CMPT 475 Project
Distributed Termination Detection

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The Distributed Termination Detection Protocol

In this project, we have designed an ASM model for Dijkstra's Termination Detection Algorithm for Distributed Computations, and extended that model to run correctly for multiple computations running on the same distributed network.

Our termination detection protocol follows the same six rules as Dijktra's algorithm:

1. When active, machine(i+1) keeps the token; when passive, it hands over the token to machine(i)
2. A machine sending a message makes itself black
    a. A machine receiving a message becomes active
3. When machine(i+1) propagates the probe, it hands over a black token to machine(i) if it is black itself, whereas while being white it hands over the color of the token unchanged
4. After the completion of an unsuccessful probe, machine(0) initiates a next probe.
5. Machine(0) initiates a probe by making itself white and sending a white token to machine(i-1)
6. Upon transmission of the token to machine(i), machine(i+1) becomes white. (Note that its original color may have influence the color of the token.)

Vocabulary used in our model

Color = {black, white}
Token = {blackToken, whiteToken, noToken}
Machine
Computation

color : Machine X Computation → Color
token : Machine X Computation → Token
terminated : Computation → Boolean

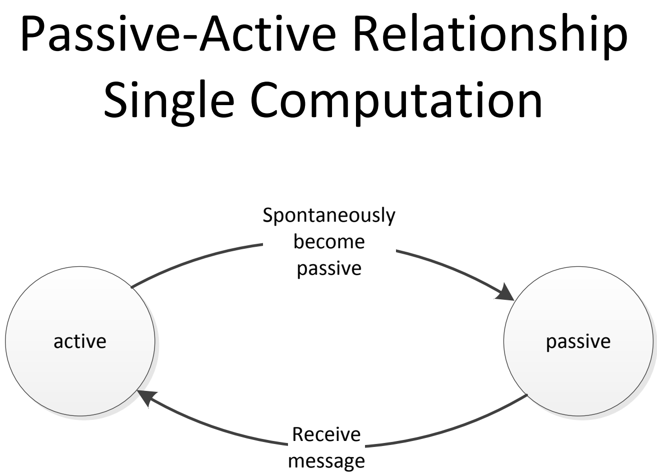
static next : Machine → Machine

monitored isActive : Machine X Computation → Boolean
monitored blackTokenEvent, whiteTokenEvent, sendMessageEvent

ASM diagrams

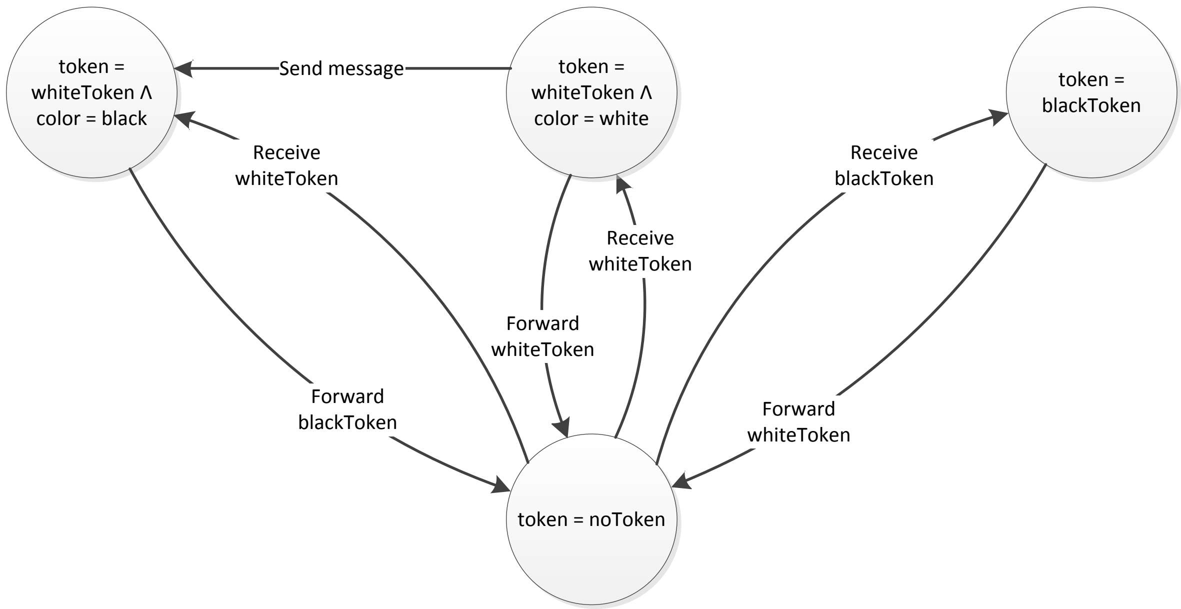
In the proof presented in class, a single computation terminates successfully under the given circumstances. Running multiple computations is no different than running a single computation since computations are treated as if they are independent of each other.

