Question 1. (14 points) Runtime data structures. Suppose we have the following three Java classes:

```
public class Marsupial {
   int weight;

   public void eat() { ... }
   public void speak() { ... }
}

public class Wombat extends Marsupial {
   boolean happy;
   int age;

   public void play() { ... }
   public void sleep() { ... }
   public void speak() { ... }
}

public class Main {
   public static void main(String[] ignored) {
      Marsupial fred = new Marsupial();
      Marsupial matilda = new Wombat();
      Wombat mate = new Wombat();

      fred.eat();
      matilda.speak();
      mate.play();
   }
}
```

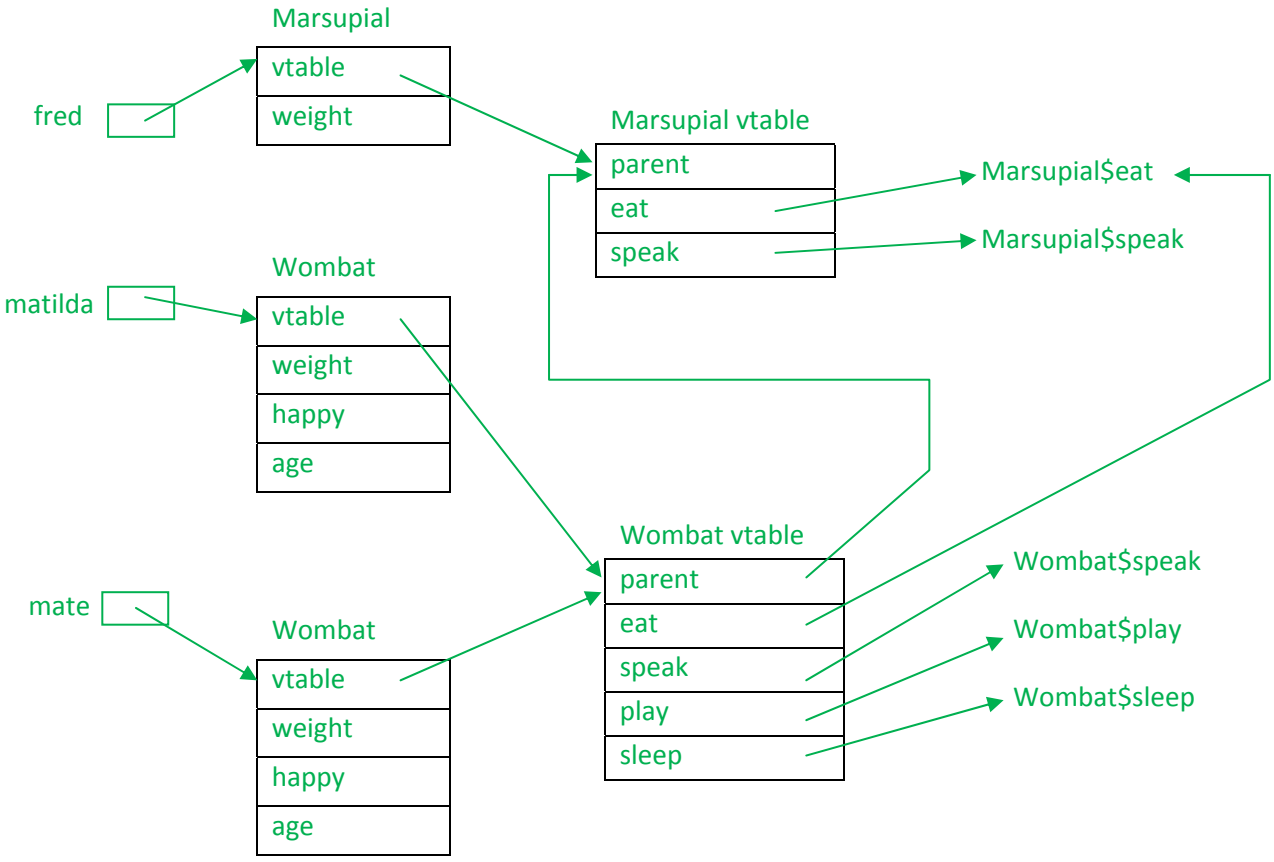
On the next page draw a diagram of the runtime data structures for this program after the declarations in the Main method have been processed, as follows:

(a) Draw pictures showing the variables in the program, the objects they refer to, and how the objects and their data members would be organized and laid out in memory.

(b) Add to your diagram from part (a) any mechanisms that support dynamic method binding as in Java (e.g., vtables). You may assume that this class structure is fixed at compile time and no new classes or methods will be added at runtime. You may also ignore constructors.

