\forall r \exists f(Serves(r, \text{TOFU}) \rightarrow (Serves(r, f) \wedge \neg Likes(\text{RANDY}, f))$.

Problem 3:

Use rules of inference to show that if the premises $\forall x(P(x) \rightarrow Q(x))$, $\forall x(Q(x) \rightarrow R(x))$, and $\neg R(a)$, where a is in the domain, are true, then the conclusion $\neg P(a)$ is true. (Note: You do not need to give the names for the rules of inference.)

Solution:

1. $\forall x(P(x) \rightarrow Q(x))$	Given
2. $\forall x(Q(x) \rightarrow R(x))$	Given
3. $\neg R(a)$	Given
4. $Q(a) \rightarrow R(a)$	Elim $\forall$ from 2
5. $\neg R(a) \rightarrow \neg Q(a)$	Contrapositive from 4
6. $\neg Q(a)$	Modus Ponens from 3 and 5
7. $P(a) \rightarrow Q(a)$	Elim $\forall$ from 1
8. $\neg Q(a) \rightarrow \neg P(a)$	Contrapositive from 7
9. $\neg P(a)$	Modus Ponens from 6 and 8

Problem 4:

Prove that if n is even and m is odd, then $(n+1)(m+1)$ is even.

Solution:

Suppose that n is even and m is odd.
Since m is odd there is some integer ℓ such that $m = 2\ell + 1$.
It follows that $m + 1 = 2\ell + 2 = 2(\ell + 1)$.
Therefore $(n+1)(m+1) = 2(n+1)(\ell+1)$.
Since n and ℓ are integers, $(n+1)(\ell+1)$ is an integer.
Therefore $(n+1)(m+1)$ is 2 times an integer $(n+1)(\ell+1)$ and therefore $(n+1)(m+1)$ is even.

Problem 5:

Prove or disprove:

a) For positive integers x, p, and q, $(x \bmod p) \bmod q = x \bmod pq$.

b) For positive integers x, p, and q, $(x \bmod p) \bmod q = (x \bmod q) \bmod p$.

Solution:

a) This is false. For a counterexample you can choose $p = 2$, $q = 3$ and $x = 3$. In this case $x \bmod p = 1$ and so $(x \bmod p) \bmod q = 1$. On the other hand $x \bmod pq = 3 \bmod 6 = 3$ so they are not equal.
b) This is also false. We can take the same values $p = 2$, $q = 3$ and $x = 3$ from part a). As we have seen, $(x \bmod p) \bmod q = 1$. On the other hand, $x \bmod q = 0$ so $(x \bmod q) \bmod p = 0$ so they are not equal.

Problem 6:

a) Find the multiplicative inverse of 2 modulo 9 (in other words, find a solution to the equation $2x \bmod 9 = 1$.)

b) Which integers in $\{1, 2, \ldots, 8\}$ have multiplicative inverses modulo 9?

Solution:

a) This is really fast. We run Euclid's algorithm to compute $gcd(9, 2)$ which is 1:The first step is $9 = 4 \cdot 2 + 1$ and of course we are done. Therefore $1 = 1 \cdot 9 - 4 \cdot 2$. The multiplicative inverse of 2 is then $(-4) \bmod 9 = 5$. This is so easy you could do it by trying all possibilities.
b) This is which integers x in have $gcd(x, 9) = 1$ so it is: $\{1, 2, 4, 5, 7, 8\}$.

Problem 7:

Let $T(n)$ be defined by: $T(0) = 1$, $T(n) = 2nT(n-1)$ for $n \geq 1$. Prove that for all $n \geq 0$, $T(n) = 2^n n!$.

Solution:

Proof:

1. Let $P(n)$ be "$T(n) = 2^n n!$". We will prove by induction that $P(n)$ is true for all $n \geq 0$.

2. Base Case: $2^0 0! = 1 \cdot 1 = 1 = T(0)$. Therefore $P(0)$ is true.

3. Inductive Hypothesis: Assume that $T(k) = 2^k k!$ for some arbitrary integer $k \geq 0$.

4. Inductive Step: $\boxed{\text{Goal: Show } T(k+1) = 2^{k+1}(k+1)!}$

$$\begin{aligned} T(k+1) &= 2(k+1)T(k) && \text{by definition since } k+1 \geq 1 \\ &= 2(k+1)2^k k! && \text{by the Inductive Hypothesis} \\ &= 2^{k+1}(k+1)k! \\ &= 2^{k+1}(k+1)! && \text{by definition of factorial} \end{aligned}$$

   which is what we wanted to prove.