Different aspects of the system, defined by the rules and vocabulary above, are shown in the following state machine diagrams. Represented are diagrams that describe how a machine switches between passive and active, how a regular machine handles tokens, how both a regular machine and a supervisor machine interact with the environment in the context of a single computation, and how the system operates, and ultimately terminates, with multiple computations.



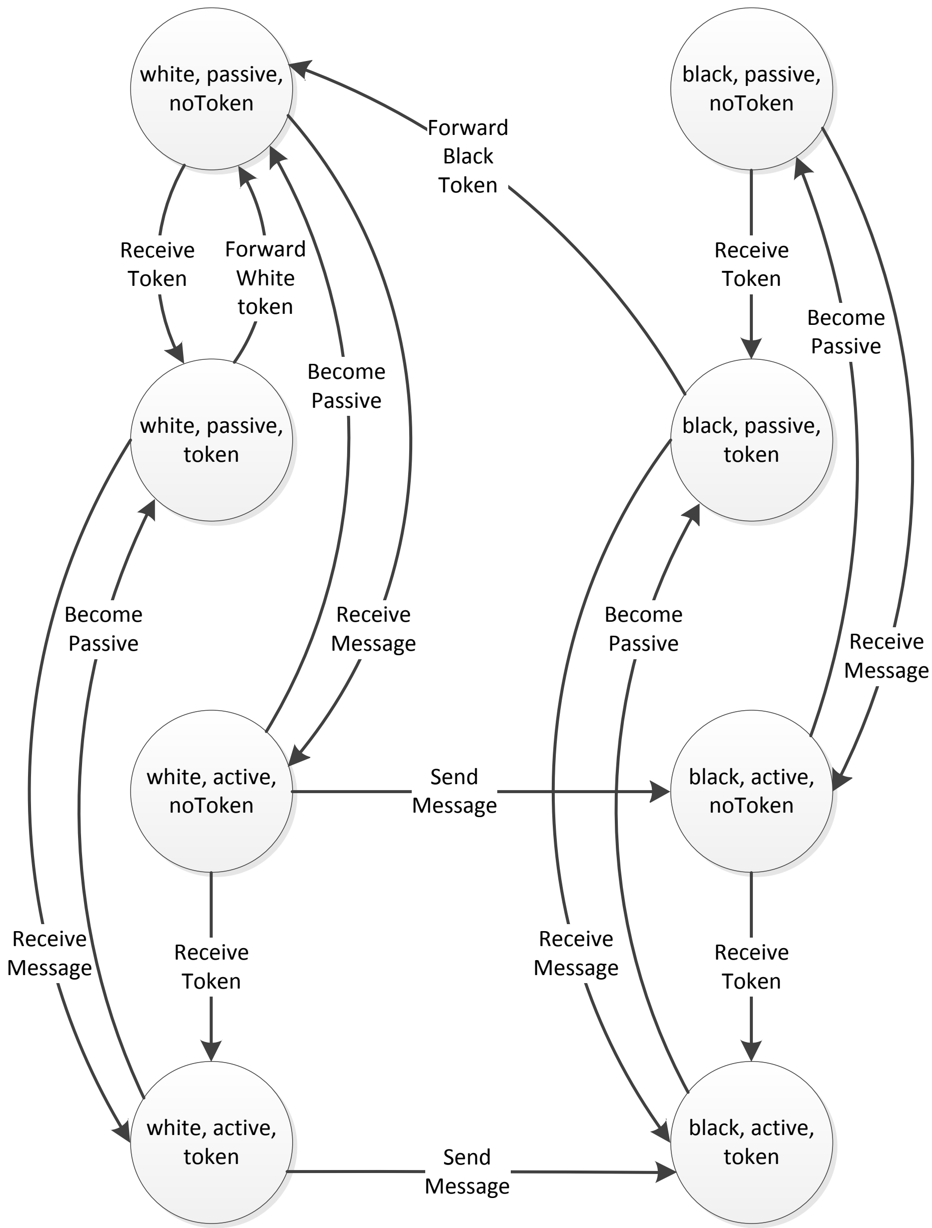
A machine is initially active and spontaneously becomes passive when it finishes a given computation. If a machine is passive, it will change to active if and when a message is received from another machine.