(You may remove this page from the exam if that is convenient.)

Question 1 (cont). Draw your diagram for question 1 below.



Notes: There is some freedom of the order of fields in the objects and vtables. But the first fields in Wombat objects must match the fields in Marsupial objects, and the order of methods in the Marsupial vtable must match the order of the methods in the beginning of the Wombat vtable exactly.

A few short questions on optimizations.

Question 2. (6 points) The new optimizing compiler we've been working on is designed to move computations outside a loop if they always produce the same value. Given the following original code,

```
for (i = 0; i < n; i++)
   a[i] = sqrt(x/y);
```

the optimizer rewrites it as follows to avoid recalculating the value inside the loop. (`sqrt` is a library function; it always will return the same result given the same input value and it has no side effects. All values are `doubles`.)

```
temp = sqrt(x/y);
for (i = 0; i < n; i++)
   a[i] = temp;
```

Assuming that we are running this code on a single processor with no concurrency, is this optimization always safe and correct? Give a brief argument why or why not.

No. The trouble is that sqrt(x/y) is always evaluated in the optimized version, but is not evaluated in the original version if n ≤ 0. Evaluation of sqrt(x/y) can potentially generate a division by 0 error or can produce an error if x/y < 0, and that should not happen if the loop is not executed.

The optimization would be safe if we guarded the assignment to temp by doing something like this:

```
if (n > 0) temp = sqrt(x/y);
```

Question 3. (6 points) All optimizing compilers perform *dead code elimination*, which eliminates code that is never executed, or which computes values that are never used. Most optimizing compilers perform dead code elimination several times during the optimization passes. Why? Why is there any advantage to doing it more than once?

Optimizations may themselves generate dead code by eliminating the need for various intermediate computations. So even after we run dead code elimination once it may be profitable to run it again later. Further even if we run it again later, it is worth doing it early since it is cheap and reduces the amount of intermediate code that later parts of the compiler need to deal with.

Question 4. (10 points) Suppose we have the code sequence shown on the left. The variables are assumed to be static, global variables.

```
if ( a + b < 0 ) {
   x = a + b;
} else {
   y = a + b;
}
```

```
temp = a + b;
if ( temp < 0 ) {
   x = temp;
} else {
   y = temp;
}
```

An optimization that would reduce the size of the generated code is shown on the right, where the value a+b is computed once and stored in a temporary variable, then used when it is needed later.

[The question should have included an explicit mention that temp was a compiler temporary or register and not visible to other threads. That is implicit in most of these kinds of examples, but did cause a bit of confusion in a couple of cases. We took that into account when grading the question.]

(a) Is this optimization always legal (i.e., safe and correct) if the code is executed in a single thread with no other concurrent threads? Give a brief argument in support of your answer.

Yes. The result of evaluating a+b will be the same if it is re-evaluated.

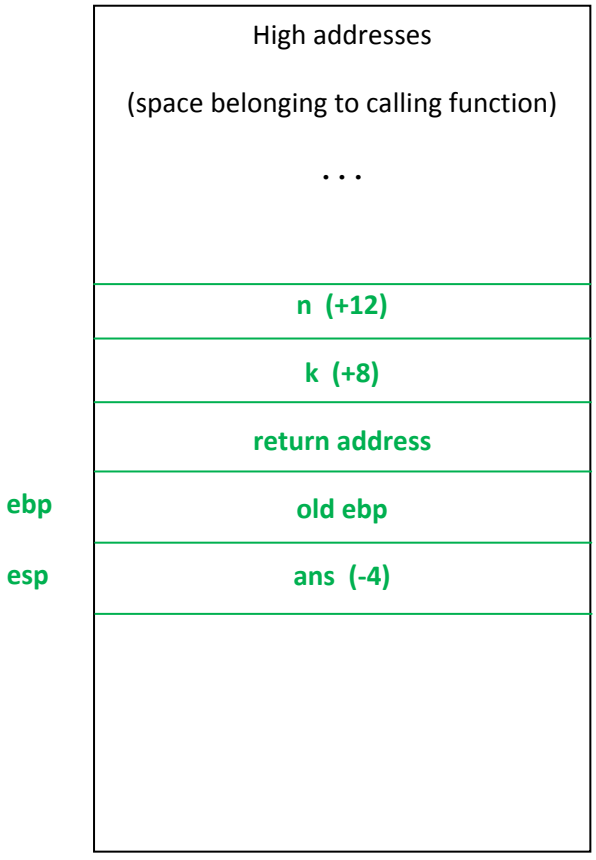
(b) Is this optimization always legal (i.e., safe and correct) if the code is executed in one thread of a multi-threaded program? Give a brief argument in support of your answer.

