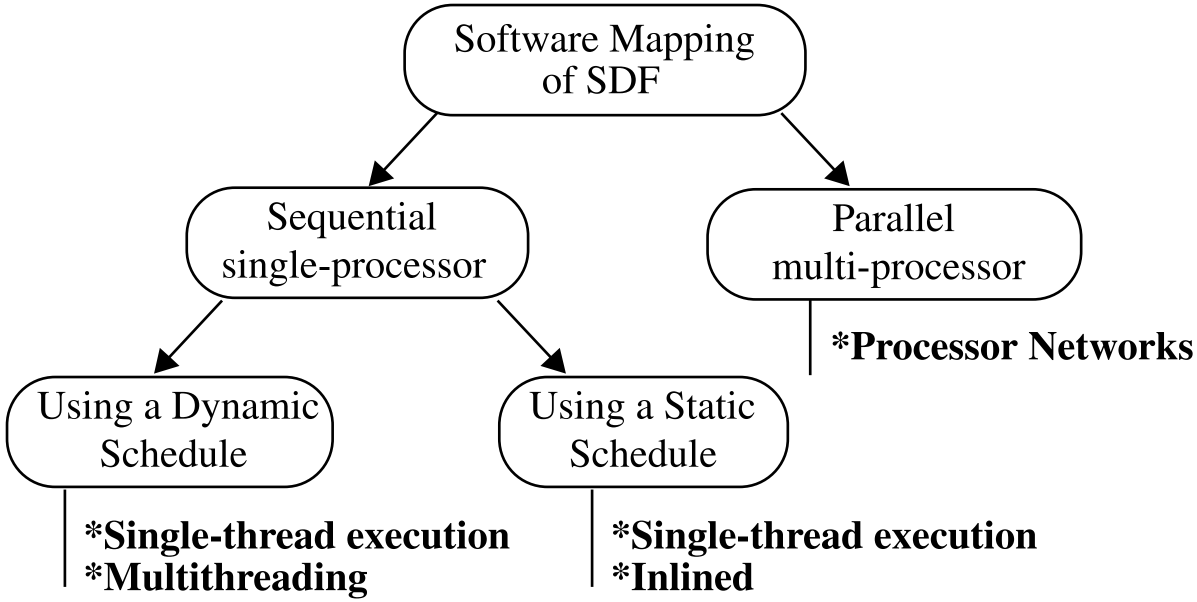
Mapping DFGs to Software

There are a wide variety of approaches of mapping DFGs to software



Sequential implementations can make use of *static* or *dynamic* schedules

Parallel, multi-processor mappings require more effort due to:

- Load balancing: Mapping *actors* such that the activity on each processor is about the same
- Minimizing inter-processor communication: Mapping *actors* such that communication overhead is minimized

Mapping DFGs to Software

We focus first on *single-processor* systems, and in particular, on finding efficient versions of *sequential schedules*

As noted on the previous slide, there are two options for implementing the schedule:

- **Dynamic** schedule

  Here, software decides the order in which *actors* execute **at runtime** by testing *firing rules* to determine which *actor* can run

  Dynamic scheduling can be done in a *single-threaded* or *multi-threaded* execution environment

- **Static** schedule

  In this case, the *firing* order is determined at design time and fixed in the implementation

  The fixed order allows for a design time optimization in which the *firing* of multiple *actors* can be treated as a *single firing*

