Data Flow Models

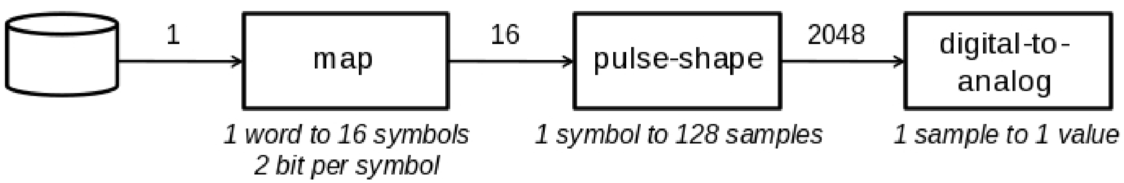
As we discussed, hardware is parallel while software is sequential

We need **concurrent** high-level models to allow designers to describe systems that are independent of software or hardware

This provides flexibility in mapping components to either HW or SW in later phases of design

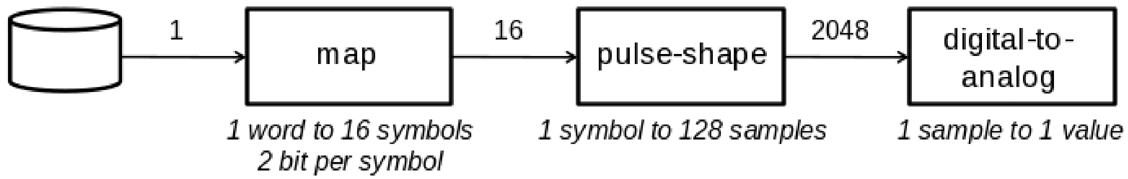
Block diagrams have become popular as a mechanism to describe systems, includ- ing DSP systems such as digital radios and radar, at a high level of abstraction

Block diagrams use symbols to represent signal processing functions, i.e., operations performed on a digital data stream, without specifying the implementation strategy



This block diagram shows an example of a ***pulse-amplitude modulation*** (**PAM**) sys- tem, used to transmit information over bandwidth-limited channels

Data Flow Models

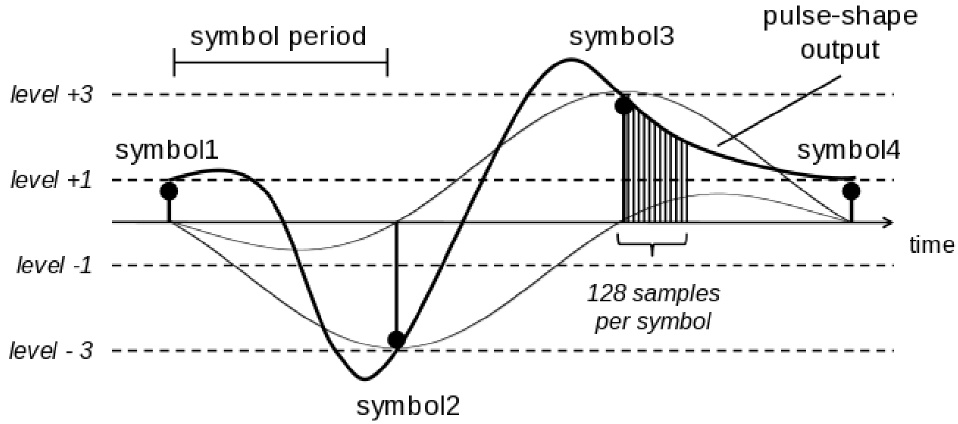


The PAM system reads a file of binary data in 32-bit chunks

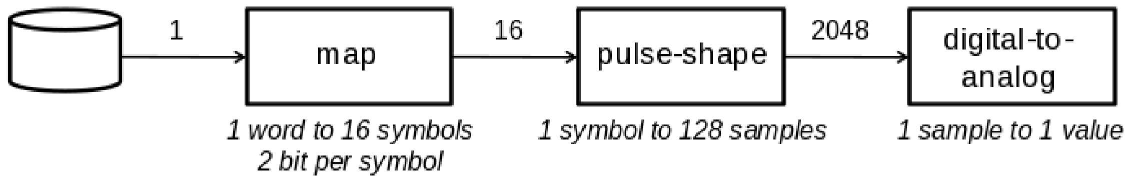
The *map* function converts the 32-bits of each word to 16 2-bit symbols (PAM-4 is used to refer to such systems

