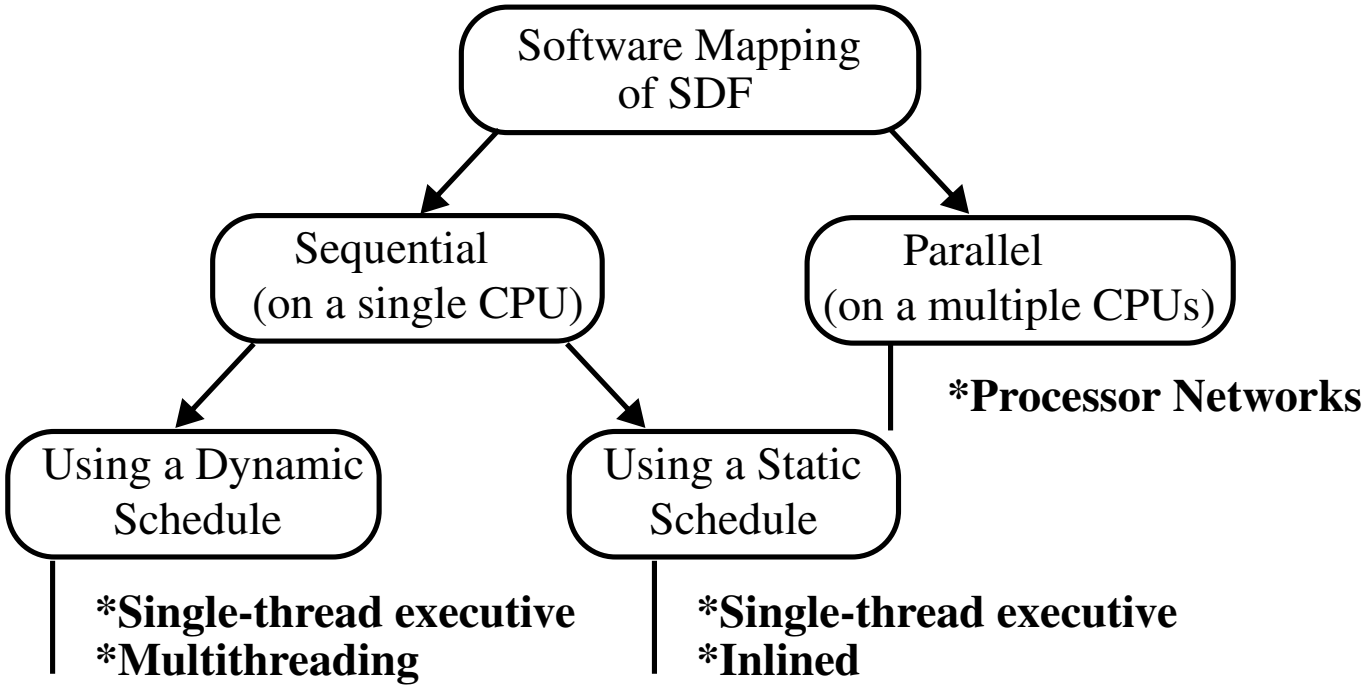
System-on-Chip Design
Data Flow Software Implementation

(Based on slides at ECE 522 at UNM)

Hao Zheng
Comp Sci & Eng
U of South Florida

Software Implementation (A Practical Introduction to HW/SW Codesign, P. Schaumont)

There are several different approaches of mapping software into hardware:



We will first focus on implementing dataflow on single-processor systems

This requires a sequential scheduling of dataflow actors

There are two methods to implement a sequential schedule

Software Implementation of Data-Flow

- Using a **dynamic** schedule

  Here, the CPU determines the order in which actors should execute **at runtime** by testing firing rules to evaluate which actor can run

  Dynamic scheduling of an SDF system can be done using a *single-thread* executive or *multi-threading*

- Using a **static** schedule

  Here, we need to determine upfront the order of actor firing

  Allows for a single-threaded execution and an optimization in which the entire dataflow graph is 'inlined' into a single function

Recall the essential features of SDF graphs:

SDF graphs represent concurrent systems, and use **actors** and **FIFO queues** to communicate