Regular Machine
Token Forwarding



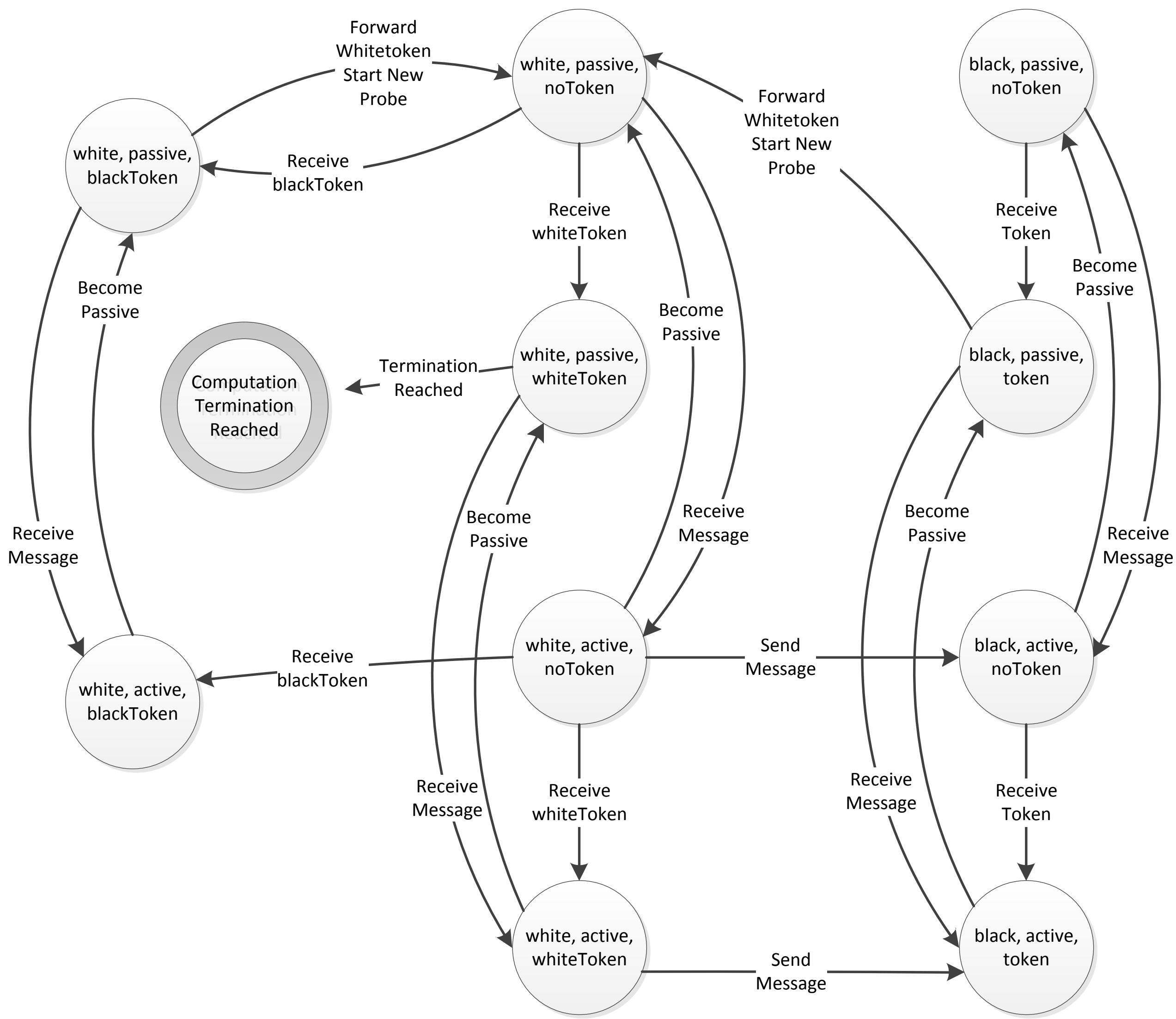
A regular machine receives a token, white or black, from the previous machine in the system. If a machine receives a black token, it will always forward a black token, whether the machine color is white or black. Note: when the machine forwards a black token, the color of the machine changes from black to white. When a machine has a white token, it forwards a white token if its color is white, otherwise if the machine's color is black, it will forward a black token.