Each 2-bit sequence maps to one of 4 separate symbols in the set {-3, -1, 1 and 3}

Each symbol represents a *pulse height*



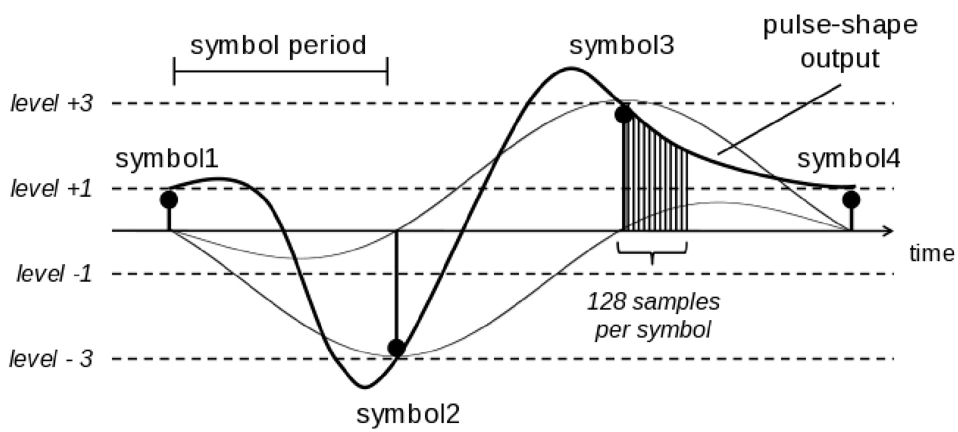
Data Flow Models



The 2-bit symbols need to be converted into a smooth shape using *pulse shaping*

The *pulse shaper* ensures that the frequency content of the smoothed curve does not exceed 2X the symbol rate to avoid adding artifacts to the generated curve

The *pulse-shape* function **oversamples** the symbols to provide a smooth function, producing 128 digital samples for each symbol as shown



A convolution-based function is used to ensure the curve goes through the symbols while providing a *memory* effect, which allows symbols to influence other symbols

Data Flow Models

The *digital-to-analog converter* (DAC) is used to convert the discrete samples into an analog output signal

Here’s a high-level simulation model for PAM-4

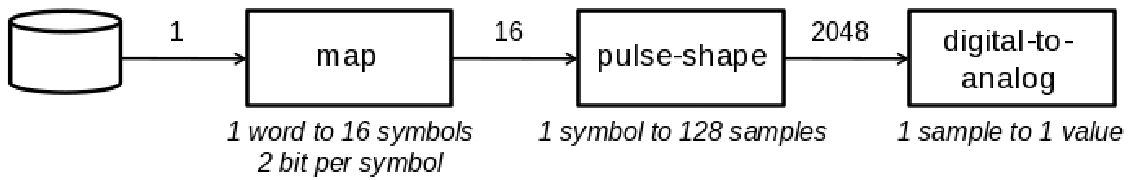
```
extern int read_from_file(), map_to_symbol(int, int);
extern int pulse_shape(int, int);
extern void send_to_da(int);
int main() {
   int word, symbol, sample;
   int i, j;
   while (1) {
      word = read_from_file();
      for ( i = 0; i < 16; i++ ) {
         symbol = map_to_symbol(word, i);
         for ( j = 0;j< 128;   j++ ) {
            sample = pulse_shape(symbol, j);
            send_to_da(sample);
   } } } }
```

Data Flow Models

Although this is a good model for simulation, it is **not** for an implementation