  This in turn allows for 'inlined' implementations

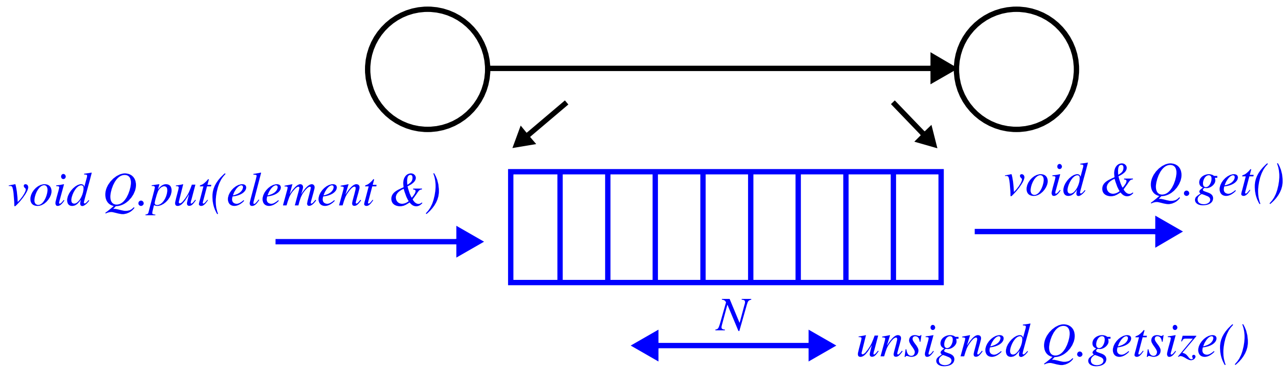
DFG Elements

Before discussing these, let's first look at C implementations of *actors* and *queues*

FIFO Queues:

Although DFGs theoretically have **infinite** length *queues*, in practice, *queues* are limited in size

We discussed earlier that constructing a PASS allows the ***maximum*** *queue* size to be determined by analyzing *actor* firing sequences



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

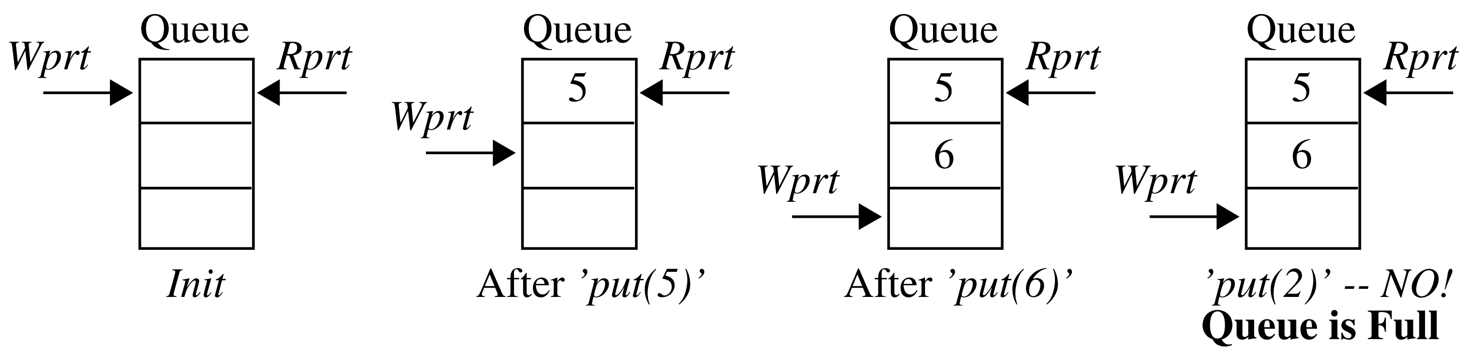
- The **# of elements** *N* that can be stored in the *queue* and the **data type** of the elements
- Methods that **put** elements into the *queue*, **get** elements from the *queue*, and **query** the current size of the *queue*

DFG Elements

Queues are well defined (standardized) data structures

A ***circular queue*** consists of an *array*, a *write-pointer* and a *read-pointer*

They use *modulo* addressing, e.g., the *Ith* element is at position (*Rptr* + *I*) *mod* *Q.getsize()*



Example *fifo* data structure definition in C:

```
#define MAXFIFO 1024

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

DFG Elements