No. If a and b are global then another thread can change their values at any time. So, in the original case, a+b may have a different value the second time it is evaluated. In the optimized version, a+b is only evaluated once and changes between the original evaluation and the assignment would be missed.

Question 5. (20 points) x86 hacking. Consider the following C function that returns the sum of a sequence of numbers recursively.

```
/* return the sum k + (k+1) + (k+2) + ... n */
int sum(int k, int n) {
   int ans;
   if (k == n) {
      ans = n;
   } else {
      ans = k + sum(k+1, n);
   }
   return ans;
}
```

(a) (6 points) In the space below draw a picture of the stack frame for function `sum` right before executing the `return` statement at the end of the function. Your picture should show where the parameters and variables are located, as well as any additional items that are part of the stack frame, such as the return address. You should also draw labeled arrows showing where in the stack frame the registers `ebp` (frame pointer) and `esp` (stack pointer) point, and indicate the numeric offset of each parameter and local variable from the frame pointer `ebp`.



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Question 5. (cont) (b) (14 points) Translate the `sum` function into x86 assembly language. Your code does not need to look like the code generated by your compiler – any clean x86 code will do. However, your code *must* conform to the standard x86 C language calling conventions. Further, your code must include ***all*** of the statements in the original function, including the assignments to the local variable `ans` and the recursive function call. You may use either the Intel or GNU assembler syntax for your code – just be sure to pick one and not mix them. Note: The standard conventions require that registers ebx, esi, edi, ebp, and esp must be saved and restored if they are used in the body of a function. Code repeated for reference, but reformatted to save space:

```
/* return the sum k + (k+1) + (k+2) + ... + n */
int sum(int k, int n) {
   int ans;
   if (k == n) { ans = n; } else { ans = k + sum(k+1, n); }
   return ans;
}
```

```
;; answer using intel syntax

sum:  push  ebp           ; prologue
      mov   ebp,esp
      sub   esp,4         ; frame with space for ans
      mov   eax,[ebp+12]  ; eax = n
      mov   edx,[ebp+8]   ; edx = k
      cmp   eax,edx
      jne   else          ; jump if n != k
      mov   [ebp-4],eax   ; ans = n
      jmp   exit          ; return
else: mov   eax,[ebp+12]  ; call sum(k+1,n)
      push  eax           ; push n
      mov   eax,[ebp+8]
      inc   eax
      push  eax           ; push k+1
      call  sum           ; recursive call – result in eax
      add   esp,8         ; pop arguments
      add   eax,[ebp+8]   ; add k to result
      mov   [ebp-4],eax   ; store ans
exit: mov   eax,[ebp-4]   ; return ans in eax
      mov   esp,ebp       ; standard return
      pop   ebp
      ret
```

There are obviously many possible solutions to this question. The above is fairly straightforward code, and definitely not the most compact possible.

Although the instructions said to include all of the original code in the solution, many people used eax to hold variable ans without storing it in the stack frame. We let that go when grading.

Question 6. (32 points) Compiler hacking: the question of many parts.

Most programming languages have loops that either test the loop condition before the loop body executes (`while`, `for`) or after (`do-while`). But often it would be very convenient to have a loop with a test in the middle. An example is when reading an input file that is terminated with an end marker in the data. This is easy to express if we have a loop that looks like this (pseudo-code, not necessarily real MiniJava):

```
loop
   read(value)
while (value != eof-marker)
   process(value)
repeat
```

We'd like to add such a loop to our MiniJava compiler. The syntax of the loop statement is:

`loop` *statement1* `while (` *condition* `)` *statement2* `repeat`

(Aside: We ignore the question of whether there should be a semicolon following `repeat` – for the sake of this question, assume there is no semicolon.)

The meaning is as expected from the example. First, *statement1* is executed. Then the *condition* is evaluated. If it is false, execution of the `loop` statement terminates, and control continues with whatever follows the keyword `repeat`. If *condition* is true, *statement2* is executed, then we loop back to the top and execute *statement1* again to begin the next iteration.

Answer the rest of this question on the next few pages. You can remove this page and the following one, which contains the MiniJava grammar, and use those for reference as you work on the question.

Also, for reference, remember that the AST package in MiniJava contains the following key classes.

abstract ASTNode
abstract Exp extends ASTNode
abstract Statement extends ASTNode

Specific classes in the AST have constructors like While(Exp cond, Statement body, int line_nbr), and contain suitable instance variables to hold references to appropriate subtrees in the AST.

