Introducing DEVS for Collaborative Building Simulation Development

Rhys Goldstein and Azam Khan

Autodesk Research

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Simulation Use

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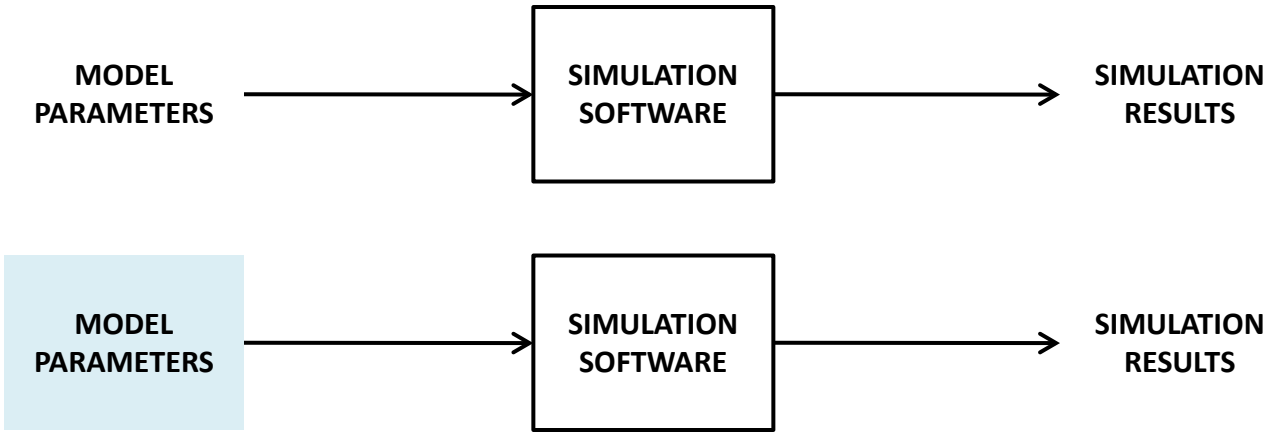
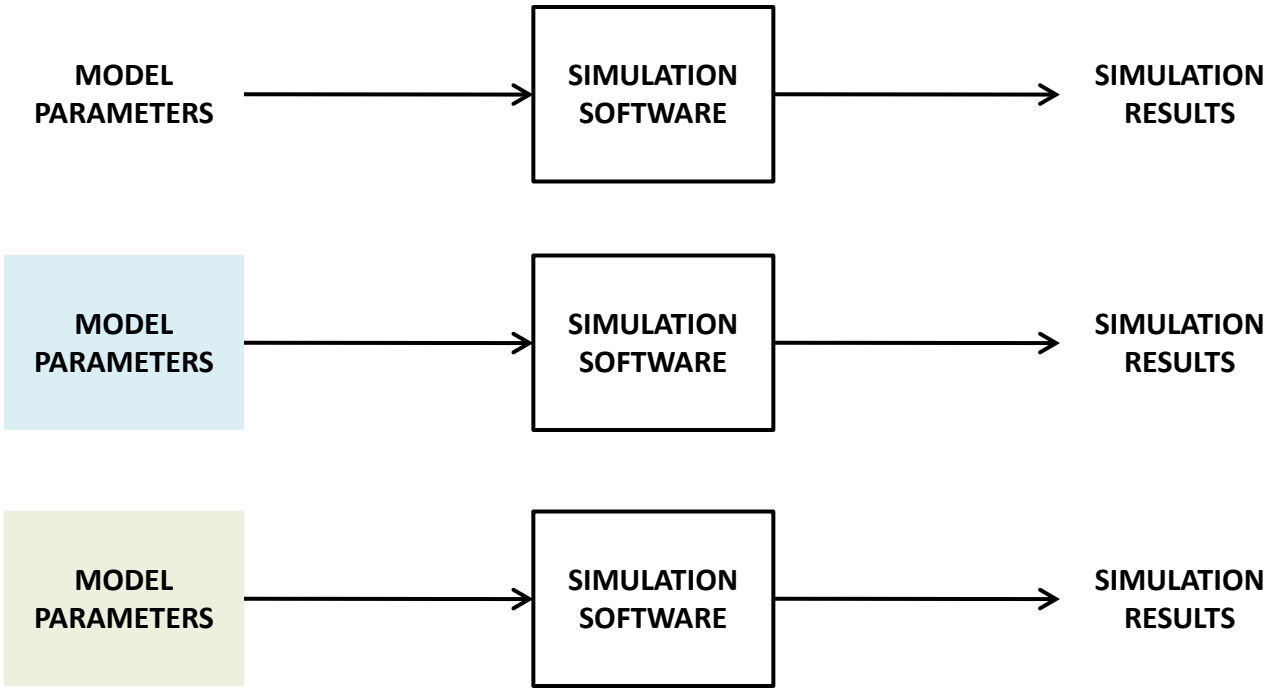
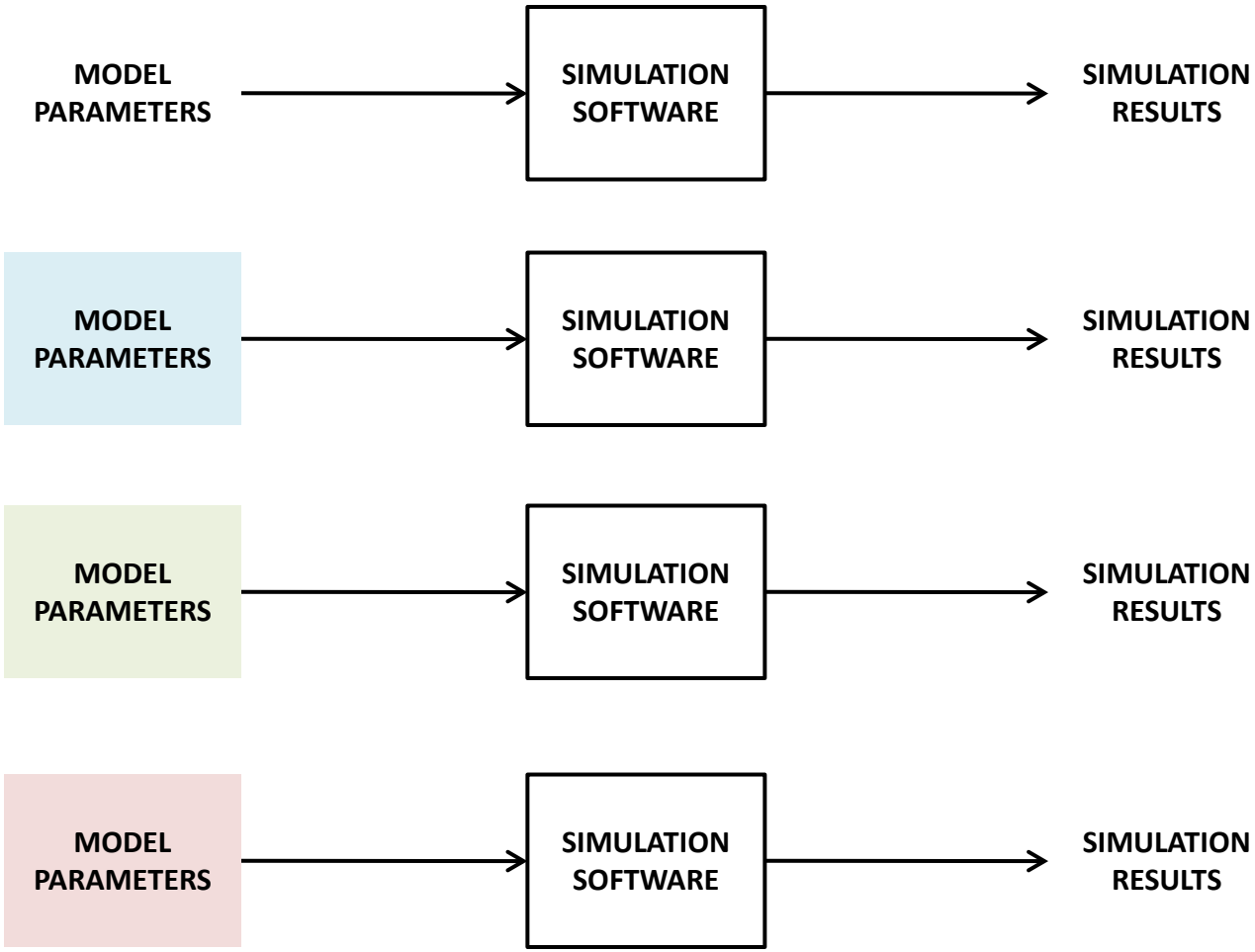