Firing only depends on the availability of data (tokens) in the FIFO queues

The amount of tokens produced/consumed per firing is given by labels

Software Implementation of Data-Flow

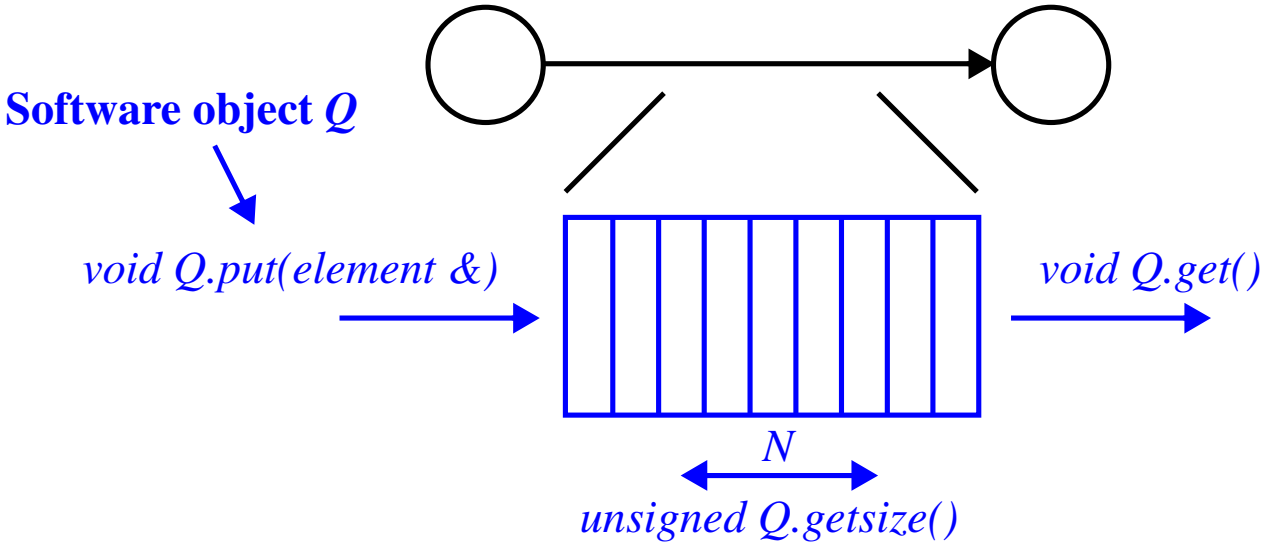
FIFO Queues:

In principle, SDF systems require **infinite** FIFO queues

In practice, queues have a limited # of positions, and need overflow detection

Another approach is to create a FIFO that grows dynamically each time the FIFO overflows

However, if we know a PASS, we know the *maximum number* of tokens on each queue and can set the queue size accordingly



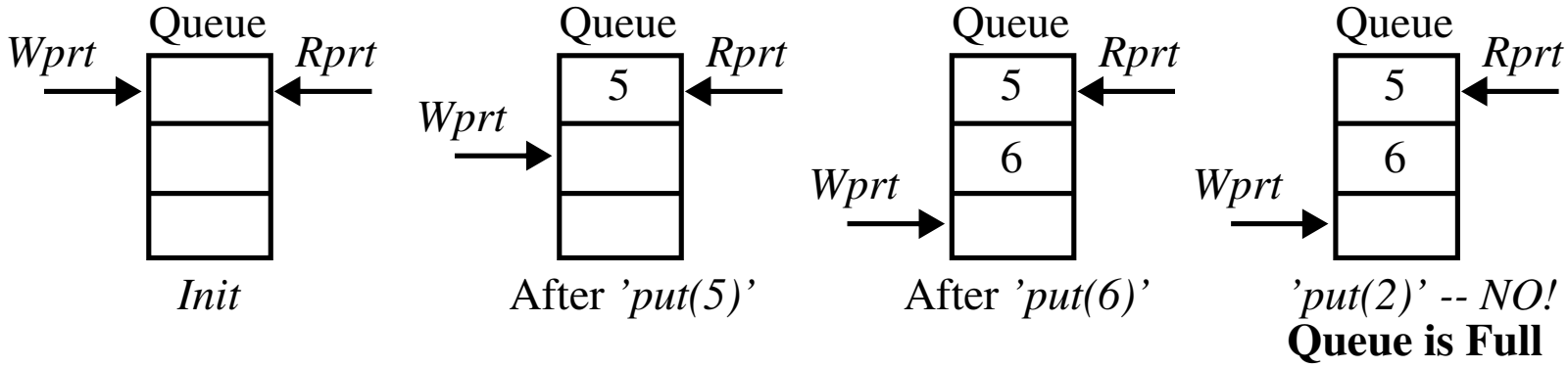
Software Implementation of Data-Flow

A typical software interface of a FIFO queue has *two parameters* and *three methods*

- The number of elements *N* that can be stored by the queue
- The data type *element* of queue components
- A method to *put* elements into the queue
- A method to *get* elements from the queue
- A method to *test the number* of elements in the queue

A standard data structure such as a *circular queue* can be used

A ***circular queue*** consists of an *array*, a *write-pointer* and a *read-pointer*, and use *modulo* addressing, i.e., element *I* at (*Rptr* + *I*) *mod array_size*.



