Software implementations of dataflow models

Lecture 04 on Dedicated systems

Teacher: Giuseppe Scollo

University of Catania
Department of Mathematics and Computer Science
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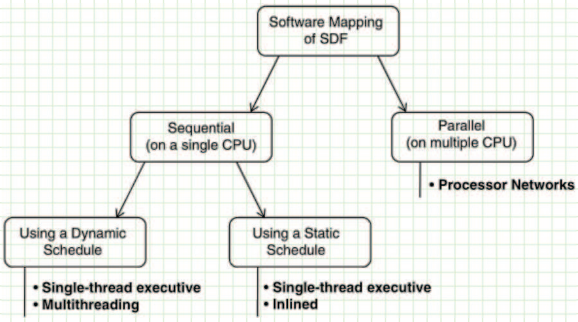
outline:

- overview of software implementation methods for dataflow models
- implementation of FIFO queues in C
- implementation of actors in C
- example: SDF model of an FFT and its implementation
- dynamic scheduling with cooperative multithreading
- use of the QuickThreads library
- implementation optimization with static schedule and inlining

model elements to be mapped to software: actors, queues, firing rules

wide spectrum of implementation options:



Schaumont, Figure 3.1 - Overview of possible approaches to map dataflow into software

parallel implementation, optimization of distribution of actors over the processors:

- computational load balancing
- minimization of inter-processor communication

sequential implementation, options: scheduling, threading

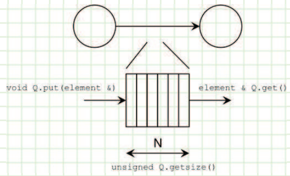
static scheduling → further optimization opportunities

implementation of FIFO queues

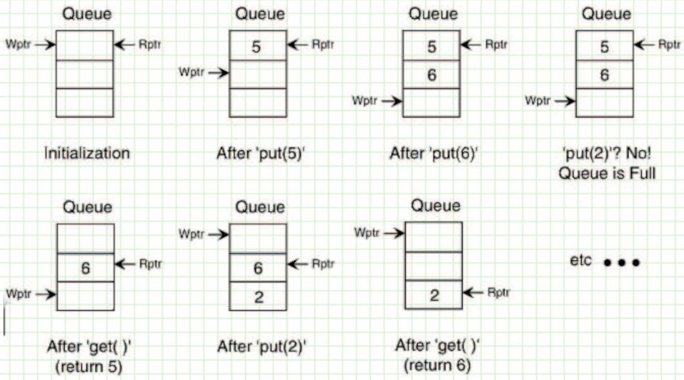
FIFO queue, structure with:

- two parameters: size, element data type
- three operations: void put(element), element get(), int getsize()

it may be implemented as a circular array with two pointers to the access locations for the read and write operations, that are incremented mod N if the array size is N+1



Schaumont, Figure 3.2 – A software queue



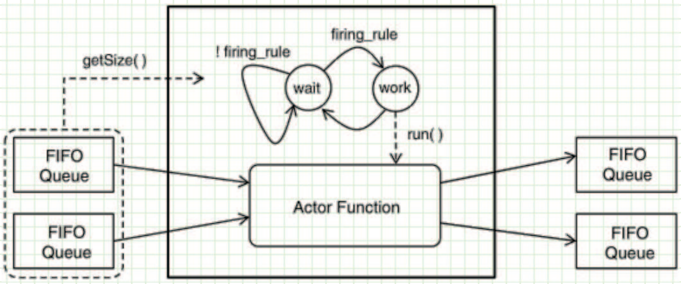
Schaumont, Figure 3.3 – Operation of the circular queue

FIFO queue in C

```
#define MAXFIFO 8
typedef struct fifo {
  int data[MAXFIFO]; // token storage
  unsigned wptr; // write pointer
  unsigned rptr; // read pointer
} fifo_t;

void init_fifo(fifo_t *F) {
  F->wptr = F->rptr = 0;
}

void put_fifo(fifo_t *F, int d) {
  if (((F->wptr + 1) % MAXFIFO) != F->rptr) {
    F->data[F->wptr] = d;
    F->wptr = (F->wptr + 1) % MAXFIFO;
  }
}

int get_fifo(fifo_t *F) {
  int r;
  if (F->rptr != F->wptr) {
    r = F->data[F->rptr];
    F->rptr = (F->rptr + 1) % MAXFIFO;
    return r;
  }
  return -1;
}

unsigned fifo_size(fifo_t *F) {
  if (F->wptr >= F->rptr)
    return F->wptr - F->rptr;
  else
    return MAXFIFO - (F->rptr - F->wptr);
}

int main() {
  fifo_t F1;
  init_fifo(&F1); // resets wptr, rptr;
  put_fifo(&F1, 5); // enter 5
  put_fifo(&F1, 6); // enter 6
  printf("%d %d\n", fifo_size(&F1), get_fifo(&F1));
  // prints: 2 5
  printf("%d\n", fifo_size(&F1)); // prints: 1
}
```