Regular Machine
Single Computation



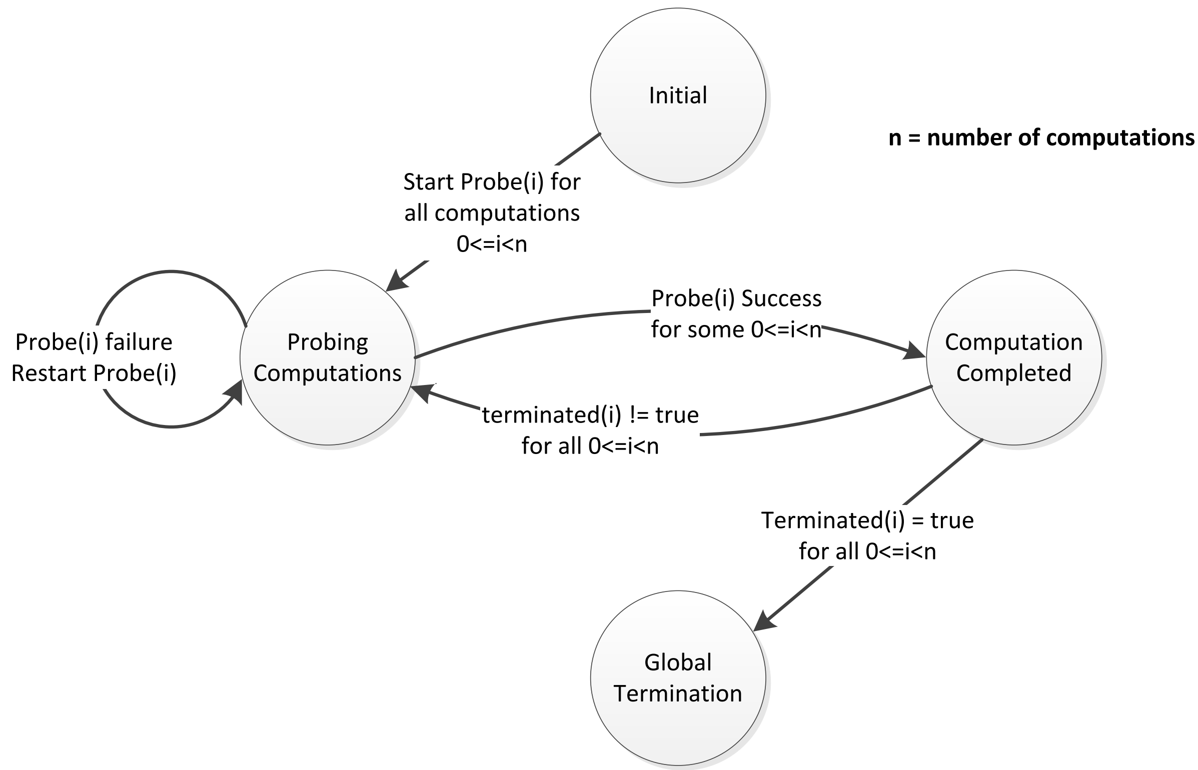
With three binary attributes (white/black, active/passive, token/noToken), there are eight possible states a regular machine can take for a single computation. These states are shown above with all possible transitions between states. The cause of a given transition is listed on the arrow and is determined by the rules set out in the specification.

Supervisor Machine
Single Computation



The key differences between the supervisor machine and the regular machine are in the token handling. Since the supervisor is responsible for starting probes, it always forwards a white token and is always looking for the termination condition based on the token color and its own color when it receives a token. Termination for the individual computation is reached when a white, passive, supervisor machine receives a white token.

System
Multiple Computations



The system handles the multiple computations by treating them as separate individual entities. Each computation has its own token, token color, and machine color for each machine. So, while machine 1 might be black for computation 1 it can simultaneously be white for computation 2. In this example, machine 1 would be labeled both black and white, but for different computations. Overall, the supervisor continually initiates probes and terminates each computation separately and concurrently when appropriate, until all computations have reached termination; at this point, the global system termination condition has been reached.

The Abstract State Machine Model

```
ReactOnEvents( m : Machine , c : Computation ) ≡
    if blackTokenEvent(m,c) then
        token(m,c) := blackToken
    if whiteTokenEvent(m,c) then
        token(m,c) := whiteToken
    if sendMachineEvent(m,c) then
        color(m,c) := black


InitializeMachine ( m : Machine, c : Computation ) ≡
    token(m,c) := noToken
    color(m,c) := white


RegularMachineProgram ( m : Machine ) ≡
    (∀ c ∈ Computation with ¬terminated(c) )
        ReactOnEvents(m,c)
        if ¬isActive(m,c) ∧ ¬token(m,c)=noToken
            InitializeMachine(m,c)
            if color(m,c) = black
                ForwardToken(blackToken, nextMachine(m), c)
            else if color(m,c) = white
                ForwardToken(token(m,c), nextMachine(m), c)


SupervisorMachineProgram ( m : Machine ) ≡
    (∀ c ∈ Computation with ¬terminated(c) )
        ReactOnEvents(m,c)
        if ¬isActive(m,c) ∧ ¬token(m,c)=noToken
            terminated(c) := true
            if (terminated(c) for ∀ c ∈ Computation)
                ReportGlobalTermination
        else
            InitializeMachine(m,c)
            ForwardToken(m, whiteToken, nextMachine(m), c)


Initial State ≡
    (∀ c ∈ Computation)
        terminated(c) := false
    (∃ machine0 ∈ Machine) (program(machine0) = SupervisorMachineProgram) ∧
token(machine0) = blackToken) ∧
    (∀ m ∈ Machine) (m≠machine0 ⇒ program(m) = RegularMachineProgram)
    (∀ m ∈ Machine) (color(m) = white)
```

- The above ASM model abstractly models the generalized version of our protocol and its requirements. Each computational agent (regular or supervisor machine) is assigned a machine program in the above model.