Software Implementation of Data-Flow Model

Example *fifo* in C:

```
#define MAXFIFO 1024

typedef struct fifo {
   int data[MAXFIFO]; // array
   unsigned wptr;     // write pointer
   unsigned rptr;     // read pointer
} fifo_t;

void init_fifo(fifo_t *F);
void put_fifo(fifo_t *F, int d);
int get_fifo(fifo_t *F);
unsigned fifo_size(fifo_t *F);

int main()
   {
   fifo_t F1;
   init_fifo(&F1);  // resets wptr, rptr
```

Queue storage can either be fixed statically or growable dynamically

Software Implementation of Data-Flow Model

```
        put_fifo(&F1, 5);
        put_fifo(&F1, 6); // prints: 2 5
        printf("%d %d\n", fifo_size(&F1), get_fifo(&F1));
        printf("%d\n", fifo_size(&F1)); // prints: 1
        }
```

Actors:

A dataflow actor can be represented as a *function*, with an interface to FIFOs

The **firing** of an actor can be implemented as a simple C function

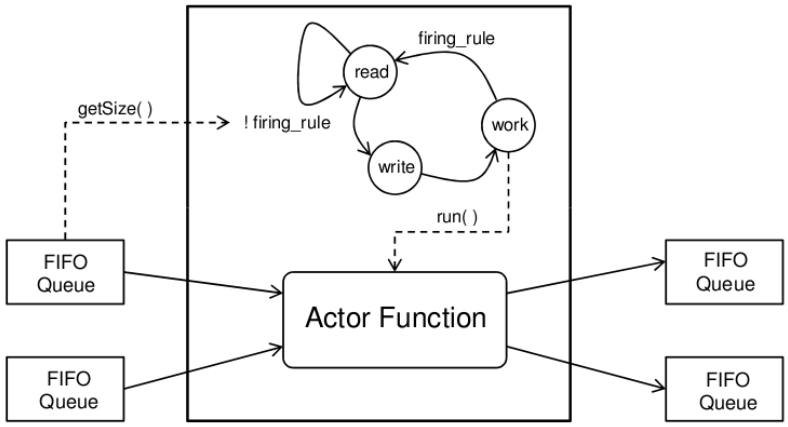


Fig. 2.18 Software implementation of the datafow actor

Software Implementation of Data-Flow Model

The function checks the firing rules and manipulates the input and output queue

Think of this as a *small controller* that controls its execution

The *local controller* of an actor has **three** states

In the *read state*, it remains idle until a token arrives at the input queue

In the *work state,* the controller reads one token and runs the function, producing an output token which is put on the output queue in the *write state*

We must make sure the firing rule is implemented correctly

When an SDF actor fires, it reads all input queues and writes into all output queues according to the specified production and consumption rates

A C implementation:

```
typedef struct actorio {
    fifo_t *in1, *in2;
    fifo_t *out1, *out2;
} actorio_t;
```

Software Implementation of Data-Flow Model

```
void sort_actor(actorio_t *g)
    {
    int r1, r2;
    while((fifo_size(g->in1) > 0) &&
          (fifo_size(g->in2) > 0))
       {
       r1 = get_fifo(g->in1);
       r2 = get_fifo(g->in2);
       put_fifo(g->out1, (r1 > r2) ? r1 : r2);
       put_fifo(g->out2, (r1 > r2) ? r2 : r1);
       }
    }
```

Sequential Targets with a Dynamic Schedule:

In a dynamic system schedule, the firing rules of the actors will be tested at runtime

