

## Overview

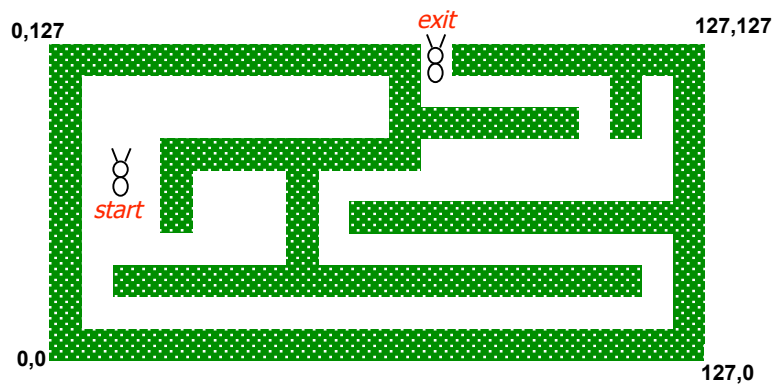
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- ◆ Last lecture
  - Introduction to finite-state machines
    - ⇒ Example: A sequence detector FSM
    - ⇒ Example: A vending machine FSM
- ◆ Today
  - A bigger example
    - ⇒ Ant-brain FSM

## Ant in a maze

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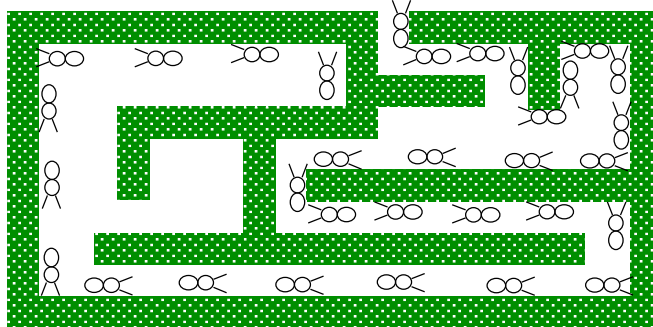
- ◆ Electronic ant, electronic maze
  - Design the ant



## Example: ant brain (Ward, MIT)

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- ◆ Sensors: L and R antennae, 1 if in touching wall
- ◆ Actuators: F - forward step, TL/TR - turn left/right slightly
- ◆ Goal: find way out of maze
- ◆ Strategy: keep the wall on the right



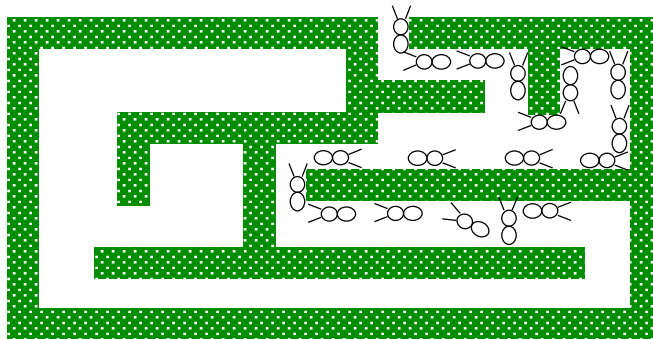
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## Example: ant brain (special case 1)

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- ◆ Left (L) Antenna touching the wall



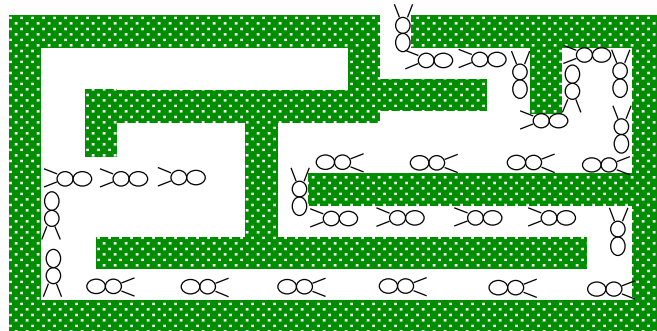
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## Example: ant brain (special case 2)

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- ◆ Ant Lost



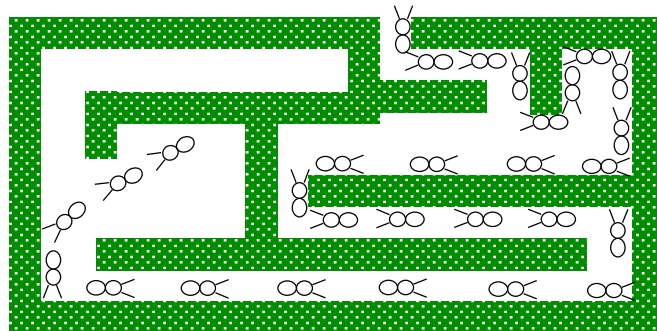
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## Example: ant brain (special case 2)