Abstractions

The following have been left abstract in our ASM model:

- Operations
  - ForwardToken (t : Token, m : Machine, c : Computation)
  - ReportGlobalTermination
- Tables (static functions)
  - static next : Machine → Machine
- Interfaces (monitored functions)
  - blackTokenEvent : Machine X Computation → Boolean
  - whiteTokenEvent : Machine X Computation → Boolean
  - sendMessageEvent : Machine X Computation → Boolean
  - isActive : Machine X Computation → Boolean
- Computation processing

Assumptions

We make the following assumptions about our system model with regards to its interactions with the environment, and the initial machine state.

- **Interactions with the environment**
  - Passing tokens, sending messages, becoming active/passive happen immediately (each event incurs no lag time)
  - Computations take random amounts of time to complete
  - Machines send messages with random probability
  - No concept of data concurrency control
  - Each token is held by only one machine at a time at any given instant
  - Computations are independent of each other
- **Initial machine state**
  - All machines are initially active
  - All computations being considered are initially running
  - Each machine is initially white
  - The Supervisor machine initially has a black token, and regular machines have no token

Safety and Liveness

The protocol ensures that:
- The system is terminated only when all machines are passive, and no machine is running any computation (safety)
- The machines forward tokens as soon as they become passive, without any delay (liveness)

Proof that the protocol works

In order to grasp why this system works for all cases we must again refer back to the 6 basic rules of the system.

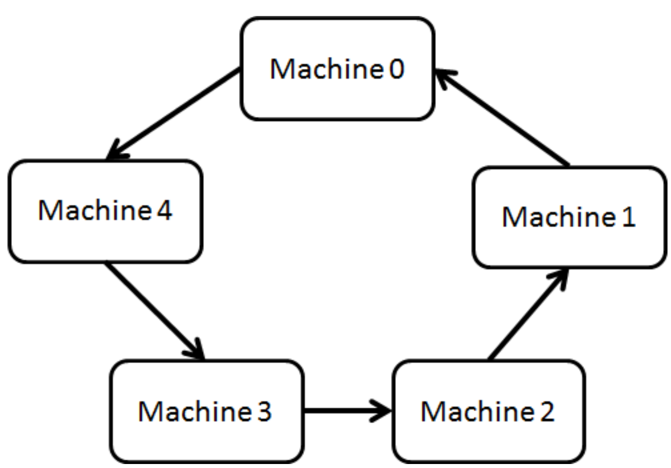
1. *Rule:* When active, *machine i*+1 keeps the token; when passive, it hands over the token to *machine i*.
2. *Rule*: A machine sending a message makes itself black.
3. *Rule*: When *machine i*+1 propagates the probe, it hands over a black token to *machine i* if it is black itself, whereas while being white it leaves the colour of the token unchanged.
4. *Rule*: After the completion of an unsuccessful probe, *machine* 0 initiates a next probe.
5. *Rule*: *Machine* 0 initiates a probe by making itself white and sending a white token to *machine i*-1.
6. *Rule*: Upon transmission of the token to *machine i*, *machine i*+1 becomes white. (Note that its original colour may have influenced the colour of the token.)

There are 3 cases that this system must handle:
1. No machines are sending or receiving messages
2. Machines are sending messages (or become active) during the probing
3. Multiple computations on each machine along with Case 1 and 2

Keep in mind this algorithm runs in real-time. The algorithm probes the system by propagating a white token through the system. If the token is propagated through the system and remains white, we know that all machines are inactive and we can terminate the entire distributed system.

Case 1

For this example we will consider a simple system with 5 machines as seen below.



From the diagram it is quite easy to see that passing a white token through the system will reach the end white (Rule 3). Provided that no machines send any messages, the system will terminate. We will examine this in more detail.

We start with Rule 5. Machine 0 initiates the probe by making itself white. Since none of the machines are sending messages, all machines remain white. The white token is passed from Machine 0 to Machine 4.

Since Machine 4 is white, it passes on the white token to Machine 3 as stated in Rule 3. Similarly this will happen for each subsequent machine until the token reaches Machine 0. Since each machine cannot change the colour of the token, the token remains white. Machine 0 receives the white token and then the whole system can be terminated.