GCD Example

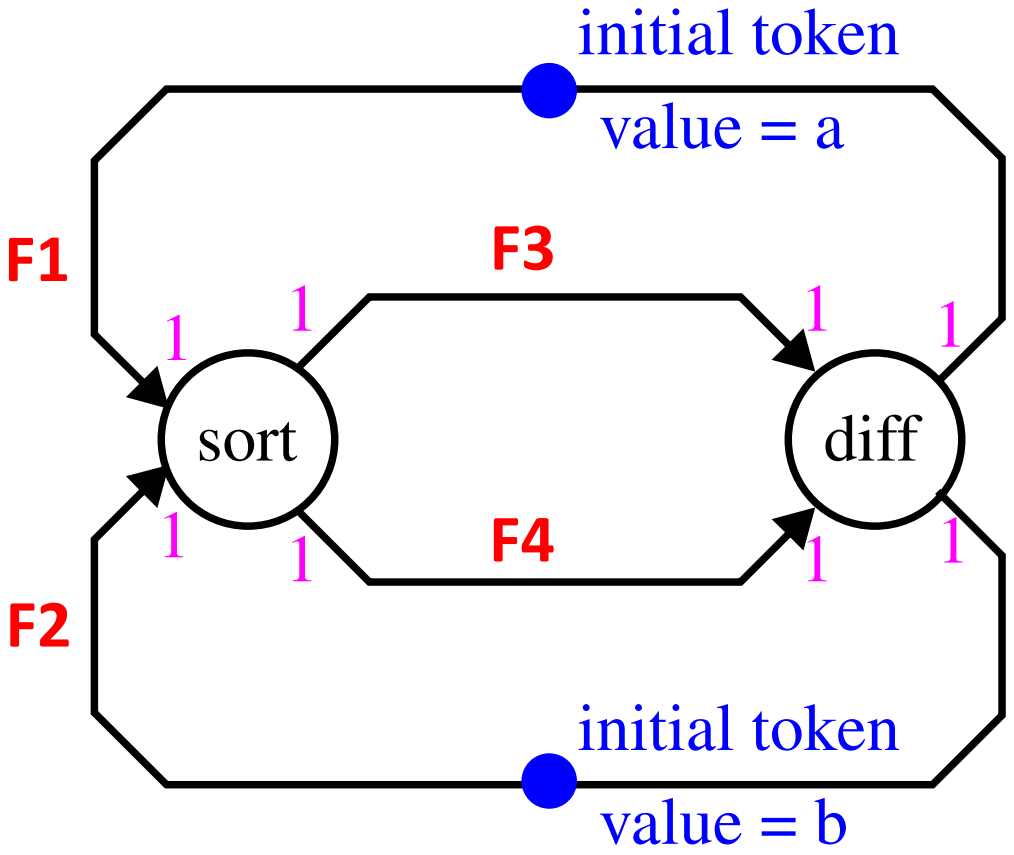
Consider an SDF that models *Euclid's Greatest Common Divisor* (GCD):

sort

```
out1 = (a > b) ? a : b;
out2 = (a > b) ? b : a;
```

diff

```
out1 = (a != b) ? a-b: a;
out2 = b;
```



Software Implementation: Single-Thread Dynamic Schedules

In a single-thread dynamic schedule, we implement the system schedule as a function that instantiates all actors and queues

And then it calls the actors in a round-robin fashion

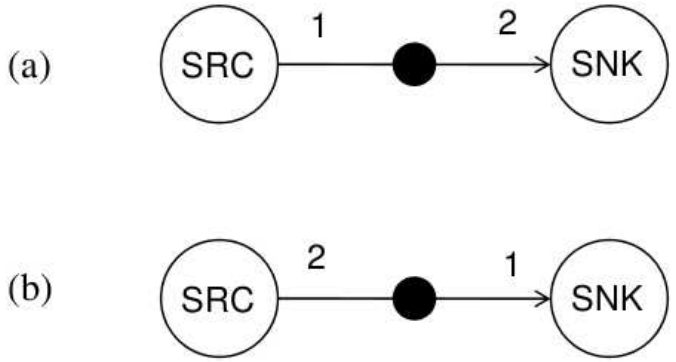
```
void main() {
    fifo_t F1, F2, F3, F4;
    actorio_t sort_io;
    ...
    sort_io.in1 = &F1;
    sort_io.in2 = &F2;
    sort_io.out1 = &F3;
    sort_io.out2 = &F4;
    while (1)
        {
        sort_actor(&sort_io);
        // .. call other actors
        }
    }
```

Software Implementation: Single-Thread Dynamic Schedules

But what is the most appropriate call order of the actors in the system schedule?