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Question 6 (cont.) (a) (3 points) What new tokens would need to be added to the scanner and parser of our MiniJava compiler to add the new `loop` statement to the original MiniJava grammar? Just list the tokens; you don't need to give a JFlex or CUP specification for them.

LOOP REPEAT

(b) (7 points) Complete the following class to define a new AST node class for the `loop` statement. You only need to define instance variables and the constructor. Assume that all appropriate package and import declarations are supplied, and don't worry about visitor code.

```
public class Loop extends Statement {
   // add instance variables below
```

```
Statement stmt1, stmt2;
Exp cond;
```

```
   // constructor – add parameters and body
   public Loop( Exp e, Statement s1, Statement s2, int line_nbr ) {
```

```
super(line_nbr);
cond = e;
stmt1 = s1;
stmt2 = s2;
```

```
   }
}
```

Question 6 (cont.) (c) (7 points) Complete the CUP specification below to define a new production for the `loop` statement and the associated semantic action(s) needed to parse a `loop` and insert an appropriate `Loop` node (as defined in part (b)) into the AST. We have added the necessary additional code to the parser rule for `Statement` as shown below.

```
Statement ::= ...
            | LoopStatement:s  {: RESULT = s; :}
            ...
            ;

LoopStatement ::=
```

```
LOOP Statement:s1 WHILE LPAREN Exp:e RPAREN
  Statement:s2 REPEAT
     {: RESULT = new Loop(e,s1,s2,s1left); :}
```

(d) (5 points) Describe the checks that would be needed in the semantics/type-checking part of the compiler to verify that a `loop` statement was legal. You do not need to give code for a visitor method or anything like that – just describe what rules (if any) need to be checked.

Verify that the condition expression has type Boolean

Question 6 (cont.) (e) (10 points) Describe the code that would be generated for the new loop. You need to show the instructions, labels, and any other assembly language code that need to be generated for the `loop` statement itself, and show where the generated code for *statement1*, *statement2*, and the *condition* would appear in the code sequence for `loop`. In writing your code, you should assume that the compiled code for *condition* will leave the value 1 in `eax` during execution if the condition evaluates to true, and will leave a 0 in `eax` if it evaluates to false. Use that value to control whether the loop continues or not; don't use any fancier branching scheme.

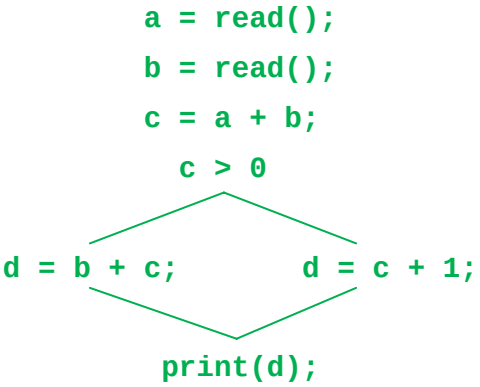
Many people included a great deal of detail here, but answers were ok as long as they included the labels, branches, and other code for the loop itself and showed where the nested statements and expressions would be included.

```
loop_label:
        statement1 code
        condition code
        cmp     eax,0
        je      loop_exit
        statement2 code
        jmp     loop_label
loop_exit:
```

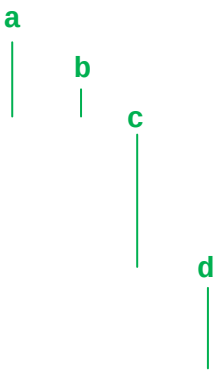
Question 7. (12 points) A little coloring. Considering the following code fragment:

```
a = read();
b = read();
c = a+b;
if (c > 0) {
  d = b+c;
} else {
  d = c+1;
}
print(d);
```

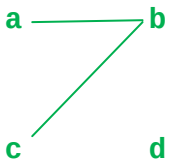
(a) Draw the control flow graph for the code, keeping the diagram to the left side of the paper.



(b) To the right of the control flow graph, neatly show the live ranges of the variables.



(c) Below, draw the interference graph for the variables. Use the left side of the paper.



Need two registers. One possibility:

r1 = { a, c, d }

r2 = { b }

(d) To the right of the interference graph, indicate which groups of variables can occupy the same register, based on the information in the interference graph. You do not need to go through the steps of the graph coloring algorithm explicitly, although it may be helpful as a guide to assigning registers. If there is more than one possible answer that uses the minimum number of registers, any of them will be fine.