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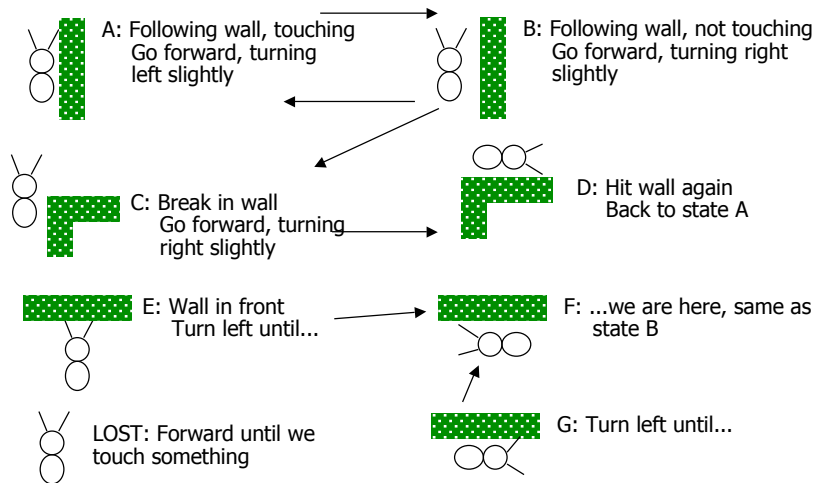
- ◆ Ant Lost (another example)



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## Ant behavior



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## Goal: Find a way out of maze

- ◆ Sensors on L and R antennae
  - Sensor = "1" if touching wall; "0" if not touching wall
    - ⇒ L'R' ≡ no wall
    - ⇒ L'R ≡ wall on right
    - ⇒ LR' ≡ wall on left
    - ⇒ LR ≡ wall in front
    - ⇒ \*\*\* ≡ exit
- ◆ Movement:
  - F ≡ forward one step
  - TL ≡ turn left 90 degrees
  - TR ≡ turn right 90 degrees

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## Notes & strategy

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### ◆ Notes

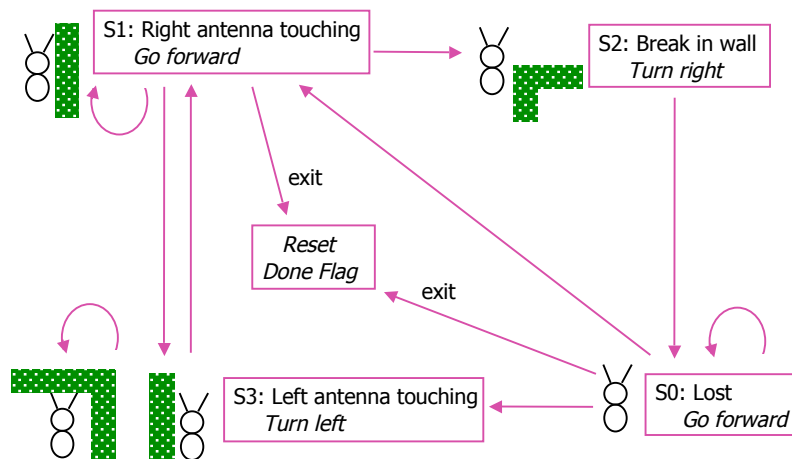
- Maze has no islands
- Corridors are wider than ant
- Don't worry about startup
- Assume a Moore machine
- Assume D flip-flops

### ◆ Strategy

- Partition your design into datapath and control
- Keep the wall on the right

## The ant's behavior

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## The maze

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### ◆ Virtual maze

- 128 × 128 grid
  - ⇒ Stored in memory
  - ⇒ 16384 8-bit words
- YX is maze addresses
  - ⇒ X is the ant's horizontal position (7 bits)
  - ⇒ Y is the ant's vertical position (7 bits)
- Each memory location says
  - ⇒ 00000001 = No wall
  - ⇒ 00000010 = North wall
  - ⇒ 00000100 = West wall
  - ⇒ 00001000 = South wall
  - ⇒ 00010000 = East wall
  - ⇒ 00100000 = Exit

Can have multiple walls  
Example: 00001100  
⇒ Walls on South and East

## Where do you start???

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**Don't look ahead**

## What you need

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- ◆ An FSM for the ant
  - 3 outputs
    - ⇒ Go forward
    - ⇒ Turn left
    - ⇒ Turn right
- ◆ Two 7-bit registers for  $X$  and  $Y$ 
  - With preload, increment, decrement
- ◆ A register to hold the ant's heading
- ◆ Logic to convert memory data to antennae info