Remember that it is **impossible** to call the actors in the **wrong** order,

This is true b/c each of them still has a firing rule that prevents them from running when there is no data available



System Schedule

```
void main() {
  ..
  while (1) {
    src_actor(&src_io);
    snk_actor(&snk_io);
  }
}
```

Fig. 2.19 Two graph topologies and a dynamic system schedule

Even though ***snk*** will be called as often as ***src***, the firing rule of ***snk*** will only allow that actor to run when there is sufficient data available

In Figure 2.19a, this means that the ***snk*** actor will fire ONLY **every other time** it is called

Software Implementation: Single-Thread Dynamic Schedules

While this type of dynamic scheduling prevents actors from running prematurely, some actors will produce tokens and cause queues to grow

In Figure 2.19b, the ***src*** actor produces two tokens per invocation while the ***snk*** actor reads ONLY one per invocation

The basic problem with the system schedule in Figure 2.19 is that the system schedule firing rate **differs** from the firing rate for a PASS

For example, the PASS for this system would be (***src***, ***snk***, ***snk***)

Two solutions:

• Solution 1: Adjust the system schedule to match the PASS

```
void main() {
   ..
   while (1) {
      src_actor(&src_io);
      snk_actor(&snk_io);
      snk_actor(&snk_io);
      } }
```

Software Implementation: Single-Thread Dynamic Schedules

Unfortunately, this solution is not elegant, because it voids the purpose of having a dynamic scheduler

- Solution 2: Adjust the ***snk*** actor code to continue execution as long as there are tokens present

```
void snk_actor(actorio_t *g) {
  int r1, r2;
  while ((fifo_size(g->in1) > 0)) {
    r1 = get_fifo(g->in1);
    ... // do processing
  }
}
```

Multi-Thread Dynamic Schedules

The actor functions as described are captured as real functions which **exit** in between invocations

This prevents them from maintaining *local* state, and forces global variables

Software Implementation: Multi-Thread Dynamic Schedules

In multi-threaded programming, each actor lives in a separate thread

For example, in a C program with two functions, each thread is executing one of the functions

In a single CPU scenario, the threads are time-interleaved by a scheduler and the threads **voluntarily** release control back to the scheduler

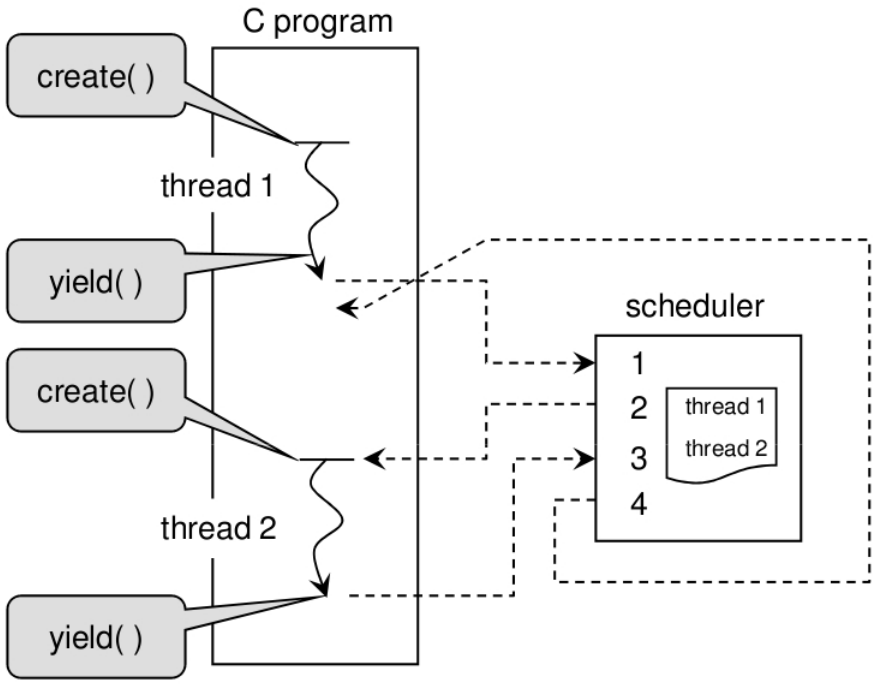


Fig. 2.20 Example of cooperative multi-threading

Software Implementation: Multi-Thread Dynamic Schedules

Two functions are needed to build a threading system: *create()* and *yield()*

The scheduler can apply different strategies to schedule thread execution, with the simplest one shown above as a *round-robin* schedule