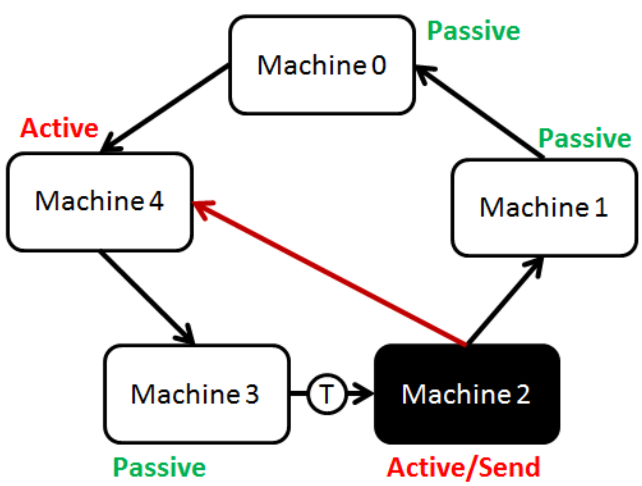
In summary, the white token passes through the white machines without changing colour. When it reaches the end, the system terminates.

Case 2

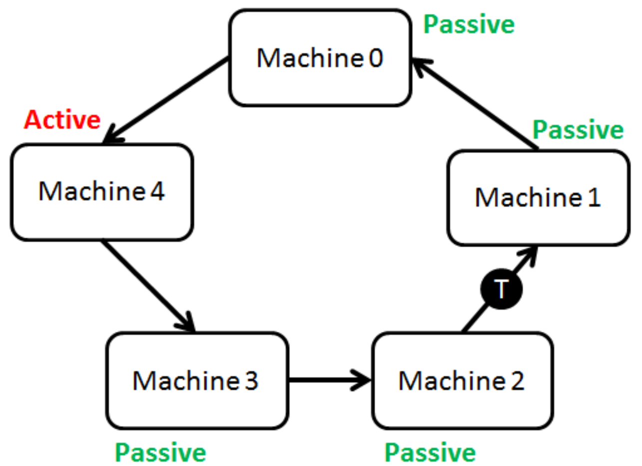
How about the case where messages are sent during the probing?

We consider again the same diagram as shown above, suppose that Machine 4 sends a message. Rule 2 would make this machine then turn black. When the token is passed from Machine 0 to Machine 4 (Rule 2), Machine 4 holds the token until it becomes passive and turns white (Rule 1). Rule 3 would make the token Black. At this point the token will not become white until it reaches Machine 0. Hence, the system will not terminate at the end of this first probe.

Now Rule 4 comes in to effect, the system is probed again. Let's also suppose the white token reaches Machine 3 and Machine 2 decides to send a message before the token reaches it.

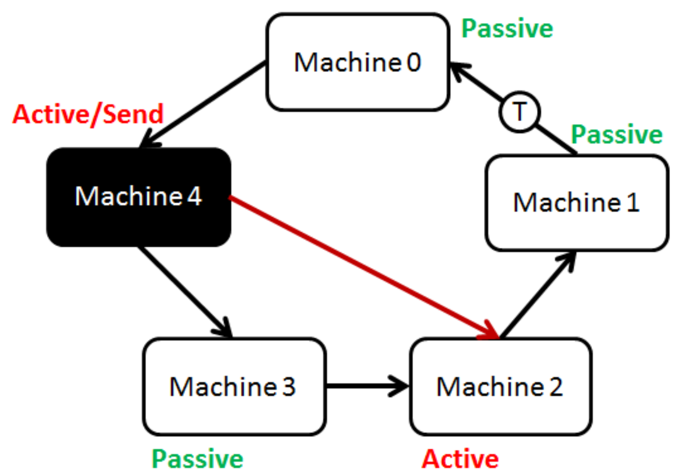


Again, the token will turn black after Machine 2 passes it along, turns white (Rule 6) and the whole process is repeated again.



Notice how Machine 4 is active but did not turn black. The token will eventually reach Machine 4. As long as Machine 4 does not send a message, the token will remain white and reach Machine 0 again thus terminating the whole system.

But what if we have this situation?



Machine 0 will theoretically receive a white token and terminate with Machine 4 still active! However, this situation is impossible because of Rule 1 and Rule 6. The system would have to become passive and white in order to pass the token along.

Furthermore, only active machines can send messages. So only machines in the token's path will be able to send messages and turn black.

Case 3

So far we have only seen the system operate with each machine processing 1 computation at a time. Now, consider the case where each machine can have multiple computations along with the above 2 cases.

Suppose our machines can have n number of simultaneous computations, our algorithm will be slightly modified so that we have n tokens that probe the system independently from each other. All of the n tokens have to be white before they reach Machine 0. When all of the tokens return to Machine 0 white, the system can terminate.

Therefore the system works for all cases.