5. Therefore by induction we have shown that $T(n) = 2^n n!$ for all $n \geq 0$. $\square$

Problem 8:

Let $x_1, x_2, \ldots, x_n$ be odd integers. Prove by induction that $x_1 x_2 \cdots x_n$ is also an odd integer.

Solution:

Proof:

1. Let $P(n)$ be "$x_1 x_2 \cdots x_n$ is an odd integer". We will prove by induction that $P(n)$ is true for all $n \geq 1$.

2. Base Case: Since x_1 is an odd integer, $x_1 x_2 \cdots x_1$ is odd. Therefore $P(1)$ is true.

3. Inductive Hypothesis: Assume that $x_1 x_2 \cdots x_k$ is an odd integer for some arbitrary integer $k \geq 1$.

4. Inductive Step: $\boxed{\text{Goal: Show } x_1 x_2 \cdots x_{k+1} \text{ is an odd integer}}$
   By the Inductive Hypothesis $x_1 x_2 \cdots x_k$ is an odd integer so there is some integer ℓ such that $x_1 x_2 \cdots x_k = 2\ell + 1$. Since x_{k+1} is an odd integer there is some integer m such that $x_{k+1} = 2m + 1$. Therefore

   $$x_1 x_2 \cdots x_{k+1} = x_1 x_2 \cdots x_k \cdot x_{k+1} = (2\ell+1)(2m+1) = 4\ell m + 2\ell + 2m + 1 = 2(2\ell m + \ell + m) + 1.$$

   Since $(2\ell m + \ell + m)$ is an integer, $x_1 x_2 \cdots x_{k+1}$ is an odd integer, which is what we wanted to prove.

5. Therefore by induction we have shown that $x_1 x_2 \cdots x_n$ is an odd integer for all $n \geq 1$. $\square$

Problem 9:

Determine whether the following compound proposition is a tautology, a contradiction, or a contingency: $((s \vee p) \wedge (s \vee \neg p)) \rightarrow ((p \rightarrow q) \rightarrow r)$.

Solution:

This is a contingency: Under the truth assignment $s = \mathbf{T}$, $p = \mathbf{F}$, $q = \mathbf{T}$ and $r = \mathbf{F}$, it evaluates to $\mathbf{F}$ because we have $((s \vee p) \wedge (s \vee \neg p)) = \mathbf{T}$ and $((p \rightarrow q) \rightarrow r) = \mathbf{F}$ because $(p \rightarrow q) = \mathbf{T}$ and $r = \mathbf{F}$. On the other hand if all of p, q, r, s are $\mathbf{F}$, the whole formula evaluates to $\mathbf{T}$.

Problem 10:

Find predicates $P(x)$ and $Q(x)$ such that $\forall x(P(x) \oplus Q(x))$ is true, but $\forall x P(x) \oplus \forall x Q(x)$ is false.

Solution:

Let $P(x)$ be "x is even" and let $Q(x)$ be "x is odd" and let the universe be the set of all integers. Every integer is either even or odd but not both so $\forall x(P(x) \oplus Q(x))$ is true, but not all integers are even and not all integers are odd, so $\forall x P(x)$ and $\forall x Q(x)$ are both false and hence $\forall x P(x) \oplus \forall x Q(x)$ is false.

Problem 11:

Show that the following is a tautology: $(((\neg p \vee q) \wedge (p \vee r)) \rightarrow (q \vee r))$.