Schaumont, Listing 3.1 – FIFO object in C a C function, parameterized with a data structure to support I/O on the FIFO queues

- actor I/O is subject to validity of its firing rule
  - presence of the required number of tokens on each of its input queues
- firing rule validity is checked by the actor itself upon every invocation
  - a first, elementary example of FSM with datapath (FSMD), see figure



Schaumont, Figure 3.4 - Software implementation of the datafow actor

a data structure to support up to eight input queues and as many output queues:

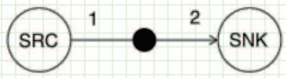
```
#define MAXIO 8
typedef struct actorio {
  fifo_t *in[MAXIO];
  fifo_t *out[MAXIO];
} actorio_t;
```

an actor which reads two integer tokens and produces their sum and their difference:

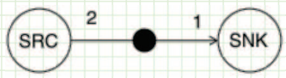
```
void fft2(actorio_t *g) {
  int a, b;
  if (fifo_size(g->in[0]) >= 2) {
    a = get_fifo(g->in[0]);
    b = get_fifo(g->in[0]);
    put_fifo(g->out[0], a+b);
    put_fifo(g->out[0], a-b);
  }
}
```

with this arrangement, actors may be instantiated in the main program and invoked by dynamic scheduling a dynamic system scheduler instantiates and initializes actors and queues, then it invokes the actors—say, 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
 }
}
```



Schaumont, Figure 3.5a – A graph which will simulate under a single rate system schedule



Schaumont, Figure 3.5b – A graph which will cause extra tokens under a single rate schedule

system schedule

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

a problem is apparent with the example in the second figure

solution 1: adjust system schedule

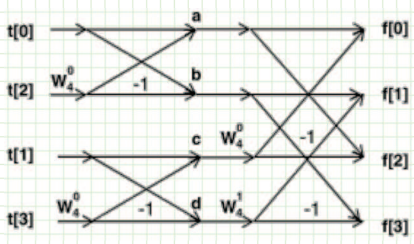
```
void main() {
 ..
 while (1) {
  src_actor(&src_io);
  snk_actor(&snk_io);
  snk_actor(&snk_io);
 }
}
```

solution 2: adjust actor `snk` code

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


the fast (discrete) Fourier transform is widely used in signal processing

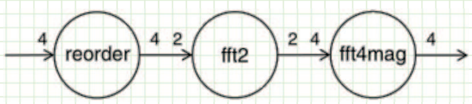
- *twiddle factors* (complex roots of unity): $W_N^k = W(k, N) = e^{-j2\pi k/N}$



Schaumont, Figure 3.6a – Flow diagram for a four-point Fast Fourier Transform

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

an SDF model for the magnitude computation in the frequency domain:



Schaumont, Figure 3.7 – Synchronous dataflow diagram for a four-point Fast Fourier Transform

- reorder : (t[0],t[1],t[2],t[3])→(t[0],t[2],t[1],t[3])
- fft2 : the actor in example on p. 7
- fft4mag : → 4-point transform magnitudes

software implementation of the FFT model