CoreASM Specification

```
// CMPT 475 Course Project (Spring, '12)
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CoreASM DistributedTerminationDetection

use StandardPlugins
use TimePlugin
use MathPlugin

enum Colour = {black, white}
enum Token = {noToken, blackToken, whiteToken}

enum Machine = {machine0, machine1, machine2, machine3, machine4, machine5,
machine6, machine7, machine8}
enum Computation = {comp1, comp2, comp3}


function colour : Machine * Computation -> Colour
function token : Machine * Computation -> Token
function nextMachine: Machine -> Machine

function isActive : Machine * Computation -> boolean
function blackTokenEvent : Machine * Computation -> boolean
function whiteTokenEvent : Machine * Computation -> boolean
function sendMessageEvent : Machine * Computation -> boolean

function terminated : Computation -> boolean

universe Agents = {supervisorMachine, regularMachine}

init InitRule

rule InitRule = seqblock
      startTime := now
      forall c in Computation do
      seqblock
            terminated(c) := false
            forall m in Machine do
            seqblock
                  if m = machine0 then seqblock
                        InitializeMachine(m, c)
                        token(m, c) := blackToken
                        AssignNextMachine(m)
                  endseqblock
                  else par
                        InitializeMachine(m, c)
                        AssignNextMachine(m)
                  endpar
                  isActive(m, c) := true
            endseqblock
            PrintProgram(c)
      endseqblock

      program(supervisorMachine) := @SupervisorMachineProgram
      program(regularMachine) := @RegularMachineProgram
```

```
      program(self) := undef
endseqblock


rule PrintProgram(c) = seqblock
      print "Time: " + ((now - startTime) / 1000) + " seconds:"
      choose m in Machine with token(m, c) != noToken do seqblock
            print "Computation " + c + ":"
            print "Machine " + m + " holding " + token(m, c)
            print "Machine " + m + ":- colour: " + colour(m, c) + "  , Active: "
+ isActive(m, c)
            print ""
      endseqblock
endseqblock



rule AssignNextMachine(m) = par
      if m = machine1 then
            nextMachine(m) := machine0
      if m = machine2 then
            nextMachine(m) := machine1
      if m = machine3 then
            nextMachine(m) := machine2
      if m = machine4 then
            nextMachine(m) := machine3
      if m = machine5 then
            nextMachine(m) := machine4
      if m = machine6 then
            nextMachine(m) := machine5
      if m = machine7 then
            nextMachine(m) := machine6
      if m = machine8 then
            nextMachine(m) := machine7
      // Add more statements here to add new machines to the network

      // Assign the last machine as machine0's nextMachine
      if m = machine0 then
            nextMachine(m) := machine8
endpar


rule ForwardToken(t, m, c) = seqblock
      token(m, c) := t
      if t = blackToken or colour(m, c) = black then
            blackTokenEvent(m, c) := true
      else
            whiteTokenEvent(m, c) := true

      PrintProgram(c)
endseqblock


rule ReactOnEvents(m, c) = par
      if blackTokenEvent(m, c) then
            token(m, c) := blackToken

      if whiteTokenEvent(m, c) then
            token(m, c) := whiteToken
```

```
      if sendMessageEvent(m, c) then seqblock
            colour(m, c) := black
            choose mac1 in Machine with m != mac1 do seqblock

                  if (not isActive(mac1, c)) then
                        isActive(mac1, c) := true
            endseqblock
      endseqblock
endpar


rule InitializeMachine(m, c) = seqblock
      token(m, c) := noToken
      colour(m, c) := white
      blackTokenEvent(m, c) := false
      whiteTokenEvent(m, c) := false
      sendMessageEvent(m, c) := false
endseqblock


rule RegularMachineProgram =
      forall c in Computation with (not terminated(c)) do
      par
            forall m in Machine with m != machine0 do
            par
                  seq
                        ReactOnEvents(m, c)
                  next
                        if (not isActive(m, c)) and token(m, c) != noToken then
seqblock
                              col(c) := colour(m, c)
                              tok(c) := token(m, c)
                              InitializeMachine(m, c)
                              if col(c) = black then
                                    ForwardToken(blackToken, nextMachine(m), c)
                              else if col(c) = white then
                                    ForwardToken(tok(c), nextMachine(m), c)
                        endseqblock

                        else
                              ActiveCondition(m, c)
            endpar
      endpar



rule SupervisorMachineProgram = seqblock
      if (forall c in Computation holds terminated(c)) then par
            ReportGlobalTermination
      endpar
      forall c in Computation with (not terminated(c)) do
      par
            choose m in Machine with m = machine0 do
            par
                  seq
                        ReactOnEvents(m, c)
                  next
```

```
                        if (not isActive(m, c)) and token(m, c) != noToken then
par
                              if colour(m, c) = white and token(m, c) =
whiteToken then seqblock
                                    terminated(c) := true
                                    print "Computation " + c + " terminated\n"

                              endseqblock
                              else seqblock
                                    InitializeMachine(m, c)
                                    ForwardToken(whiteToken, nextMachine(m), c)
                              endseqblock
                        endpar

                        else
                              ActiveCondition(m, c)
            endpar
      endpar
endseqblock


rule ActiveCondition(m, c) = seqblock
      if isActive(m, c) then seqblock
            rand := random
            if rand < 0.1 then par
                  sendMessageEvent(m, c) := true
            endpar

            if rand > 0.75 then seqblock
                  isActive(m, c) := false
                  if token(m, c) != noToken then
                        PrintProgram(c)
            endseqblock
      endseqblock
endseqblock


rule ReportGlobalTermination = seqblock
      program(supervisorMachine) := undef
      program(regularMachine) := undef
      program(self) := undef
      print "Global Termination"
endseqblock
```

