Asynchronous Circuit Design

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Lecture 3: Communication Protocols
Chapter 3

Handshaking Level Representation

```
library ieee;
use ieee.std_logic_1164.all;
use work.nondeterminism.all;
use work.handshake.all;
entity shopPA_dualrail is
  port (bottle1:in std_logic;
        bottle0:in std_logic;
        ack_wine:buffer std_logic:='0';
        shelf1:buffer std_logic:='0';
        shelf0:buffer std_logic:='0';
        ack_patron:in std_logic);
end shopPA_dualrail;
```

Naive Handshaking Level Representation

```
shopPA_dualrail:process
begin
  wait until ack_patron = '0';
  wait until bottle0 = '1' or bottle1 = '1';
  if bottle0='1' then shelf0<='1' after delay(1,3);
  elsif bottle1='1' then shelf1<='1' after delay(1,3);
  end if;
  ack_wine <= '1' after delay(1,3);
  wait until ack_patron = '1';
  shelf0 <= '0' after delay(1,3);
  shelf1 <= '0' after delay(1,3);
  wait until bottle0 = '0' and bottle1 <= '0';
  ack_wine <= '0' after delay(1,3);
end process;
```

Handshaking Level Representation

```
shopPA_dualrail:process
begin
  guard(ack_patron,'0');
  guard_or(bottle0,'1',bottle1,'1');
  if bottle0 = '1' then assign(shelf0,'1',1,3);
  elsif bottle1 = '1' then assign(shelf1,'1',1,3);
  end if;
  assign(ack_wine,'1',1,3);
  guard(ack_patron,'1');
  vassign(shelf0,'0',1,3,shelf1,'0',1,3);
  guard_and(bottle0,'0',bottle1,'0');
  assign(ack_wine,'0',1,3);
end process;
```

Handshake Package: *guard* Procedures

- *guard*(*s*,*v*) takes a signal, *s*, and a value, *v*, and replaces:

```
if (s /= v) then
   wait until s = v;
end if;
```

- *guard_or*(*s*1,*v*1,*s*2,*v*2,. . .) takes a set of signals and values, and replaces:

```
if ((s1 /= v1) and (s2 /= v2) ...  )  then
   wait until (s1 = v1) or (s2 = v2) ...;
end if;
```

- *guard_and*(*s*1,*v*1,*s*2,*v*2,. . .) takes a set of signals and a set of values, and replaces:

```
if ((s1 /= v1) or (s2 /= v2) ...  )  then
   wait until s1 = v1 and s2 = v2 ...;
end if;
```

Handshake Package: *assign* Procedures

- *assign*(*s*,*v*,*l*,*u*) takes a signal, *s*, a value, *v*, a lower bound of delay, *l*, and an upper bound of delay, *u*, and replaces:

```
assert (s /= v)
   report "Vacuous assignment!"
   severity failure;
s <= v after delay(l,u);
wait until s = v;
```

- *assign*(*s*1,*v*1,*l*1,*u*1,*s*2,*v*2,*l*2,*u*2) implements a parallel assignment as follows:

```
assert ((s1 /= v1) or (s2 /= v2))
   report "Vacuous assignment!"
   severity failure;
s1 <= v1 after delay(l1,u1);
s2 <= v2 after delay(l2,u2);
wait until (s1 = v1) and (s2 = v2);
```

Handshake Package: *vassign* Procedures

- *Vacuous assign (vassign)* procedure is defined below:

```
if (s /= v) then
  s <= v after delay(l,u);
  wait until s = v;
end if;
```

- *vassign* procedure also allows parallel assignments:

```
if (s1 /= v1) then
  s1 <= v1 after delay(l1,u1);
end if;
if (s2 /= v2) then
  s2 <= v2 after delay(l2,u2);
end if;
if (s1 /= v1) or (s2 /= v2) then
  wait until s1 = v1 and s2 = v2;
end if;
```

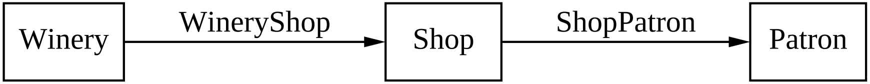
Active and Passive Ports

- Channel has an *active* and a *passive* port.
- Active port initiates communication.
- Passive port must patiently wait.
- If a process uses the *probe* function on a channel, it must connect to the passive port.
- If a channel is not probed, then the assignment is arbitrary.

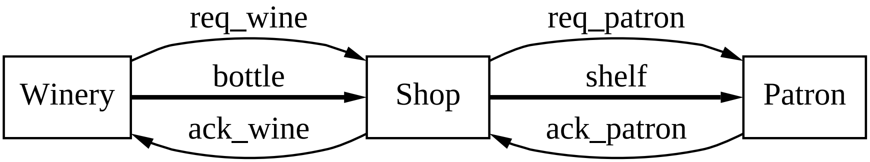
Active and Passive Ports

```
entity shopPA is
  port(wine_delivery:inout channel:=passive;
       wine_selling:inout channel:=active);
end shopPA;
```

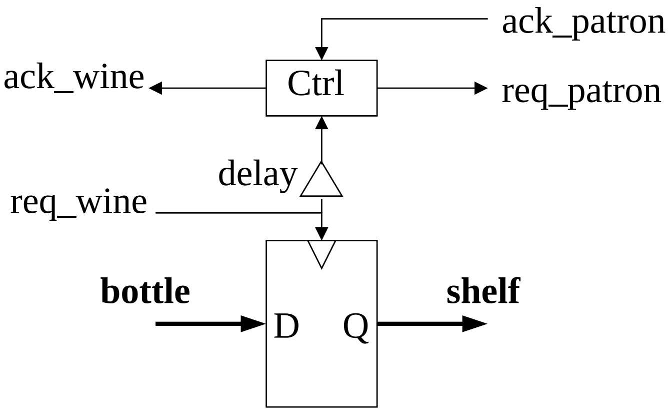
Passive/Active *wine_shop* using Bundled Data