```
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);
  }
}
```

```
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);
  }
}
```

```
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);
  }
}
```

```
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);
  // 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;
}
```

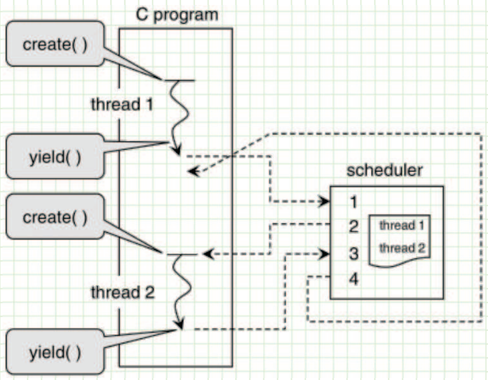
Schaumont, Listing 3.2 - 4-point FFT as an SDF system

dynamic scheduling with cooperative multithreading

with multithreading, dynamic scheduling is implemented by assigning each actor its own thread of execution

> *cooperative* multithreading: actors release control, execution of each actor resumes from the point where that actor released control

often: round-robin scheduler + solution 2 seen earlier



Schaumont, Figure 3.8 - Example of cooperative multi-threading

QuickThreads library functions:

- stp_init()
- stp_create(stp_userf_t *F, void *G)
- stp_start()
- stp_yield()
- stp_abort()

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implementation using the QuickThreads library

control release with stp_yield() keeps local variables throughout subsequent runs

```
#include "../qt/stp.h"
#include <stdio.h>
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();
  }
}
int main(int argc, char **argv) {
  stp_init();
  stp_create(hello, 0);
  stp_create(world, 0);
  stp_start();
  return 0;
}
```

application of this technique to the example developed in Listing 3.2 is very simple, e.g. for actor fft2:

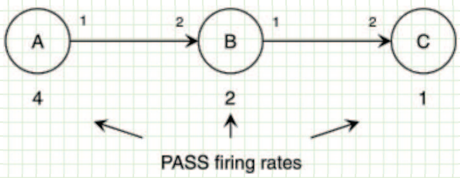
```
void fft2(actorio_t *g) {
  int a, b;
  while (1) {
    while (fifo_size(g->in[0]) >= 2) {
      a = get_fifo(g->in[0]);
      b = get_fifo(g->in[0]);
      put_fifo(g->out[0], a+b);
      put_fifo(g->out[0], a-b);
    }
    stp_yield();
  }
}

int main() {
  fifo_t q1, q2;
  actorio_t fft2_io = {{&q1}, {&q2}};
  ...
  stp_create(fft2, &fft2_io); // create thread
  ...
  stp_start(); // run the schedule
}
```


optimization of implementation under static schedule

static scheduling allows optimization of a software implementation in three respects:

- no need to check the firing rules in the actors' code
- schedule optimization to minimize the storage requirements for the FIFO queues
- code inlining:
  - variables replace FIFO queues → space saving
  - no function calls → time saving

example:




```
while(1) {
  // call A four times
  A(); A(); A(); A();
  // call B two times
  B(); B();
  // call C one time
  C();
}
```

Schaumont, Figure 3.9 - System schedule for a multirate SDF graph

the static schedule in the figure is a PASS, yet it is not optimal for the minimization of the capacity of the queues: the firing sequence (A, A, B, A, A, B, C) is optimal

optimized implementation of the FFT4 model on p. 9 with static schedule and inlining:

```
void dfsystem(int in0, in1, in2, in3, *out0, *out1, *out2, *out3) {
  int reorder_out0, reorder_out1, reorder_out2, reorder_out3;
  int fft2_0_out0, fft2_0_out1, fft2_1_out0, fft2_1_out1;
  int fft4mag_out0, fft4mag_out1, fft4mag_out2, fft4mag_out3;

  reorder_out0 = in0;
  reorder_out1 = in2;
  reorder_out2 = in1;
  reorder_out3 = in3;

  fft2_0_out0 = reorder_out0 + reorder_out1;
  fft2_0_out1 = reorder_out0 - reorder_out1;
  fft2_1_out0 = reorder_out2 + reorder_out3;
  fft2_1_out1 = reorder_out2 - reorder_out3;

  out0 = fft4mag_out0 = (fft2_0_out0 + fft2_1_out0) * (fft2_0_out0 + fft2_1_out0);
  out1 = fft4mag_out1 = fft2_0_out1*fft2_0_out1 - fft2_1_out1*fft2_1_out1;
  out2 = fft4mag_out2 = (fft2_0_out0 - fft2_1_out0) * (fft2_0_out0 - fft2_1_out0);
  out3 = fft4mag_out3 = fft2_0_out1*fft2_0_out1 - fft2_1_out1*fft2_1_out1;
}
```

Schaumont, Listing 3.4 - Inlined data flow system for the four-point FFT

recommended readings:

Schaumont (2012) Ch. 3, Sect. 3.1

for further consultation:

Schaumont (2012) Ch. 4