```
void init_fifo(fifo_t *F); // These functions defined
void put_fifo(fifo_t *F, int d); // in text
int get_fifo(fifo_t *F);
unsigned fifo_size(fifo_t *F);

int main()
   {
   fifo_t F1;
   init_fifo(&F1);   // resets wptr, rptr
   put_fifo(&F1, 5);
   put_fifo(&F1, 6);
   printf("%d %d\n", fifo_size(&F1), get_fifo(&F1));
   printf("%d\n", fifo_size(&F1)); // prints 1
   }
```

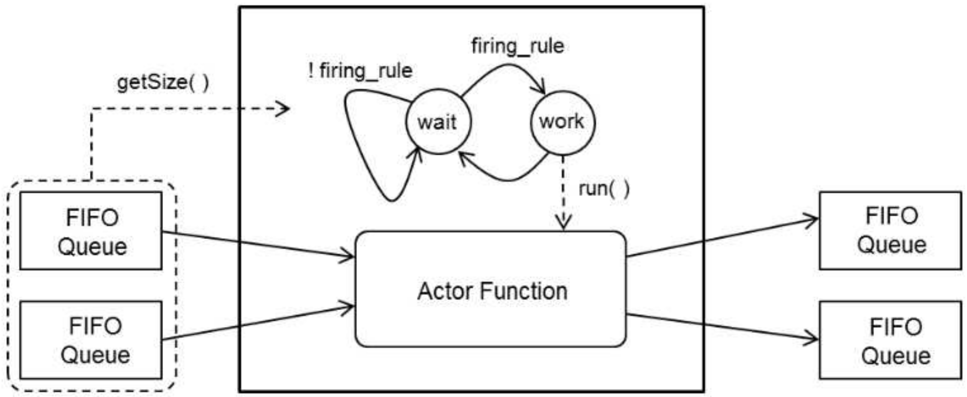
Note that the *queue* size is fixed here at compile time

Alternatively, *queue* size can be changed dynamically at runtime using *malloc()*

DFG Elements

Actors:

An *actor* can be represented as a C function, with an interface to the FIFOs



The *actor* function incorporates a finite state machine (FSM), which checks the *firing rules* to determine whether to execute the *actor* code

The *local controller* (FSM) of an *actor* has two states

wait state: start state which checks the *firing rules* immediately after being invoked by a scheduler

work state*: wait* transitions to *work* when *firing rules* are satisfied

The *actor* then reads tokens, performs calculation and writes output tokens

Example C Implementation of DFG

An example which supports up to 8 inputs and outputs per *actor*:

```
#define MAXIO 8
typedef struct actorio {
   fifo_t *in[MAXIO], *out[MAXIO];
} actorio_t;
```

An example *actor* implementation:

```
void fft2(actorio_t *g)
   {
   int a, b;
   if( fifo_size(g->in[0]) >= 2 ) // Firing rule check
      {
      a = get_fifo(g->in[0]);
      b = get_fifo(g->in[0]);
      put_fifo(g->out[0], a+b);
      put_fifo(g->out[0], a-b);
      }
   }
```

Mapping DFGs to Single Processors: Dynamic Schedule

In a dynamic system schedule, the *firing rules* of the *actors* are tested at runtime

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

The scheduler typically calls the *actors* in a *round-robin* fashion

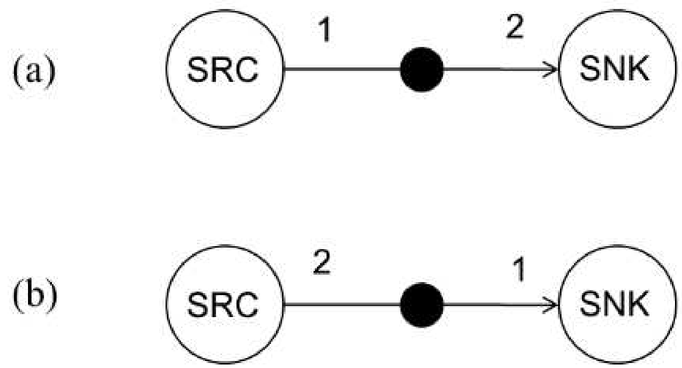
```
void main() {
    fifo_t q1, q2;
    actorio_t fft2_io = {{&q1}, {&q2}};
    ...
    init_fifo(&q1);
    init_fifo(&q2);
    while (1)
        {
        fft2_actor(&fft2_io);
        // .. call other actors
        }
    }
```

Mapping DFGs to Single Processors: Dynamic Schedule

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

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

An interesting question is 'is there a call order of the *actors* that is best?'



System Schedule

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

The schedule on the right shows that ***snk*** in (a) is called as often as ***src***

However, ***snk*** will only *fire* on even numbered invocations

(b) shows a problem that is **not** handled by static schedulers

Round-robin scheduling in this case will eventually lead to *queue* overflow

Mapping DFGs to Single Processors: Dynamic Schedule

The underlying problem with (b) is that the implemented *firing rate* **differs** from the *firing rate* for a PASS, which is given as (***src***, ***snk***, ***snk***)

There are two solutions to this issue:

- Adjust the system schedule to match the PASS

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

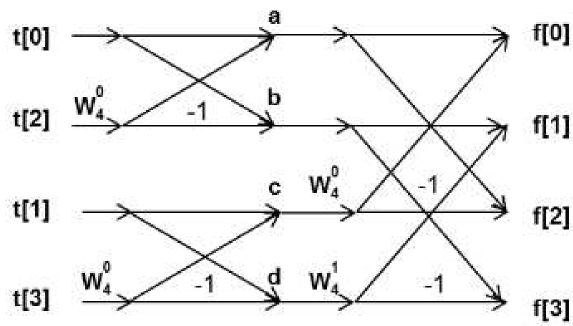
Unfortunately, this solution defeats one of the goals of a dynamic scheduler, i.e., that it automatically ***converges*** to the PASS *firing rate*

Mapping DFGs to Single Processors: Dynamic Schedule

- A better solution is to add a **while** loop to the ***snk*** *actor* code to allow it to continue execution while there are *tokens* in the *queue*

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

Mapping DFGs to Single Processors: Example Dynamic Schedule



(a)