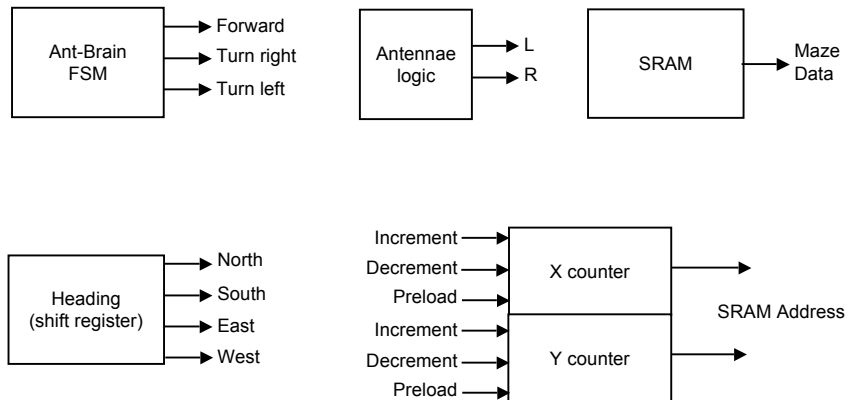
## Recommendations

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- ◆ 7-bit counters for  $X$ ,  $Y$ 
  - Move horizontally: Increment or decrement  $X$
  - Move vertically: Increment or decrement  $Y$
- ◆ Shift register for heading
  - N: 0001
  - W: 0010
  - S: 0100
  - E: 1000
  - Rotate right when ant turns right
  - Rotate left when ant turns left
- ◆ Combinational logic for antennae decoder

## Partition the design

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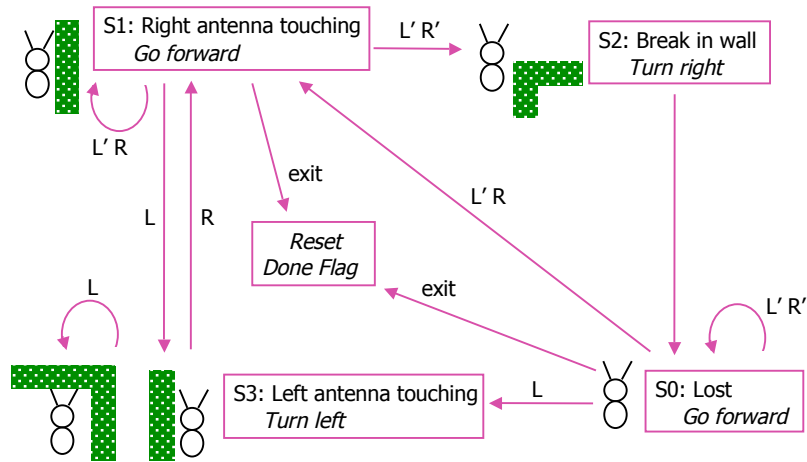
## Design the ant-brain FSM

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1. State diagram and state-transition table
2. State minimization
3. State assignment (or state encoding)
4. Minimize next-state logic
5. Implement the design



## Step 1a: State diagram



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## Step 1b: State-transition table

Exit	State	L	R	Next State	Output
1	Reset				
0	S0	0	0	S0	F
		0	1	S1	F
		1	0	S3	F
		1	1	S3	F
0	S1	0	0	S2	F
		0	1	S1	F
		1	0	S3	F
		1	1	S3	F
0	S2	0	0	S0	TR
		0	1	S0	TR
		1	0	S0	TR
		1	1	S0	TR
0	S3	0	0	S1	TL
		0	1	S1	TL
		1	0	S3	TL
		1	1	S3	TL

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## Step 2: State minimization

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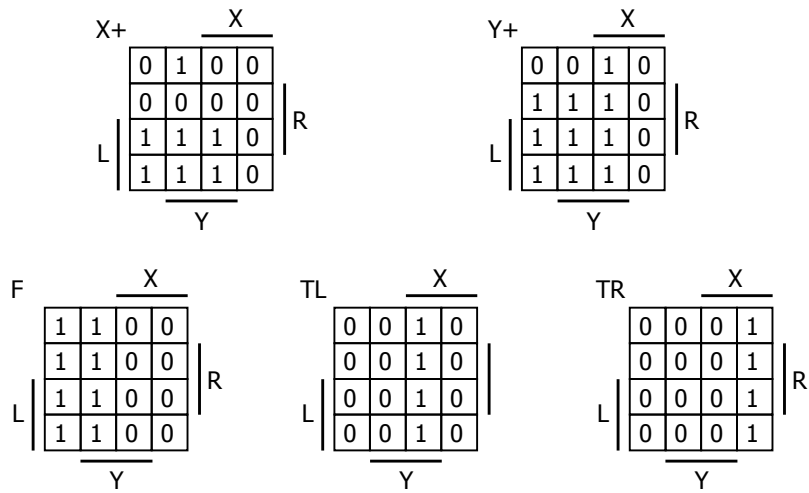
- ◆ Two states are equivalent if they cannot be distinguished at the outputs of the FSM
  - The outputs are the same for any input sequence
- ◆ Two conditions for two states to be equivalent
  - 1) Outputs must be the same in both states
  - 2) Machine must transition to equivalent states for all inputs
- ◆ Any equivalent states in our state diagram?