Quickthreads is a **cooperative multithreading library**

The quickthreads API (Application Programmers Interface) consists of 4 functions

- *spt_init()*: initializes the threading system
- *spt_create(stp_userf_t *F, void *G)* creates a thread that will start execution with user function F, and will be passed a single argument G
- *stp_yield()* releases control over the thread to the scheduler
- *stp_abort()* terminates a thread (prevents it from being scheduled)

Here's an example

```
#include "../qt/stp.h"
#include <stdio.h>
```

Software Implementation: Multi-Thread Dynamic Schedules

```
void hello(void *null)
    {
    int n = 3;
    while (n-- > 0)
        {
        printf("hello\n");
        stp_yield();
        }
    }

void world(void *null)
    {
    int n = 5;
    while (n-- > 0)
        {
        printf("world\n");
        stp_yield();
        } }
```

Software Implementation: Multi-Thread Dynamic Schedules

```
int main(int argc, char **argv)
   {
   stp_init();
   stp_create(hello, 0);
   stp_create(world, 0);
   stp_start();
   return 0;
   }
```

To compile and execute:

```
gcc -c ex1.c -o ex1 ../qt/libstp.a ../qt/libqt.a
./ex1
hello
world
hello
world
hello
world\nworld\nworld
```

Software Implementation: Multi-Thread Dynamic Schedules

A multi-threaded version of the SDF scheduler, using the *sort_actor*

```
void sort_actor(actorio_t *g) {
  int r1, r2;
  while (1) {
    if ((fifo_size(g->in1) > 0) &&
        (fifo_size(g->in2) > 0)) {
      r1 = get_fifo(g->in1);
      r2 = get_fifo(g->in2);
      put_fifo(g->out1, (r1 > r2) ? r1 : r2);
      put_fifo(g->out2, (r1 > r2) ? r2 : r1);
    }
    stp_yield();

void main()
   {
   fifo_t F1, F2, F3, F4;
   actorio_t sort_io;
   ...
```

Software Implementation: Multi-Thread Dynamic Schedules

```
        sort_io.in1 = &F1;      // connect queues to actor
        sort_io.in2 = &F2;
        sort_io.out1 = &F3;
        sort_io.out2 = &F4;
        stp_create(sort_actor, &sort_io); // create thread
        stp_start();           // start system scheduler
        }
```

Note, that as before, the execution rate of the actor code must be equal to the PASS firing rate in order to avoid unbounded growth of tokens

Thus we use Solution 2 above, from the single-thread executive method described earlier

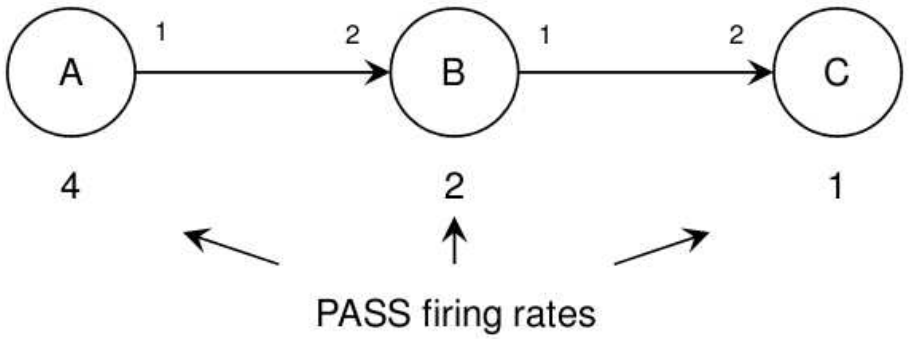
Sequential Targets with Static Schedule

From the PASS analysis of an SDF graph, we know at least one solution for a feasible sequential schedule

This solution can be used to optimize the implementation in several ways

Software Implementation: Sequential Targets with Static Schedule

- We can remove the firing rules since we know the exact sequential schedule
  This will yield a small performance advantage (NOTE: it also prevents the use of dynamic scheduler)
- We can also determine an optimal interleaving of the actors to minimize the storage requirements for the queues
- We can create a fully **inlined** version of the SDF graph which will allow us to get rid of the queues entirely




```
while(1) {
  // call A four times
  A(); A(); A(); A();

  // call B two times
  B(); B();

  // call C one time
  C();
}
```

