# CS314 Spring 2014

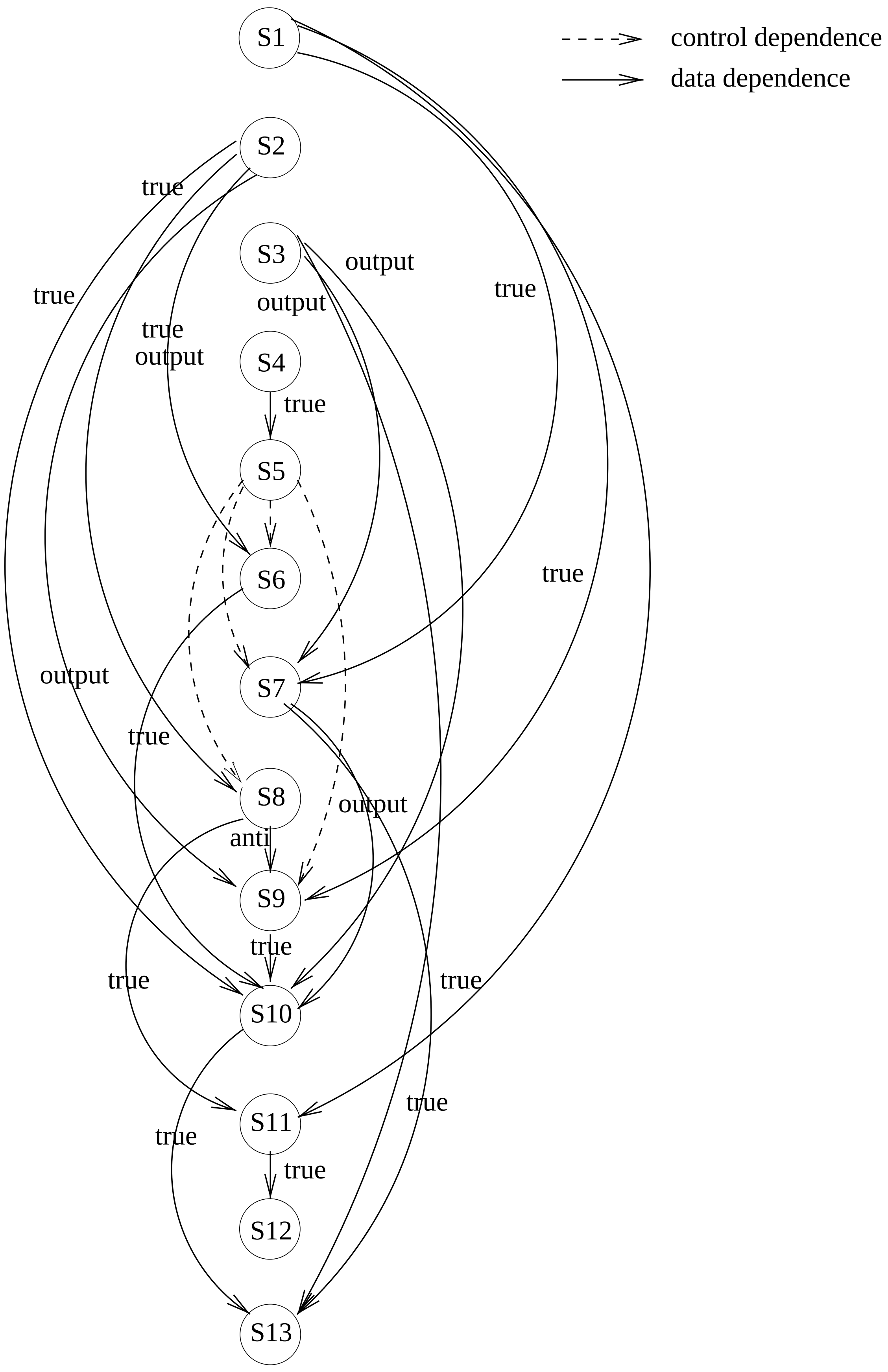
Assignment 8

Due Tuesday, April 29, **before** class

## Problem 1 – Dependencies

```
S1:   a := 3;
S2:   b := 5;
S3:   c := 7;
S4:   read(d);
S5:   if (d > 0) then
        begin
S6:       b := b + 1;
S7:       c := a + 3;
        end
      else
        begin
S8:      a := b + 2;
S9:      b := a - 3;
        end;
S10:  c := b * d;
S11:  e := a + 2;
S12:  print(e);
S13:  print(c);
end.
```

1. Give the statement-level dependence graph for the above program. A node in the statement-level dependence graph represents a statement, and edges represent dependences between the statements (nodes). Label each edge as a **true** data dependence, an **anti** data dependence, an **output** data dependence, or a **control** dependence.


control dependence
data dependence
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
true
true
true
output
output
output
true
true
true
true
output
true
output
anti
true
true
true
true
true
true
true

2. Assume that each statement takes 1 cycle to execute. What is the execution time of the sequential code? What is the fastest parallel execution time of the program? You may assume that I/O operations (read, print) can be done in parallel.