C implicitly assumes sequential execution

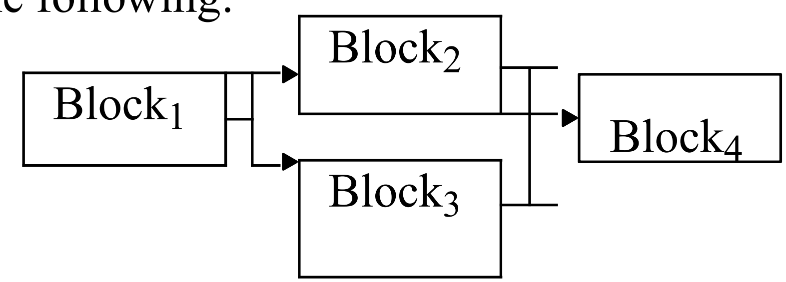
The block diagram, on the other hand, is implicitly parallel



The lines between blocks represent *data dependencies*, and therefore, they force an ordering to the sequence of operations

However, unlike C, each block can execute simultaneously with other blocks

Another example of the difference between C and block diagrams is shown by the 'fanout' in the following:



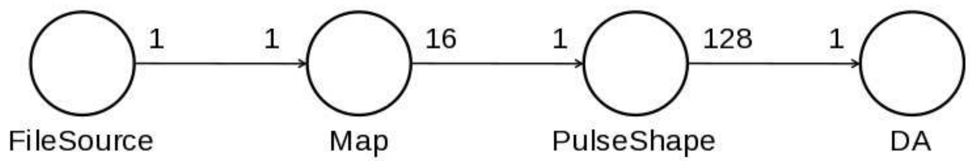
Here, *Block*$_2$ and *Block*$_3$ are clearly parallel but C would execute them sequentially

Data Flow Models

Note that, in general, it is *easier* to create a sequential implementation from a parallel model than it is to create a parallel implementation from a sequential model

This argues in favor of **Data Flow** diagrams for modeling

The following is a Data Flow model of PAM-4:



The bubbles, called **actors**, represent the functions in the block diagram

Actors are linked together using directional lines, called **queues**

The numbers on the lines represent the relative **rates** of communications between modules, e.g., *Map* converts a 32-bit word into 16 2-bit symbols

Note that each *actor* works **independently**, i.e., it checks its input queue for the proper number of elements and executes immediately when satisfied

Data Flow Models vs. C Programs

We cover Data Flow in this lecture but for now, we note the following important differences between C and Data Flow models:

- Data Flow is a ***concurrent model*** (this is a major driver for their popularity), which means they can easily be mapped to hardware or software implementations
- Data Flow models are *distributed*, i.e., there is no centralized controller, i.e., each *actor* operates autonomously
- Data Flow models are *modular*, allowing libraries of components to be constructed and utilized in a *plug-and-play* fashion
- Data Flow models can be *analyzed*, e.g., for *deadlock* conditions that can result in system lock-up

    Deterministic, mathematical methods can be used to analyze Data Flow models, which is generally not possible using C

Data Flow models have been around since the early 1960s

The 70's and 80's were active periods of research and development of Data Flow programming languages and even Data Flow architectures

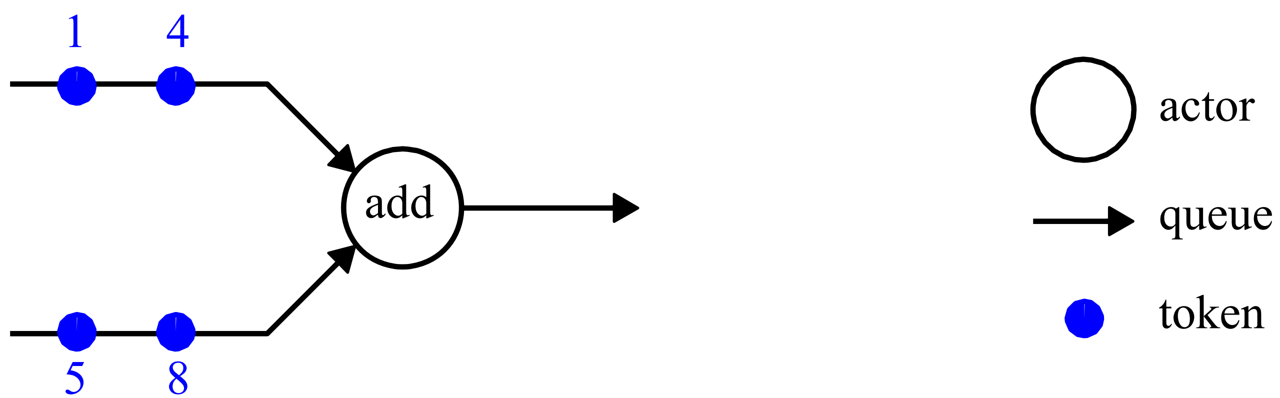
NI's **Labview** is a classic example of a Data Flow programming language