Fig. 2.21 System schedule for a multirate SDF graph

Here, the relative firing rates of A, B, and C must be 4, 2, and 1 to yield a PASS

Software Implementation: Sequential Targets with Static Schedule

Given the interleaving schedule on the right, it can be seen that queue AB will carry a max of four tokens and queue BC will carry a max of two tokens in steady-state

However, there is a BETTER interleaving schedule, i.e., by calling the actors in the sequence (A,A,B,A,A,B,C)

Here, the maximum # of tokens on any queue is reduced to two

Therefore, the schedule determined using PASS is **not** necessarily the optimal (finding the optimal is an optimization problem)

As noted, implementing a truly static schedule means we do NOT need to check firing rules since the required tokens are quaranteed to be present

Consider optimizing GCD using a **single-thread** SDF system with a **static schedule**

Recall that a valid PASS requires firing each node once

Software Implementation: Sequential Targets with Static Schedule

```
void sort_actor(actorio_t *g) {
   int r1, r2;
   if ((fifo_size(g->in1) > 0) &&
      (fifo_size(g->in2) > 0)) {
      r1 = get_fifo(g->in1);
      r2 = get_fifo(g->in2);
      put_fifo(g->out1, (r1 > r2) ? r1 : r2);
      put_fifo(g->out2, (r1 > r2) ? r2 : r1);
      }}
void diff_actor(actorio_t *g) {
   int r1, r2;
   if ((fifo_size(g->in1) > 0) &&
      (fifo_size(g->in2) > 0)) {
      r1 = get_fifo(g->in1);
      r2 = get_fifo(g->in2);
      put_fifo(g->out1, (r1 != r2) ? r1 - r2 : r1);
      put_fifo(g->out2, r2);
      }}
```

// firing rule testing

// firing rule testing

Software Implementation: Sequential Targets with Static Schedule

```
void main() {
    fifo_t F1, F2, F3, F4;
    actorio_t sort_io, diff_io;
    sort_io.in1 = &F1;
    sort_io.in2 = &F2;
    sort_io.out1 = &F3;
    sort_io.out2 = &F4;
    diff_io.in1 = &F3;
    diff_io.in2 = &F4;
    diff_io.out1 = &F1;
    diff_io.out2 = &F2;
    // initial tokens
    put_fifo(&F1, 16);
    put_fifo(&F1, 12);
    // system schedule
    while (1) {
        sort_actor(&sort_io);
        diff_actor(&diff_io); }}
```

Software Implementation: Sequential Targets with Static Schedule

There are two simple **optimizations** that can be applied here

- The *firing schedule* is **static** and **fixed**, and therefore the access order of queues is also fixed

  This allows the queues to be *optimized out* and replaced with **fixed variables**

For example, assume that we have determined that the access sequence on a particular FIFO queue will always be as follows:

```
loop {                          // actor body
    ...
    F1.put(value1);
    F1.put(value2);
    ...
    .. = F1.get();
    .. = F1.get();
    }
```

Software Implementation: Sequential Targets with Static Schedule

Given that only two positions of the FIFO **F1** are occupied at a time, it can be replaced by two variables.

```
loop {                          // Optimized actor body
    ...
    r1 = value1;
    r2 = value2;
    ...
    .. = r1;
    .. = r2;
    }
```

- A second optimization involves **inline**'ing actor code in the main program

  In combination with the above optimization, this *eliminates* the firing rules and reduces the entire dataflow graph to a **single** function

For the GCD example, each queue (*F1*, *F2*, *F3*, and *F4*) will contain no more than a single token, which means that each queue can be replaced by an *integer*

Software Implementation: Sequential Targets with Static Schedule

```
void main() {
    int f1, f2, f3, f4;
    // initial token
    f1 = 16;
    f2 = 12;
    // system schedule
    while (1) {
      // code for actor 1
       f3 = (f1 > f2) ? f1 : f2;
       f4 = (f1 > f2) ? f2 : f1;
      // code for actor 2
       f1 = (f3 != f4) ? f3 - f4: f3;
       f2 = f4;
       }
    }
```

Software Implementation: Sequential Targets with Static Schedule

These optimizations reduce the runtime of the program significantly

For example, we have dropped testing of the *firing rules* and manipulating the FIFOs

This is possible here because we have determined a *valid PASS* for the initial data-flow system, and determined a *fixed schedule* to implement that PASS

Note that we have traded some of the **runtime flexibility** for **improved efficiency**