Passive/Active *wine_shop* using Bundled Data



Two-Phase Bundled-Data Datapath



Double−edge Triggered Flip−flop

Two-Phase Bundled-Data Winery (part I)

```
library ieee;
use ieee.std_logic_1164.all;
use work.nondeterminism.all;
use work.handshake.all;
entity winery_bundled is
  port(req_wine:buffer std_logic:='0';
       ack_wine:in std_logic;
       bottle:buffer
         std_logic_vector(2 downto 0):="000");
end winery_bundled;
```

Two-Phase Bundled-Data Winery (part II)

```
architecture two_phase of winery_bundled is
begin
winery_bundled_2phase:process
begin
  bottle <= selection(8,3);
  wait for delay(5,10);
  assign(req_wine,not req_wine,1,3); – call shop
  guard(ack_wine,req_wine);      – wine delivered
end process;
end two_phase;
```

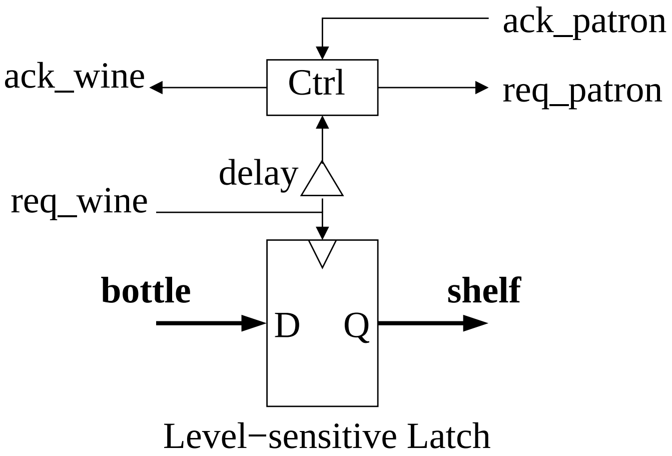
Two-Phase Bundled-Data Patron

```
patronP_bundled_2phase:process
begin
  guard(req_patron,not ack_patron);    - shop calls
  bag <= shelf after delay(2,4);
  wait for delay(5,10);
  assign(ack_patron,not ack_patron,1,3); - buys wine
end process;
```

Two-Phase Bundled-Data Shop

```
shop_bundled_2phase:process
begin
  guard(req_wine,not ack_wine);       -- winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(req_patron,not req_patron,1,3);
                                       -- call patron
  guard(ack_patron,req_patron);   -- patron buys wine
  assign(ack_wine,not ack_wine,1,3);   -- wine sold
end process;
```

Four-Phase Bundled-Data Datapath



Four-Phase Bundled-Data Winery

```
winery_bundled_4phase:process
begin
  bottle <= selection(8,3);
  wait for delay(5,10);
  assign(req_wine,'1',1,3);     -- call shop
  guard(ack_wine,'1');           -- wine delivered
  assign(req_wine,'0',1,3);     -- reset req_wine
  guard(ack_wine,'0');           -- ack_wine resets
end process;
```

Four-Phase Bundled-Data Patron

```
patronP_bundled_4phase:process
begin
  guard(req_patron,'1');        - shop calls
  bag <= shelf after delay(2,4);
  wait for delay(5,10);
  assign(ack_patron,'1',1,3);  - patron buys wine
  guard(req_patron,'0');        - req_patron resets
  assign(ack_patron,'0',1,3);  - reset ack_patron
end process;
```

Four-Phase Bundled-Data Shop

```
shop_bundled_4phase:process
begin
  guard(req_wine,'1');          – winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(ack_wine,'1',1,3);   – shop receives wine
  guard(req_wine,'0');          – req_wine resets
  assign(ack_wine,'0',1,3);   – reset ack_wine
  assign(req_patron,'1',1,3); – call patron
  guard(ack_patron,'1');        – patron buys wine
  assign(req_patron,'0',1,3); – reset req_patron
  guard(ack_patron,'0');        – ack_patron resets
end process;
```

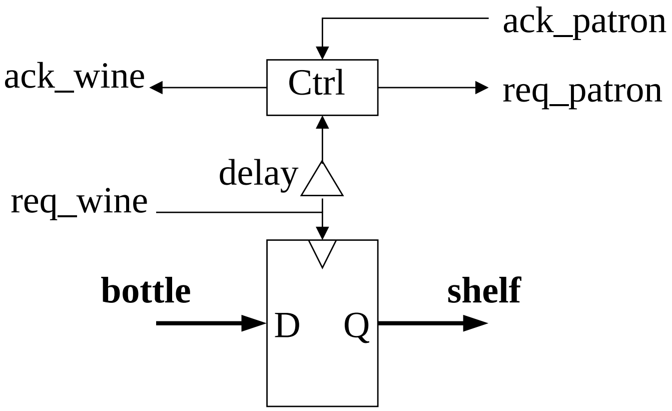
Reshuffled Shop

```
Shop_PA_reshuffled:process
begin
  guard(req_wine,'1');          - winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(ack_wine,'1',1,3);   - shop receives wine
  assign(req_patron,'1',1,3); - call patron
  guard(req_wine,'0');          - req_wine resets
  assign(ack_wine,'0',1,3);   - reset ack_wine
  guard(ack_patron,'1');        - patron buys wine
  assign(req_patron,'0',1,3); - reset req_patron
  guard(ack_patron,'0');        - ack_patron resets
end process;
```