Tokens, Actors and Queues

Here, we define the elements that make up a Data Flow model, and discuss a special class of Data Flow models called *Synchronous Data Flow* (SDF) Graphs

SDFs allow for the application of formal analysis techniques

A simple example:



A Data Flow model is made up of three elements:

- **Actors**: Contain the actual operations

  Actors have a precise beginning and end, i.e., they have *bounded* behavior, and they *iterate* that behavior continuously

  Each iteration is called a ***firing***, e.g., an addition is performed on each firing

Tokens, Actors and Queues

- **Tokens**: Carry information from one *actor* to another

  A token has a *value*, such '1' and '4' as shown above

- **Queues**: Unidirectional communication links that transport tokens between *actors*

  We assume Data Flow *queues* have an **infinite** amount of storage

  Data Flow *queues* are first-in, first-out (FIFO)

  In above example, token '1' is entered after token '4' so token '4' is processed first

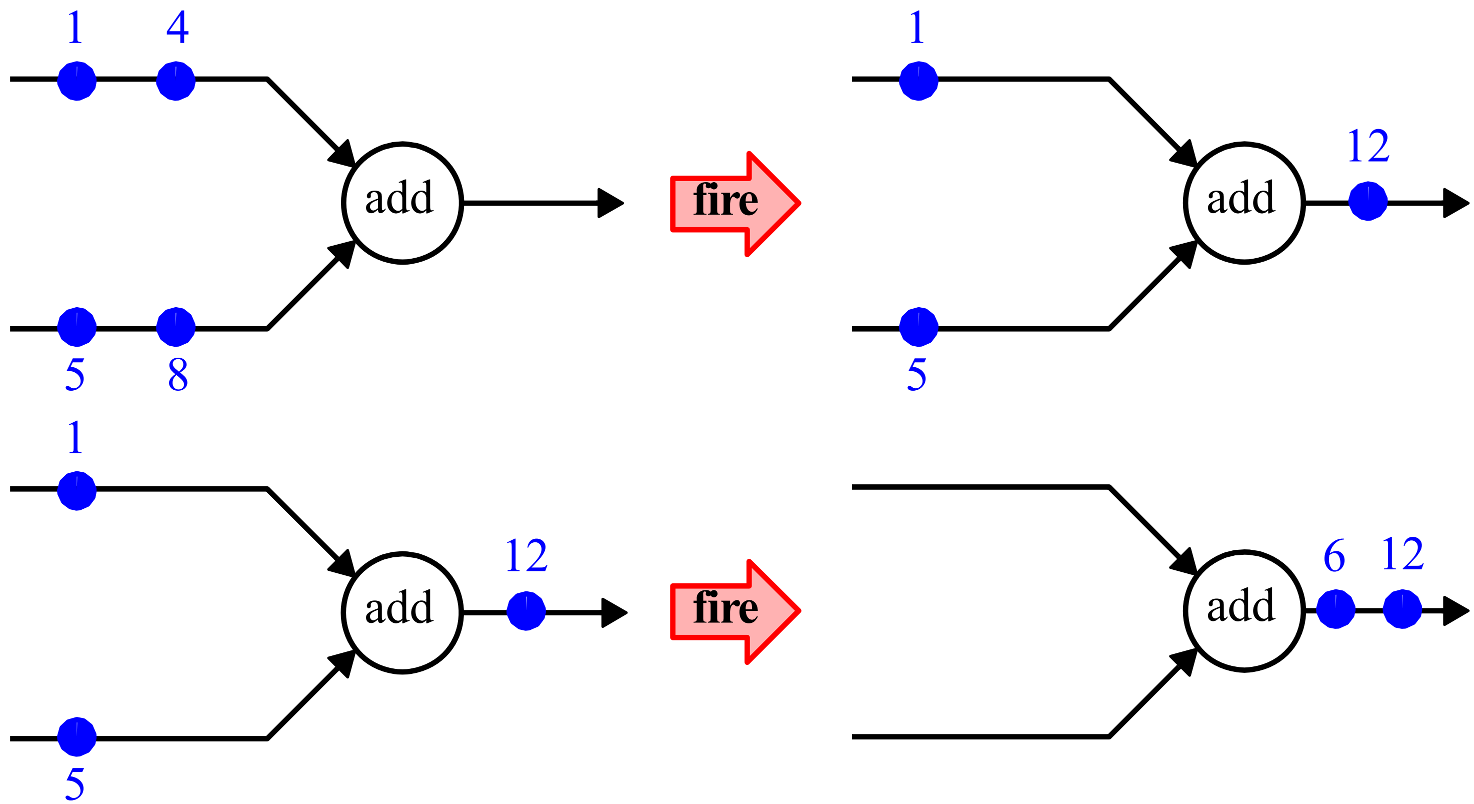
When a Data Flow model executes, *actors* read tokens from their **input** *queues*, apply an operation and then write values to the **output** *queue*