Testing the CoreASM Model

We tested our CoreASM specification with a varied number of machines and computations.
In the submission made to the TA are included the complete outputs for the following test runs:
- 8 machines, running 3 computations
- 10 machines, running 3 computations
- 10 machines, running 4 computations
- 9 machines, running 5 computations
- 8 machines, running 3 computations (boundary case, where the system terminates in one probe)

In order to repeat these experiments, the following modifications need to be made to the CoreASM specification:
- Add/remove machines from the enum Machine (line#15):
```
enum Machine = {machine0, machine1, machine2, machine3, machine4,
machine5, machine6, machine7, machine8}
```
- Add/remove computations from the enum Computation (line#16):
```
enum Computation = {comp1, comp2, comp3}
```
- Modify the rule AssignNextMachine(m) (line# 73) according to the modified Machine.

For example, say we want to add a new machine (machine9).
- Our enum Machine becomes:
```
enum Machine = {machine0, machine1, machine2, machine3, machine4,
machine5, machine6, machine7, machine8, machine9}
```
- The new last machine would become Machine0's next machine, and the new machine would need to be assigned a next machine too.

  Our AssignNextMachine(m) rule would then be modified to:
```
rule AssignNextMachine(m) = par
    .........
    .........

    if m = machine8 then
        nextMachine(m) := machine7
    // Add more statements here to add new machines to the network
    if m = machine9 then
        nextMachine(m) := machine8
    // Assign the last machine as machine0's nextMachine
    if m = machine0 then
        nextMachine(m) := machine9
endpar
```

Test Runs

I. 8 machines, running 3 computations

Time: 0 seconds:
Computation comp2:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: true

Time: 0 seconds:
Computation comp1:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: true

Time: 0 seconds:
Computation comp3:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: true

Time: 0.241 seconds:
Computation comp2:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: false

Time: 0.241 seconds:
Computation comp1:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: false

Time: 0.241 seconds:
Computation comp3:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: false

Time: 0.664 seconds:
Computation comp3:
Machine machine8 holding whiteToken
Machine machine8:- colour: white , Active: true

……..
………
………

Time: 28.62 seconds:
Computation comp3:
Machine machine0 holding whiteToken
Machine machine0:- colour: white , Active: false

Computation comp3 terminated
………
……….

Time: 29.486 seconds:
Computation comp2:
Machine machine0 holding whiteToken
Machine machine0:- colour: white , Active: false

Computation comp2 terminated

……..
……..

Time: 32.197 seconds:
Computation comp1:
Machine machine1 holding whiteToken
Machine machine1:- colour: white , Active: false

Time: 32.402 seconds:
Computation comp1:
Machine machine0 holding whiteToken
Machine machine0:- colour: white , Active: false

Computation comp1 terminated

Global Termination

II. 10 machines, running 4 computations

Time: 0 seconds:
Computation comp2:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: true

Time: 0 seconds:
Computation comp1:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: true

Time: 0 seconds:
Computation comp3:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: true

Time: 0 seconds:
Computation comp4:
Machine machine0 holding blackToken
Machine machine0:- colour: white , Active: true

………..
………..

Time: 3.675 seconds:
Computation comp4:
Machine machine0 holding blackToken
Machine machine0:- colour: black , Active: false

Time: 3.675 seconds:
Computation comp1:
Machine machine0 holding blackToken
Machine machine0:- colour: black , Active: false

Time: 3.884 seconds:
Computation comp4:
Machine machine10 holding whiteToken
Machine machine10:- colour: black , Active: false

Time: 3.884 seconds:
Computation comp3:
Machine machine10 holding whiteToken
Machine machine10:- colour: black , Active: false

………
………

Time: 15.248 seconds:
Computation comp3:
Machine machine0 holding whiteToken
Machine machine0:- colour: white , Active: false

Computation comp3 terminated

……….
……….

Time: 15.888 seconds:
Computation comp1:
Machine machine0 holding whiteToken
Machine machine0:- colour: white , Active: false
Computation comp1 terminated

……….
……….

Time: 22.691 seconds:
Computation comp2:
Machine machine0 holding whiteToken
Machine machine0:- colour: white , Active: false

Computation comp2 terminated

……….
……….

Time: 27.626 seconds:
Computation comp4:
Machine machine0 holding whiteToken
Machine machine0:- colour: white , Active: false

Computation comp4 terminated

Global Termination