Lazy-Active Shop

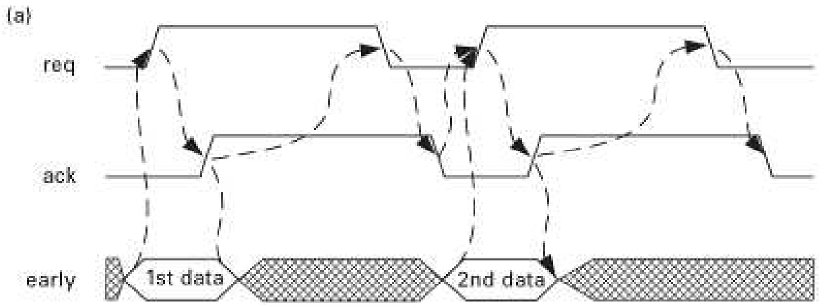
```
Shop_PA_lazy_active:process
begin
  guard(req_wine,'1');          – winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(ack_wine,'1',1,3);   – shop receives wine
  guard(ack_patron,'0');        – ack_patron resets
  assign(req_patron,'1',1,3); – call patron
  guard(req_wine,'0');          – req_wine resets
  assign(ack_wine,'0',1,3);   – reset ack_wine
  guard(ack_patron,'1');        – patron buys wine
  assign(req_patron,'0',1,3); – reset req_patron
end process;
```

Four-Phase Bundled-Data Datapath



Level−sensitive Latch

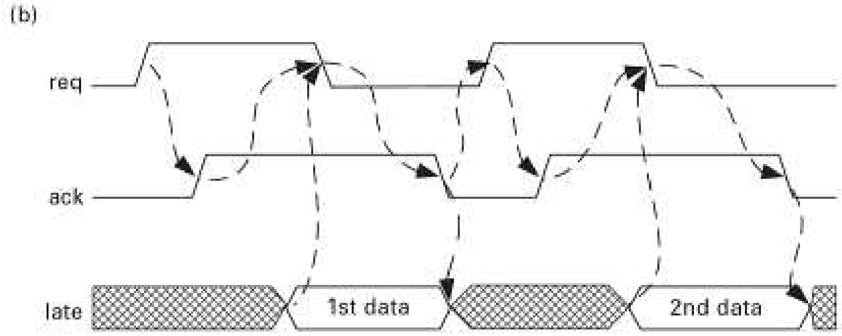
Four-Phase Bundled-Data Early Protocol



Lazy-Active Shop (Early Protocol)

```
Shop_PA_lazy_active:process
begin
  guard(req_wine,'1');          - winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  guard(ack_patron,'0');        - ack_patron resets
  assign(req_patron,'1',1,3);  - call patron
  guard(ack_patron,'1');        - patron buys wine
  assign(req_patron,'0',1,3);  - reset req_patron
  assign(ack_wine,'1',1,3);   - shop receives wine
  guard(req_wine,'0');          - req_wine resets
  assign(ack_wine,'0',1,3);   - reset ack_wine
end process;
```

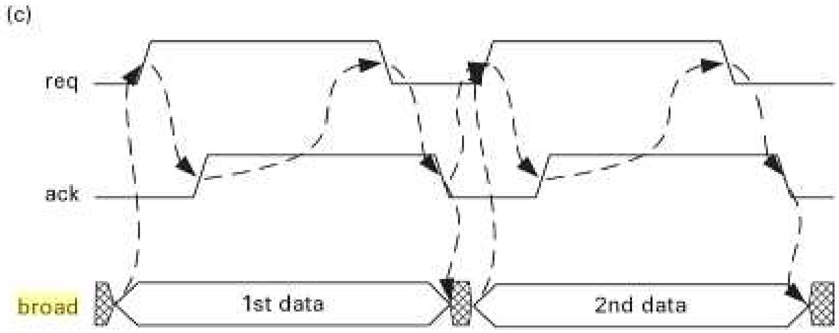
Four-Phase Bundled-Data Late Protocol



Lazy-Active Shop (Late Protocol)

```
Shop_PA_lazy_active:process
begin
  guard(req_wine,'1');         -- winery calls
  assign(req_patron,'1',1,3); -- call patron
  guard(ack_patron,'1');       -- patron buys wine
  assign(ack_wine,'1',1,3);   -- shop receives wine
  guard(req_wine,'0');         -- req_wine resets
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(req_patron,'0',1,3); -- reset req_patron
  guard(ack_patron,'0');       -- ack_patron resets
  assign(ack_wine,'0',1,3);   -- reset ack_wine
end process;
```

Four-Phase Bundled-Data Broad Protocol



Lazy-Active Shop (Broad Protocol)

```
Shop_PA_lazy_active:process
begin
  guard(req_wine,'1');          – winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(ack_wine,'1',1,3);   – shop receives wine
  guard(ack_patron,'0');        – ack_patron resets
  assign(req_patron,'1',1,3); – call patron
  guard(req_wine,'0');          – req_wine resets
  guard(ack_patron,'1');        – patron buys wine
  assign(ack_wine,'0',1,3);   – reset ack_wine
  assign(req_patron,'0',1,3); – reset req_patron
end process;
```