```
a    = t[0] + W(0,4) * t[2] = t[0] + t[2]
b    = t[0] - W(0,4) * t[2] = t[0] - t[2]
c    = t[1] + W(0,4) * t[3] = t[0] + t[3]
d    = t[1] - W(0,4) * t[3] = t[1] - t[3]
f[0] = a    + W(0,4) * c    = a    + c
f[1] = b    + W(1,4) * d    = b    - j.d
f[2] = c    - W(0,4) * c    = a    - c
f[3] = b    - W(1,4) * d    = b    + j.d
```

(b)

Let's implement the *4-point Fast Fourier Transform* (FFT) shown above using a dynamic schedule

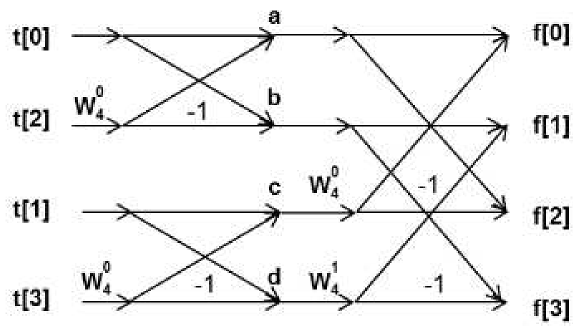
The array *t* stores 4 (time domain) samples

The array *f* will be used to store the frequency domain representation of *t*

The FFT utilizes *butterfly operations* to implement the FFT, as defined on the right side in the figure

The *twiddle* factor $W(k, N)$ is a complex number defined as $e^{-j2\pi k/N}$, with $W(0, 4) = 1$ and $W(1, 4) = -j$

Mapping DFGs to Single Processors: Example Dynamic Schedule

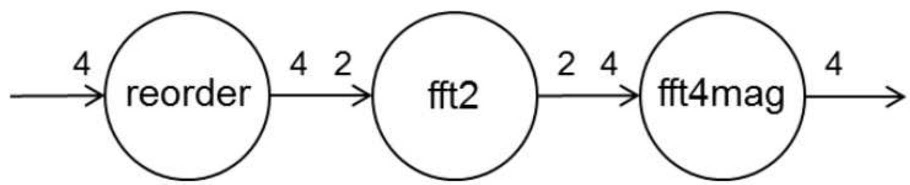


(a)