The execution of a Data Flow model is expressed as a sequence of **concurrent actor firings**

Tokens, Actors and Queues

- Data Flow models are **untimed**
  - The firing of an *actor* happens instantaneously and therefore time is **irrelevant**
    - Firings actually take non-zero time in an actual implementation
  - The execution of Data Flow models is *guided* only by **the presence of data**, i.e., an *actor* can **not** fire until data becomes available on its inputs
- A Data Flow graph with tokens distributed across its *queues* is called a **marking** of a Data Flow model
- A Data Flow graph goes through a series of *marking* when it is executed
- Each marking corresponds to a different **state** of the system
  - The distribution of tokens in the *queues* (marking) are the ONLY observable state in the system (no state is maintained inside the actors)

Firing Rates, Firing Rules and Schedules



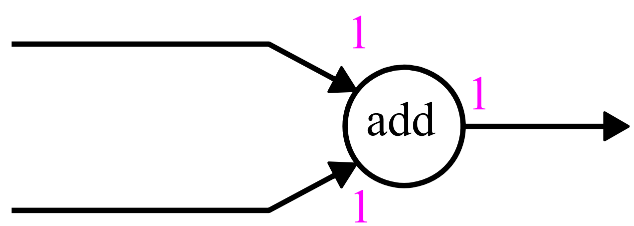
A **firing rule** defines the conditions that enable an *actor* to fire

In the above example, the firing rule checks that the *actor*'s input *queues* contain at least one token

Therefore, *actors* are able to check the number of tokens in each of its *queues*

Firing Rates, Firing Rules and Schedules

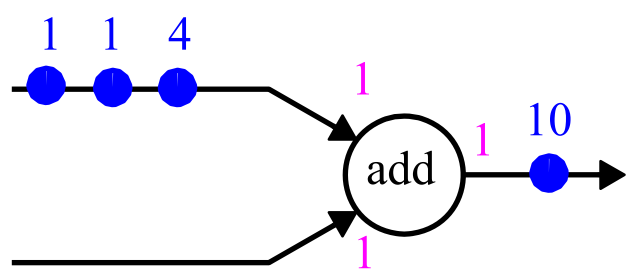
The **required** number of tokens consumed and produced can be annotated on the *actors* inputs and outputs, respectively



Inputs: **token consumption rate**

Outputs: **token production rate**

Therefore, this information combined with a marking makes is easy to decide whether an *actor* can fire



Not able to fire

Data Flow *actors* can also consume *more than one* token per firing

This is referred to as a **multi-rate** Data Flow graph