Need edge-triggered flip-flop

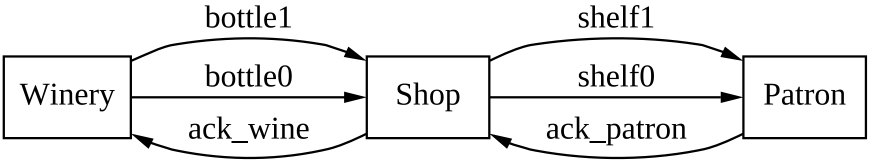
Deadlock

```
Winery_Patron:process
begin
  bottle <= selection(8,3);
  wait for delay(5,10);
  assign(req_wine,'1',1,3);  - call shop
  guard(ack_wine,'1');        - wine delivered
  guard(req_patron,'1');      - shop calls patron
  bag <= shelf after delay(2,4);
  wait for delay(5,10);
  assign(ack_patron,'1',1,3); - patron buys wine
  guard(req_patron,'0');      - req_patron resets
  assign(ack_patron,'0',1,3); - reset ack_patron
  assign(req_wine,'0',1,3);  - reset req_wine
  guard(ack_wine,'0');        - ack_wine resets
end process;
```

State Variable Insertion

```
Shop_PA_SV:process
begin
  guard(req_wine,'1');          – winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(ack_wine,'1',1,3);   – shop receives wine
  assign(x,'1',1,3);            – set x
  guard(req_wine,'0');          – req_wine resets
  assign(ack_wine,'0',1,3);   – reset ack_wine
  assign(req_patron,'1',1,3); – call patron
  guard(ack_patron,'1');        – patron buys wine
  assign(x,'0',1,3);            – reset x
  assign(req_patron,'0',1,3); – reset req_patron
  guard(ack_patron,'0');        – ack_patron resets
end process;
```

Passive/Active *wine_shop* using Dual-Rail (1 bit)



Dual-Rail Winery

```
winery_dual_rail:process
  variable z:integer;
begin
  z:=selection(2);
  case z is
    when 1 =>
      assign(bottle1,'1',1,3);
    when others =>
      assign(bottle0,'1',1,3);
  end case;
  guard(ack_wine,'1');
  vassign(bottle1,'0',1,3,bottle0,'0',1,3);
  guard(ack_wine,'0');
end process;
```

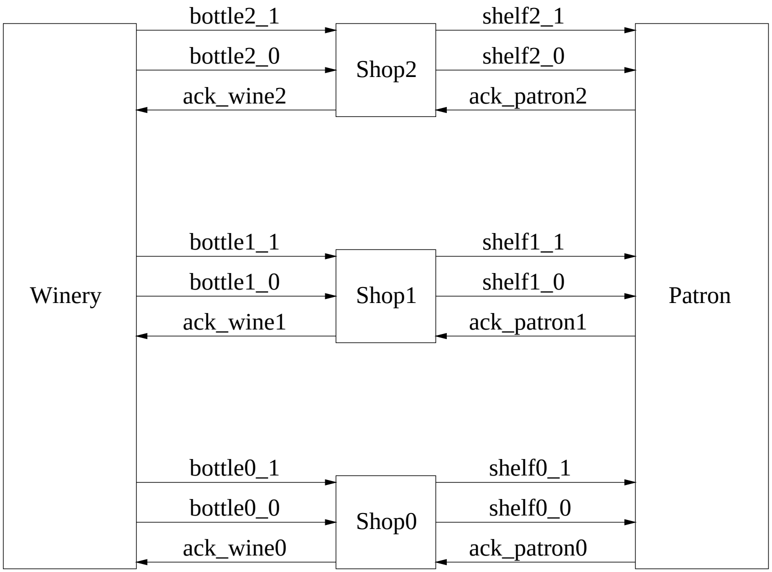
Dual-Rail Shop

```
shopPA_dual_rail:process
begin
  guard(ack_patron,'0');
  guard_or(bottle0,'1',bottle1,'1');
  if bottle0 = '1' then assign(shelf0,'1',1,3);
  elsif bottle1 = '1' then assign(shelf1,'1',1,3);
  end if;
  assign(ack_wine,'1',1,3);
  guard(ack_patron,'1');
  vassign(shelf0,'0',1,3,shelf1,'0',1,3);
  guard_and(bottle0,'0',bottle1,'0');
  assign(ack_wine,'0',1,3);
end process;
```

Dual-Rail Patron

```
patronP_dualrail:process
begin
  guard_or(shelf1,'1',shelf0,'1');
  assign(ack_patron,'1',1,3);
  guard_and(shelf1,'0',shelf0,'0');
  assign(ack_patron,'0',1,3);
end process;
```

Passive/Active *wine_shop* using Dual-Rail



Dual-Rail Winery (part I)

```
winery_dual_rail:process
  variable z:integer;
begin
  z:=selection(8);
  case z is
    when 1 =>
      assign(bottle2_0,'1',1,3,bottle1_0,'1',1,3,
             bottle0_0,'1',1,3);
    when 2 =>
      assign(bottle2_0,'1',1,3,bottle1_0,'1',1,3,
             bottle0_1,'1',1,3);
    when 3 =>
      assign(bottle2_0,'1',1,3,bottle1_1,'1',1,3,
             bottle0_0,'1',1,3);
```

Dual-Rail Winery (part II)

```
when 4 =>
  assign(bottle2_0,'1',1,3,bottle1_1,'1',1,3,
         bottle0_1,'1',1,3);
when 5 =>
  assign(bottle2_1,'1',1,3,bottle1_0,'1',1,3,
         bottle0_0,'1',1,3);
when 6 =>
  assign(bottle2_1,'1',1,3,bottle1_0,'1',1,3,
         bottle0_1,'1',1,3);
when 7 =>
  assign(bottle2_1,'1',1,3,bottle1_1,'1',1,3,
         bottle0_0,'1',1,3);
when others =>
  assign(bottle2_1,'1',1,3,bottle1_1,'1',1,3,
         bottle0_1,'1',1,3);
```