Solution:

Solution 1: Truth table:

p	q	r	$\neg p$	$\neg p \vee q$	$p \vee r$	$(\neg p \vee q) \wedge (p \vee r)$	$q \vee r$	$((\neg p \vee q) \wedge (p \vee r)) \rightarrow (q \vee r)$
F	F	F	T	T	F	F	F	T
F	F	T	T	T	T	T	T	T
F	T	F	T	T	F	F	T	T
F	T	T	T	T	T	T	T	T
T	F	F	F	F	T	F	F	T
T	F	T	F	F	T	F	T	T
T	T	F	F	T	T	T	T	T
T	T	T	F	T	T	T	T	T

Solution 2: Derivation:

1. $\neg(q \vee r)$	Assumption
2. $\neg q \wedge \neg r$	De Morgan's Law from 1
3. $p \vee \neg p$	Excluded Middle
4. $(p \vee \neg p) \wedge (\neg q \wedge \neg r)$	Intro $\wedge$ from 2 and 3
5. $(p \wedge \neg q \wedge \neg r) \vee (\neg p \wedge \neg q \wedge \neg r)$	Distributive Law from 4
6. $((p \wedge \neg q) \vee (\neg p \wedge \neg q \wedge \neg r)) \wedge (r \wedge (\neg p \wedge \neg q \wedge \neg r))$	Distributive Law from 5
7. $(p \wedge \neg q) \vee (\neg p \wedge \neg q \wedge \neg r)$	Elim $\wedge$ from 6
8. $((p \wedge \neg q) \vee (\neg p \wedge \neg r)) \wedge ((p \wedge \neg q) \vee \neg q)$	Distributive Law from 7
9. $(p \wedge \neg q) \vee (\neg p \wedge \neg r)$	Elim $\wedge$ from 8
10. $(\neg\neg p \wedge \neg q) \vee (\neg p \wedge \neg r)$	Double Negation from 9
11. $\neg(\neg p \vee q) \vee \neg(p \vee r)$	De Morgan's Law (twice) from 9
12. $\neg((\neg p \vee q) \wedge (p \vee r))$	De Morgan's Law from 10
13. $\neg(q \vee r) \rightarrow \neg((\neg p \vee q) \wedge (p \vee r))$	Direct Proof Rule
14. $((\neg p \vee q) \wedge (p \vee r)) \rightarrow (q \vee r)$	Contrapositive

Problem 12:

Prove that the sum of an odd number and an even number is an odd number.

Solution:

Suppose that n is odd and m is even. Then there exist integers k and ℓ such that $n = 2k + 1$ and $m = 2\ell$. Therefore $n + m = 2k + 1 + 2\ell = 2(k + \ell) + 1$. Since $k + \ell$ is an integer, $n + m$ is 1 more than twice an integer and thus $n + m$ is odd.

Problem 13:

Use mathematical induction to show that 3 divides $n^3 - n$ whenever n is a non-negative integer.

Solution:

Proof:

1. Let $P(n)$ be "3 divides $n^3 - n$". We will prove by induction that $P(n)$ is true for all $n \geq 0$.

2. Base Case: $0^3 - 0 = 0 = 3 \cdot 0$ therefore 3 divides $0^3 - 0$ so $P(0)$ is true.

3. Inductive Hypothesis: Assume that 3 divides $k^3 - k$ for some arbitrary integer $k \geq 0$.

4. Inductive Step: $\boxed{\text{Goal: Show 3 divides } (k+1)^3 - (k+1)}$
   Since by the Inductive Hypothesis 3 divides $k^3 - k$, there is some integer ℓ such that $k^3 - k = 3\ell$. Now

$$\begin{aligned}(k+1)^3 - (k+1) &= k^3 + 3k^2 + 3k + 1 - (k+1) \\ &= k^3 + 3k^2 + 3k - k \\ &= 3\ell + 3k^2 + 3k \\ &= 3(\ell + k^2 + k)\end{aligned}$$

   Since $\ell + k^2 + k$ is an integer, we have shown that 3 divides $(k+1)^3 - (k+1)$ which is what we wanted to prove.

5. Therefore by induction we have shown that 3 divides $n^3 - n$ for all $n \geq 0$. $\square$

Problem 14:

Let the predicates $D(x, y)$ mean "team x defeated team y" and $P(x, y)$ mean "team x has played team y." Give quantified formulas with the following meanings:

a) Every team has lost at least one game.

b) There is a team that has beaten every team it has played.