```
a    = t[0] + W(0,4) * t[2] = t[0] + t[2]
b    = t[0] - W(0,4) * t[2] = t[0] - t[2]
c    = t[1] + W(0,4) * t[3] = t[0] + t[3]
d    = t[1] - W(0,4) * t[3] = t[1] - t[3]
f[0] = a    + W(0,4) * c    = a    + c
f[1] = b    + W(1,4) * d    = b    - j.d
f[2] = c    - W(0,4) * c    = a    - c
f[3] = b    - W(1,4) * d    = b    + j.d
```

(b)

The DFG for (a) is given as follows



- *reorder*: Reads 4 tokens and shuffles them to match the flow diagram

  The *t[0]* and *t[2]* are processed by the top butterfly and *t[1]* and *t[3]* are processed by the bottom butterfly
- *fft2*: Calculates the butterflies for the left half of the flow diagram
- *fft4mag* calculates the butterflies for the right half and produces the magnitude component of the frequency domain representation

Mapping DFGs to Single Processors: Example Dynamic Schedule

The implementation first requires a valid schedule to be computed

The *firing rate* is easily determined to be $[q_{reorder}, q_{fft2}, q_{fft4mag}]$ = **[1, 2, 1]**

```
void reorder(actorio_t *g)
  {
  int v0, v1, v2, v3;
  while ( fifo_size(g->in[0]) >= 4 )
    {
    v0 = get_fifo(g->in[0]);
    v1 = get_fifo(g->in[0]);
    v2 = get_fifo(g->in[0]);
    v3 = get_fifo(g->in[0]);
    put_fifo(g->out[0], v0);
    put_fifo(g->out[0], v2);
    put_fifo(g->out[0], v1);
    put_fifo(g->out[0], v3);
    }
  }
```

Mapping DFGs to Single Processors: Example Dynamic Schedule

```
void fft2(actorio_t *g)
  {
  int a, b;
  while (fifo_size(g->in[0]) >= 2 )
    {
    a = get_fifo(g->in[0]);
    b = get_fifo(g->in[0]);
    put_fifo(g->out[0], a+b);
    put_fifo(g->out[0], a-b);
    }
  }
```

Mapping DFGs to Single Processors: Example Dynamic Schedule

```
void fft4mag(actorio_t *g)
    {
    int a, b, c, d;
    while ( fifo_size(g->in[0]) >= 4 )
        {
        a = get_fifo(g->in[0]);
        b = get_fifo(g->in[0]);
        c = get_fifo(g->in[0]);
        d = get_fifo(g->in[0]);
        put_fifo(g->out[0], (a+c)*(a+c));
        put_fifo(g->out[0], b*b - d*d);
        put_fifo(g->out[0], (a-c)*(a-c));
        put_fifo(g->out[0], b*b - d*d);
        }
    }
```

while loops are used in all *actors* as a mechanism to deal with *mismatches* between the scheduler's calls to *actors* and their actual firing rates (as noted earlier)

Mapping DFGs to Single Processors: Example Dynamic Schedule

```
int main()
  {
  fifo_t q1, q2, q3, q4;
  actorio_t reorder_io = {{&q1}, {&q2}};
  actorio_t fft2_io = {{&q2}, {&q3}};
  actorio_t fft4_io = {{&q3}, {&q4}};

  init_fifo(&q1);
  init_fifo(&q2);
  init_fifo(&q3);
  init_fifo(&q4);

// Test vector fft([1 1 1 1])
  put_fifo(&q1, 1);
  put_fifo(&q1, 1);
  put_fifo(&q1, 1);
  put_fifo(&q1, 1);
```

Mapping DFGs to Single Processors: Example Dynamic Schedule

```
// Test vector fft([1 1 1 0])
   put_fifo(&q1, 1);
   put_fifo(&q1, 1);
   put_fifo(&q1, 1);
   put_fifo(&q1, 0);

   while (1)
      {
      reorder(&reorder_io);
      fft2(&fft2_io);
      fft4mag(&fft4_io);
      }
   return 0;
   }
```

The deterministic property of SDFs and the **while** loops inside the *actors* allow the call order shown above to be re-arranged while preserving the functional behavior