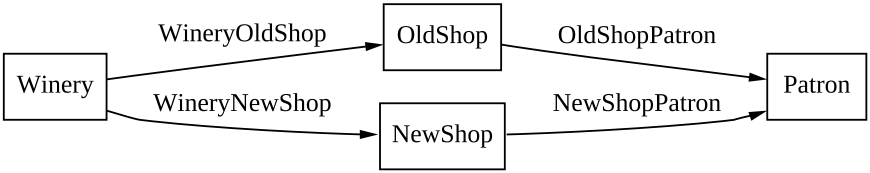
Dual-Rail Winery (part III)

```
  end case;
  guard_and(ack_wine2,'1',ack_wine1,'1',
            ack_wine0,'1');
  vassign(bottle2_0,'0',1,3,bottle1_0,'0',1,3,
          bottle0_0,'0',1,3);
  vassign(bottle2_1,'0',1,3,bottle1_1,'0',1,3,
          bottle0_1,'0',1,3);
  guard_and(ack_wine2,'0',ack_wine1,'0',
            ack_wine0,'0');
end process;
```

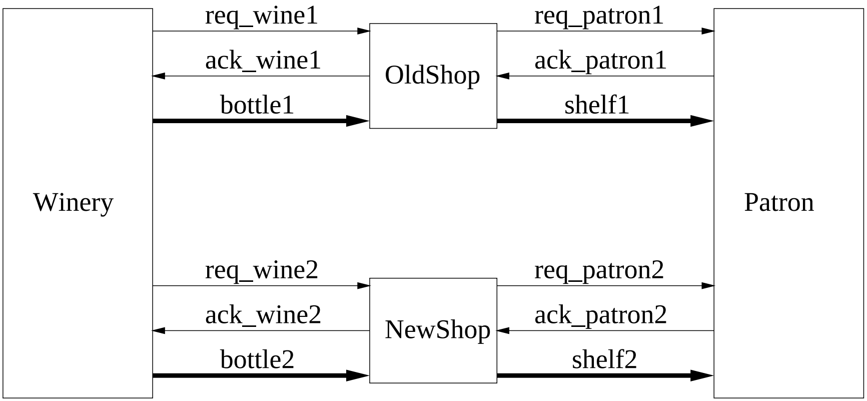
Dual-Rail Patron

```
patronP_dualrail:process
begin
  guard_or(shelf2_1,'1',shelf2_0,'1');
  guard_or(shelf1_1,'1',shelf1_0,'1');
  guard_or(shelf0_1,'1',shelf0_0,'1');
  assign(ack_patron2,'1',1,3,ack_patron1,'1',1,3,
        ack_patron0,'1',1,3);
  guard_and(shelf2_1,'0',shelf2_0,'0');
  guard_and(shelf1_1,'0',shelf1_0,'0');
  guard_and(shelf0_1,'0',shelf0_0,'0');
  assign(ack_patron2,'0',1,3,ack_patron1,'0',1,3,
        ack_patron0,'0',1,3);
end process;
```

Two Wine Shops



Two Wine Shops



Winery for Two Wine Shops

```
winery5:process
variable z:integer;
begin
  bottle <= selection(8,3);
  wait for delay(5,10);
  z:=selection(2);
  case z is
  when 1 =>
    send(WineryNewShop,bottle);
  when others =>
    send(WineryOldShop,bottle);
  end case;
end process winery5;
```

Winery for Two Wine Shops (part I)

```
winery:process
variable z :  integer;
begin
  z := selection(2);
  bottle <= selection(8,3);
  wait for delay(5,10);
  case z is
    when 1 =>
      bottle1 <= bottle after delay(2,4);
      wait for 5 ns;
      assign(req_wine1,'1',1,3);  - call winery
      guard(ack_wine1,'1');        - wine delivered
      assign(req_wine1,'0',1,3);  - reset req_wine
      guard(ack_wine1,'0');        - ack_wine resets
```

Winery for Two Wine Shops (part II)

```
      when others =>
        bottle2 <= bottle after delay(2,4);
        wait for 5 ns;
        assign(req_wine2,'1',1,3);  - call winery
        guard(ack_wine2,'1');        - wine delivered
        assign(req_wine2,'0',1,3);  - reset req_wine
        guard(ack_wine2,'0');        - ack_wine resets
    end case;
  end process;
```

Shop for Two Wine Shops

```
shop:process
begin
  receive(WineryShop,shelf);
  send(ShopPatron,shelf);
end process shop;
```

Shop for Two Wine Shops

```
Shop_PA_lazy_active:process
begin
  guard(req_wine,'1');          - winery calls
  shelf <= bottle after delay(2,4);
  wait for delay(5,10);
  assign(ack_wine,'1',1,3);   - shop receives wine
  guard(ack_patron,'0');        - ack_patron resets
  assign(req_patron,'1',1,3); - call patron
  guard(req_wine,'0');          - req_wine resets
  guard(ack_patron,'1');        - patron buys wine
  assign(ack_wine,'0',1,3);   - reset ack_wine
  assign(req_patron,'0',1,3); - reset req_patron
end process;
```

Patron for Two Wine Shops

```
patron2:process
begin
  if (probe(OldShopPatron)) then
    receive(OldShopPatron,bag);
    wine_drunk <= wine_list'val(conv_integer(bag));
  elsif (probe(NewShopPatron)) then
    receive(NewShopPatron,bag);
    wine_drunk <= wine_list'val(conv_integer(bag));
  end if;
  wait for delay(5,10);
end process patron2;
```