   The sequential execution time is 11 cycles.

   For the parallel execution time, the idea is that a statement can execute once all statements that it depends on have been executed. In other words, you can schedule statements based on the topological sort of their dependences. A compiler may use the following *static* schedule, where all statements in a group can be executed "at the same time", i.e., in parallel:

cycle 1 : { S1, S2, S3, S4 }

cycle 2 : {S5}

cycle 3 : Either { S6, S7 } or { S8 }

cycle 4 : Either nothing or { S9 }

cycle 5 : { S10, S11 }

cycle 6 : { S12, S13 }

   The compiler does not know which branch will be executed. The parallel execution time is 6 cycles.

   In a dynamic schedule, statements are scheduled for execution "on the fly", i.e., while the program executes. In other words, the dependence graph is "executed" at runtime, i.e., the schedule changes whether the `then` or `else` branch is taken.

   Dynamic `then` branch schedule:

cycle 1 : { S1, S2, S3, S4 }

cycle 2 : {S5}

cycle 3 : { S6, S7, S11 }

cycle 4 : { S10, S12 }

cycle 5 : { S13 }

   Dynamic `else` branch schedule:

cycle 1 : { S1, S2, S3, S4 }

cycle 2 : { S5 }

cycle 3 : { S8 }

cycle 4 : { S9, S11 }

cycle 5 : { S10, S12 }

cycle 6 : { S13 }

The dynamic schedules take 5 (then branch) or 6 (else branch) cycles.

3. Extend the notion of statement dependences to procedure call dependences. In a procedure-level dependence graph nodes represent procedure calls, and edges represent dependences between procedure calls. For each procedure "p", assume the following definitions. The set MUST_WRITE(p) is the set of all memory locations that are written by every call to procedure "p", the set MAY_WRITE(p) is the set of memory locations that may be written by a call to procedure "p". Therefore, the following relation holds: MUST_WRITE(p) $\subset$ MAY_WRITE(p). The sets MUST_READ(p) and MAY_READ(p) have corresponding definitions.

   Redefine true, anti, and output dependence for procedure calls based on sets MUST_WRITE(p), MAY_WRITE(p), MUST_READ(p), MAY_READ(p), where "p" is a procedure. Remember that parallelization is based on the notion of preserving dependences, so if there is no dependence bewteen two procedure calls, the calls may be executed in parallel.

   Let p and q be two procedure calls:

   - There is a **true** dependence between p and q, if p executes before q, and $MAY\_WRITE(p) \cap MAY\_READ(q) \neq \emptyset$
   - There is an **anti** dependence between p and q, if p executes before q, and $MAY\_READ(p) \cap MAY\_WRITE(q) \neq \emptyset$
   - There is an **output** dependence between p and q, if p executes before q, and $MAY\_WRITE(p) \cap MAY\_WRITE(q) \neq \emptyset$

   We need to use the MAY sets since if a dependence may exist, we have to consider it in order to preserve the semantics of the code for all possible program executions (safety issue).

## Problem 2 – Dependence Analysis

Give the direction vectors, and if possible the distance vectors for all dependences in the following loop nests. State explicitly whether a dependence is a true, anti, or output dependence.

1.
   ```
   do i = 3, 100
     a(i) = a (i-1) + a(i+1) + a(i-2)
   enddo
   ```

   | source reference | sink reference | type | distance vector | direction vector |
   |---|---|---|---|---|
   | a(i) | a(i-1) | true | (1) | (<) |
   | a(i) | a(i-2) | true | (2) | (<) |
   | a(i+1) | a(i) | anti | (1) | (<) |

2.
   ```
   do i = 1, 100
     a(2*i) = a(2*i-1) + a(2*i+1)
   enddo
   ```

   | source reference | sink reference | type | distance vector | direction vector |
   |---|---|---|---|---|

   no dependences

3.
   ```
   do i = 1, 10
     a_L(i) = a(5) + a_R(i)
   enddo
   ```

   $a_L$ and $a_R$ are write and read accesses, respectively, to the same variable "a".

   | source reference | sink reference | type | distance vector | direction vector |
   |---|---|---|---|---|
   | $a_L$(i) | a(5) | true | - | (<) |
   | a(5) | $a_L$(i) | anti | - | (<) |

## Problem 3 – Loop Parallelization and Vectorization

```
do i = 2, 100
  do j = 2, 100
S1:   a(i, j) = b(i-1, j-1) + 1
S2:   b(i, j) = a(i, j-1) - 5
  enddo
enddo
```

1. Give the statement-level dependence graph with distance vectors.

2. In its current form, can any loop level be parallelized or vectorized? If so, use the doall parallel construct, or a partically vectorized statement (e.g.: c(k, 1:100) = d(k, 1:100)) to show the resulting (partially) parallelized loop.

   No parallelization or vectorization is possible since there are loop carried dependences at both loop levels.

3. Can you increase the available parallelism by transforming the loop? If so, show the resulting parallel and vectorized versions.

   Yes, interchange the loops, and now both dependences are carried by the outer loop. This allows partial vectorization and parallelization of the innermost loop.