## Step 3: State encoding

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Exit	X Y	L R	X <sup>+</sup> Y <sup>+</sup>	F TL TR	
1	Reset				
0	0 0	0 0	0 0	1 0 0	S0 → 00
	0 0	0 1	0 1	1 0 0	S1 → 01
	0 0	1 0	1 1	1 0 0	S2 → 10
	0 0	1 1	1 1	1 0 0	S3 → 11
0	0 1	0 0	1 0	1 0 0	
	0 1	0 1	0 1	1 0 0	
	0 1	1 0	1 1	1 0 0	
	0 1	1 1	1 1	1 0 0	
0	1 0	0 0	0 0	0 0 1	
	1 0	0 1	0 0	0 0 1	
	1 0	1 0	0 0	0 0 1	
	1 0	1 1	0 0	0 0 1	
0	1 1	0 0	0 1	0 1 0	
	1 1	0 1	0 1	0 1 0	
	1 1	1 0	1 1	0 1 0	
	1 1	1 1	1 1	0 1 0	

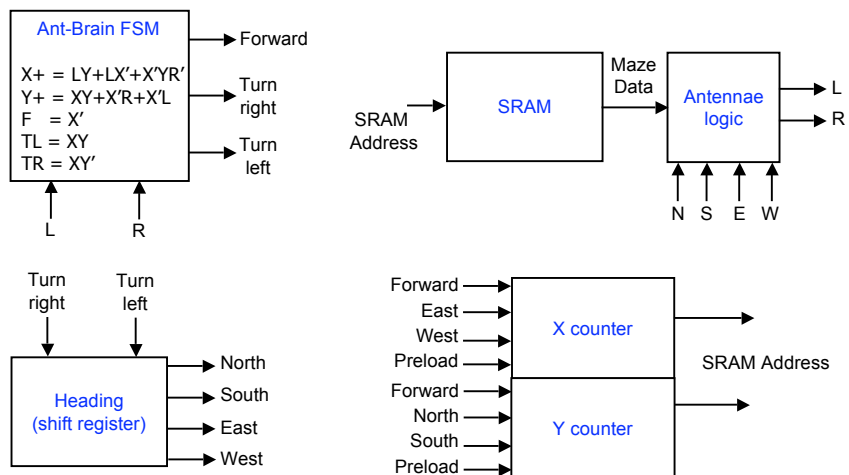
## Step 4: Minimize the logic



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## Step 5: Implement the design



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## Antennae logic

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- Each memory location says
  - ⇒ 00000001 = No wall
  - ⇒ 00000010 = North wall (NW)
  - ⇒ 00000100 = West wall (WW)
  - ⇒ 00001000 = South wall (SW)
  - ⇒ 00010000 = East wall (EW)
  - ⇒ 00100000 = Exit

- The ant can be heading
  - ⇒ N: 0001
  - ⇒ W: 0010
  - ⇒ S: 0100
  - ⇒ E: 1000

Gate count:  
4 2-input ORs  
8 2-input ANDs  
2 4-input ORs

Logic for right antennae

$$R = NW(N + W) + WW(W + S) + SW(S + E) + EW(E + N)$$

Logic for left antennae

$$L = NW(N + E) + WW(W + N) + SW(S + W) + EW(E + S)$$

## What we left out...

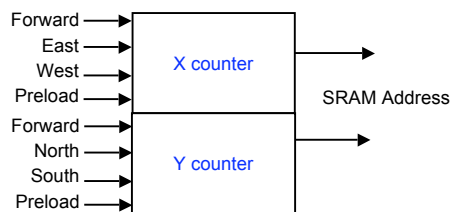
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- ◆ Crumbs in cell
  - Ant eats crumbs in every cell it visits
  - Writes crumb file back to SRAM
  - Read crumb file, for future display on monitor
- ◆ Need a memory controller
  - A state machine to talk to the SRAM
- ◆ Need to deal with startup, exit states!

## Extra Credit:

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- ◆ Design the memory controller:



- ◆ Due last day in class, Friday, June 1; printouts only
- ◆ Value: up to 1 quiz
- ◆ Graded on clarity and completeness of explanation
- ◆ No questions will be answered