Patron for Two Wine Shops (part I)

```
patronP:process
begin
  if (req_patron1 = '1') then
    bag <= shelf1 after delay(2,4);
    wait for delay(5,10);
    assign(ack_patron1,'1',1,3); - patron buys wine
    guard(req_patron1,'0');      - req_patron resets
    assign(ack_patron1,'0',1,3); - reset ack_patron
    wine_drunk <= wine_list'val(conv_integer(bag));
```

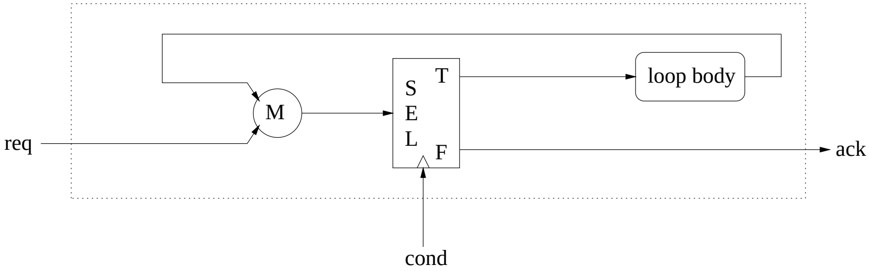
Patron for Two Wine Shops (part II)

```
  elsif (req_patron2 = '1') then
    bag <= shelf2 after delay(2,4);
    wait for delay(5,10);
    assign(ack_patron2,'1',1,3); - patron buys wine
    guard(req_patron2,'0');      - req_patron resets
    assign(ack_patron2,'0',1,3); - reset ack_patron
    wine_drunk <= wine_list'val(conv_integer(bag));
  end if;
  wait for delay(1,2);
end process;
```

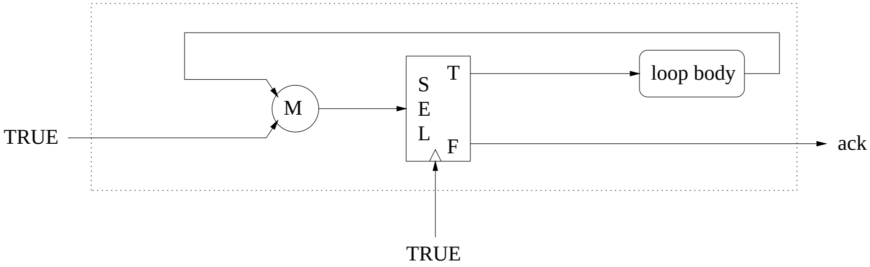
Example for Syntax-Directed Translation

```
shop:process
begin
  receive(WineryShop,shelf);
  send(ShopPatron,shelf);
end process shop;
```