Solution:

a) $\forall x \exists y D(y, x)$.

b) $\exists x \forall y (P(x, y) \rightarrow D(x, y))$.

Problem 15:

Let $P(x, y)$ be the predicate "$x < y$" and let the universe for all variables be the real numbers. Express each of the following statements as predicate logic formulas using P:

a) For every number there is a smaller one.

b) 7 is smaller than any other number.

c) 7 is between a and b. (Don't forget to handle both the possibility that b is smaller than a as well as the possibility that a is smaller than b.)

d) Between any two different numbers there is another number.

e) For any two numbers, if they are different then one is less than the other.

Solution:

a) $\forall x \exists y P(y, x)$.

b) $\forall y((y \neq 7) \rightarrow P(7, y))$.

c) $(P(a, 7) \wedge P(7, b)) \vee (P(b, 7) \wedge P(7, a))$

d) $\forall x \forall y((x \neq y) \rightarrow \exists z((P(x, z) \wedge P(z, y)) \vee (P(y, z) \wedge P(z, x))$ or $\forall x \forall y \exists z((x \neq y) \rightarrow ((P(x, z) \wedge P(z, y)) \vee (P(y, z) \wedge P(z, x))$.

e) $\forall x \forall y((x \neq y) \rightarrow (P(x, y) \vee P(y, x)))$.

Problem 16:

Let $V(x, y)$ be the predicate "x voted for y", let $M(x, y)$ be the predicate "x received more votes than y", and let the universe for all variables be the set of all people. Express each of the following statements as predicate logic formulas using V and M:

a) Everybody received at least one vote.

b) Jane and John voted for the same person.

c) Ross won the election. (The winner is the person who received the most votes.)

d) Nobody who votes for him/herself can win the election.

e) Everybody can vote for at most one person.

Solution:

a) $\forall x \exists y V(y, x)$.

b) $\exists x(V(\text{Jane}, x) \wedge V(\text{John}, x))$.

c) $\forall x((x \neq \text{Ross}) \rightarrow M(\text{Ross}, x))$.

d) Lots of good answers here; two possible answers: $\neg \exists x(V(x, x) \wedge \forall y((y \neq x) \rightarrow M(x, y)))$ or $\forall x(V(x, x) \rightarrow \exists y M(y, x))$.

e) $\forall x \forall y \forall z((V(x, y) \wedge V(x, z)) \rightarrow (y = z))$ or $\forall x \forall y \forall z((y \neq z) \rightarrow (\neg V(x, y) \vee \neg V(x, z)))$.

Problem 17:

Prove the following for all natural numbers n by induction, $\displaystyle\sum_{i=0}^{n} \frac{i}{2^i} = 2 - \frac{n+2}{2^n}$.

Solution:

Proof:

1. Let $P(n)$ be "$\sum_{i=0}^{n} \frac{i}{2^i} = 2 - (n+2)/2^n$". We will prove by induction that $P(n)$ is true for all $n \geq 0$.

2. Base Case: $\sum_{i=0}^{0} \frac{i}{2^i} = 0 \cdot 2^0 = 0$. On the other hand $2 - (0+2)/2^0 = 2 - 2/1 = 0$. Therefore $\sum_{i=0}^{0} \frac{i}{2^i} = 2 - (0+2)/2^0$ and thus $P(0)$ is true.

3. Inductive Hypothesis: Assume that $\sum_{i=0}^{k} \frac{i}{2^i} = 2-(k+2)/2^k$ for some arbitrary integer $k \geq 0$.

4. Inductive Step: $\boxed{\text{Goal: Show } \sum_{i=0}^{k+1} \frac{i}{2^i} = 2 - (k+3)/2^{k+1}}$

   Now

$$\begin{aligned} \sum_{i=0}^{k+1} \frac{i}{2^i} &= \sum_{i=0}^{k} \frac{i}{2^i} \ + \ (k+1)/2^{k+1} \qquad by definition \\ &= 2 - (k+2)/2^k \ + \ (k+1)/2^{k+1} \qquad by the Inductive Hypothesis \\ &= 2 - [2(k+2) - (k+1)]/2^{k+1} \\ &= 2 - (k+4-1)]/2^{k+1} \\ &= 2 - (k+3)/2^{k+1} \end{aligned}$$

   which is what we wanted to prove.