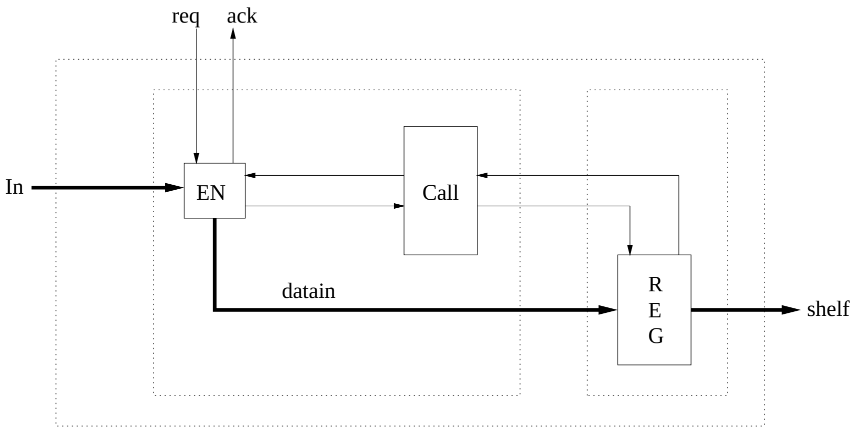
Circuit for Looping Constructs



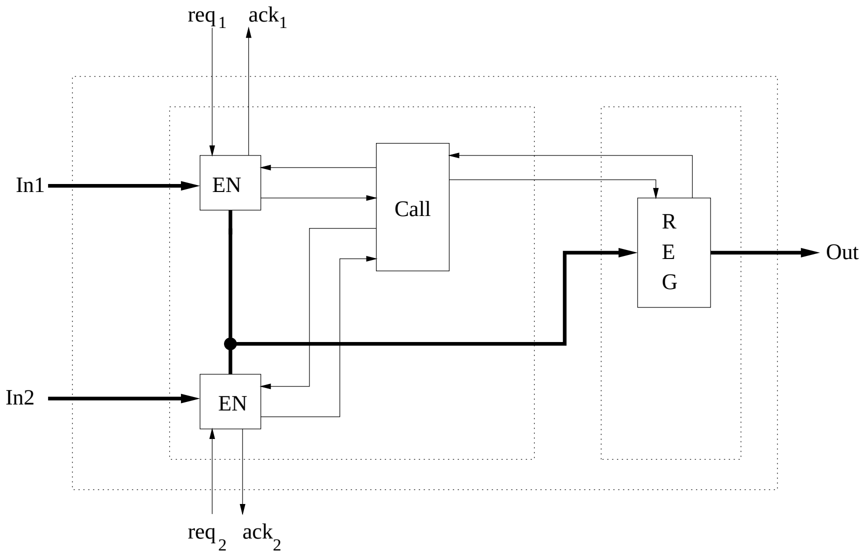
Circuit for Process Statement



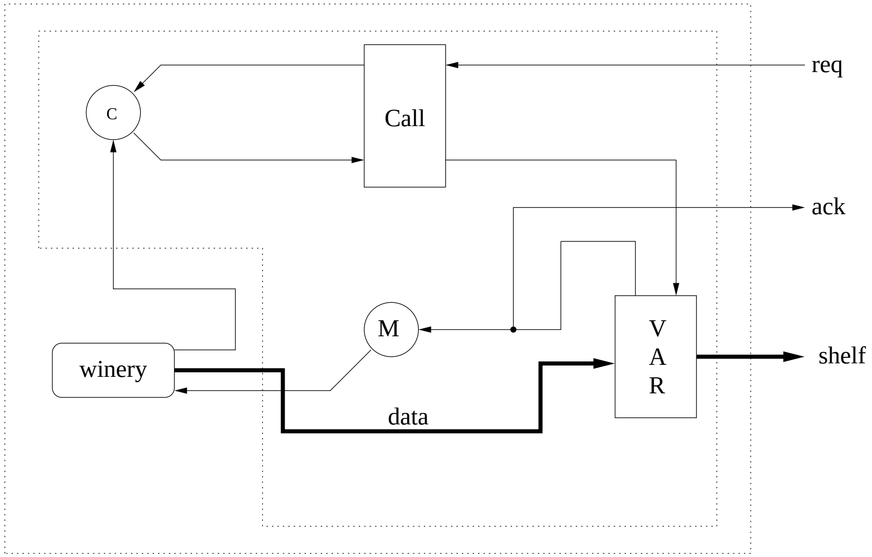
Circuit for Assignment to *shelf*



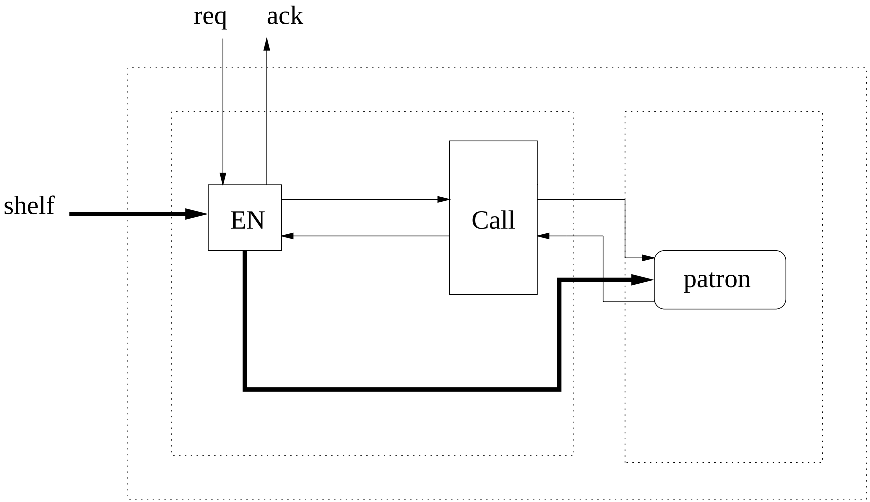
Circuit for Assignment from Two Locations



Circuit for Receive Procedure



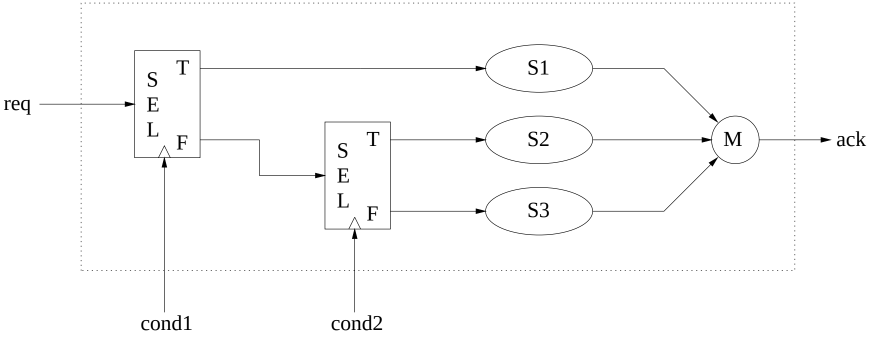
Circuit for Send Procedure



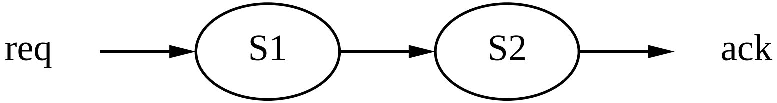
Conditional Statements

```
if (cond1) then
  S1;
elsif (cond2) then
  S2;
else
  S3;
end if;
```

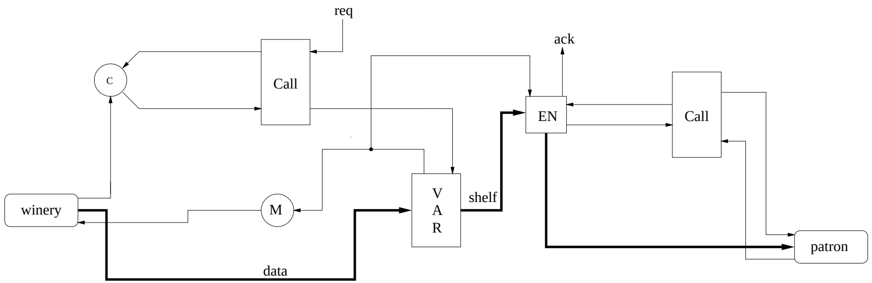
Circuit for Selection Statement



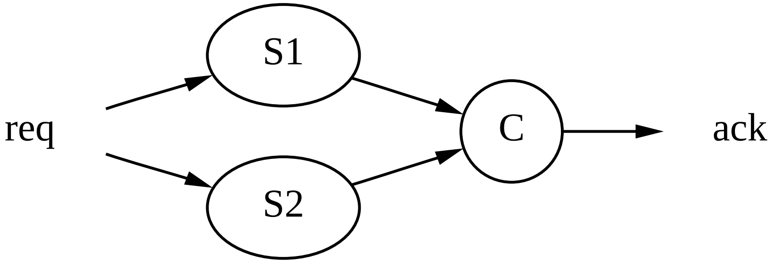
Circuit for Sequential Composition



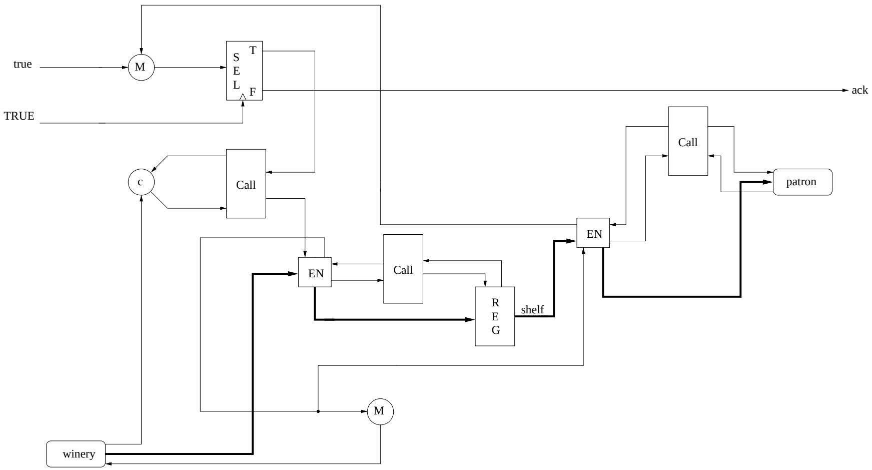
Circuit for Receive followed by Send



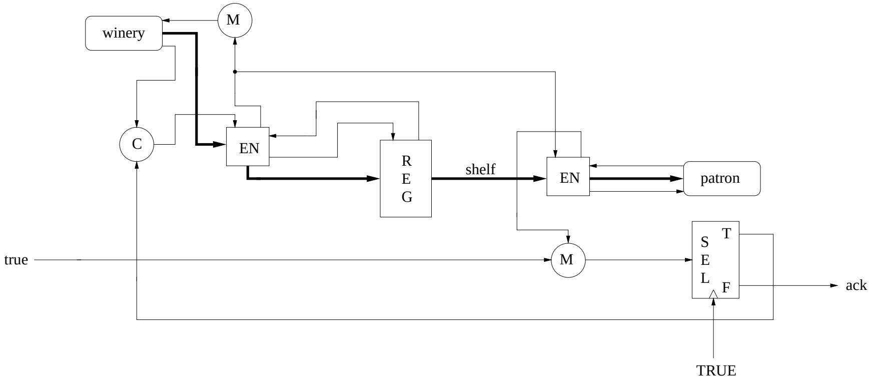
Circuit for Parallel Composition



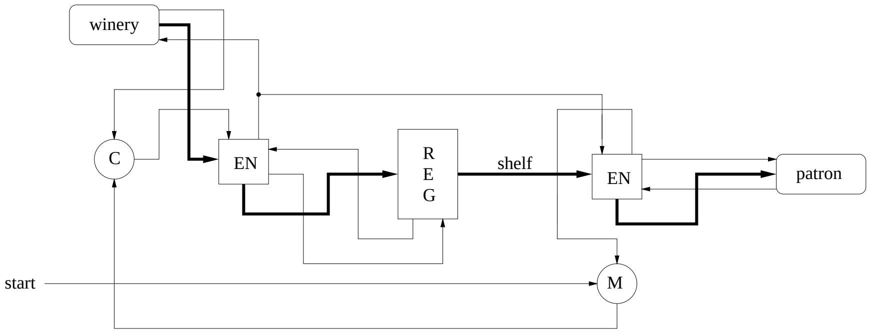
Unoptimized Circuit for the *wine_shop*



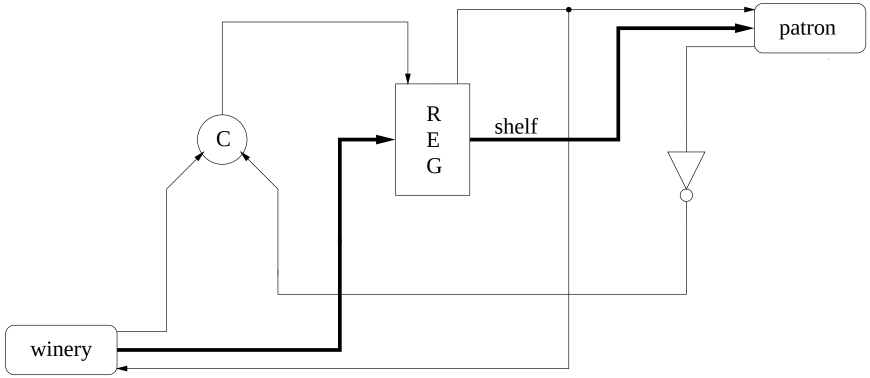
Circuit after CALL Module Optimization



Circuit after SEL and Merge Module Optimizations



Final Circuit for the *wine_shop*



Summary

- *guard*, *assign*, and *delay* functions
- Active and passive protocols
- Handshaking expansion
- Reshuffling
- State variable insertion
- Dual-rail data encoding
- Syntax-directed translation