5. Therefore by induction we have shown that $\sum_{i=0}^{n} \frac{i}{2^i} = 2 - (n+2)/2^n$ for all $n \geq 0$. $\square$

Problem 18:

Use Euclid's algorithm to help you solve $11x \equiv 4(\text{mod} 27)$ for x.

Solution:

We run Euclid's algorithm to compute $gcd(27, 11)$.

$$\begin{aligned} 27 &= 2 \cdot 11 + 5 \\ 11 &= 2 \cdot 5 + 1 \\ 5 &= 5 \cdot 1 + 0 \end{aligned}$$

Therefore $1 = 11 - 2 \cdot 5 = 11 - 2(27 - 2 * 11) = (-2) \cdot 27 + 5 \cdot 11$. Therefore 5 is the multiplicative inverse of 11 modulo 27. It follows that $x = 5 \cdot 4 = 20$ solves $11x \equiv 4(\text{mod} 27)$. (We can check that 27 times 8 is 216 and 11 times 20 is 220.)

Problem 19:

Write an expression equivalent to $(p \to q) \to r$ that is:

a) A sum of products

b) A product of sums

Solution:

a) $pq' + r$.

b) $(p+r)(q'+r)$.

Equivalences	
Identity Laws	$p \wedge \mathbf{T} \equiv p$ $p \vee \mathbf{F} \equiv p$
Domination Laws	$p \vee \mathbf{T} \equiv \mathbf{T}$ $p \wedge \mathbf{F} \equiv \mathbf{F}$
Idempotent Laws	$p \vee p \equiv p$ $p \wedge p \equiv p$
Commutative Laws	$p \vee q \equiv q \vee p$ $p \wedge q \equiv q \wedge p$
Associative Laws	$(p \vee q) \vee r \equiv p \vee (q \vee r)$ $(p \wedge q) \wedge r \equiv p \wedge (q \wedge r)$
Distributive Laws	$p \vee (q \wedge r) \equiv (p \vee q) \wedge (p \vee r)$ $p \wedge (q \vee r) \equiv (p \wedge q) \vee (p \wedge r)$
De Morgan's Laws	$\neg(p \wedge q) \equiv \neg p \vee \neg q$ $\neg(p \vee q) \equiv \neg p \wedge \neg q$
Negation Laws	$p \vee \neg p \equiv \mathbf{T}$ $p \wedge \neg p \equiv \mathbf{F}$
Double Negation Law	$\neg\neg p \equiv p$
Contrapositive Law	$p \rightarrow q \equiv \neg q \rightarrow \neg p$
Implication Law	$p \rightarrow q \equiv \neg p \vee q$
Quantifier Negation Laws	$\neg\exists x P(x) \equiv \forall x \neg P(x)$ $\neg\forall x P(x) \equiv \exists x \neg P(x)$

Propositional and Predicate Equivalences

Inferences	
Modus Ponens	$\dfrac{p,\ p \to q}{\therefore q}$
Direct Proof	$\dfrac{p \Rightarrow q}{\therefore p \to q}$
Elim $\wedge$	$\dfrac{p \wedge q}{\therefore p,\ q}$
Intro $\wedge$	$\dfrac{p,\ q}{\therefore p \wedge q}$
Elim $\vee$	$\dfrac{p \vee q,\ \neg p}{\therefore q}$
Intro $\vee$	$\dfrac{p}{\therefore p \vee q,\ q \vee p}$
Excluded Middle	$\dfrac{}{\therefore p \vee \neg p}$
Elim $\forall$	$\dfrac{\forall x P(x)}{\therefore P(a) \text{ for any } a}$
Intro $\forall$	$\dfrac{\text{Let } a \text{ be anything...} P(a)}{\therefore \forall x P(x)}$
Elim $\exists$	$\dfrac{\exists x P(x)}{\therefore P(c) \text{ for some special } c}$
Intro $\exists$	$\dfrac{P(c) \text{ for some } c}{\therefore \exists x P(x)}$

Propositional and Predicate Inferences