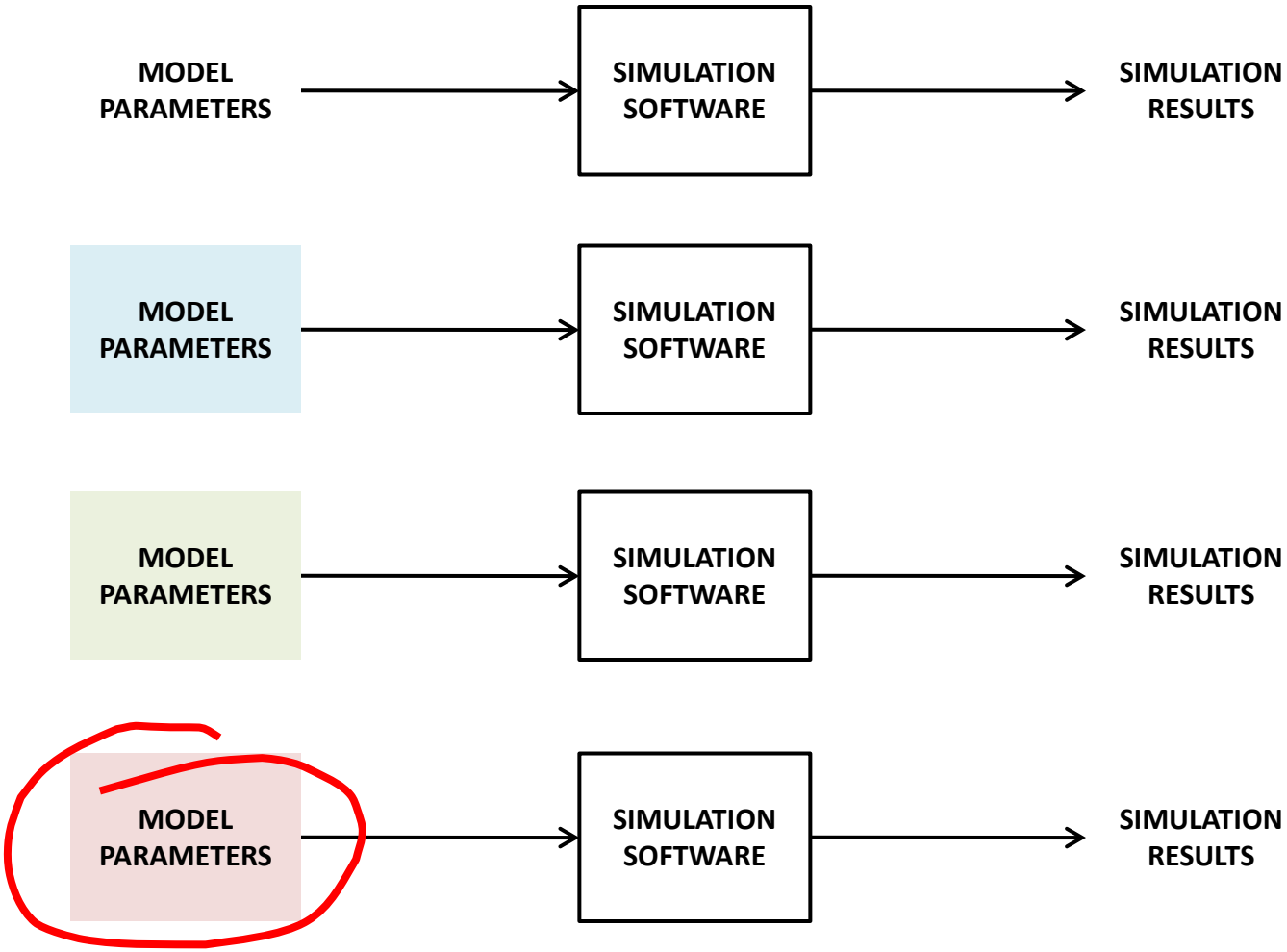
Simulation Use



Simulation Use

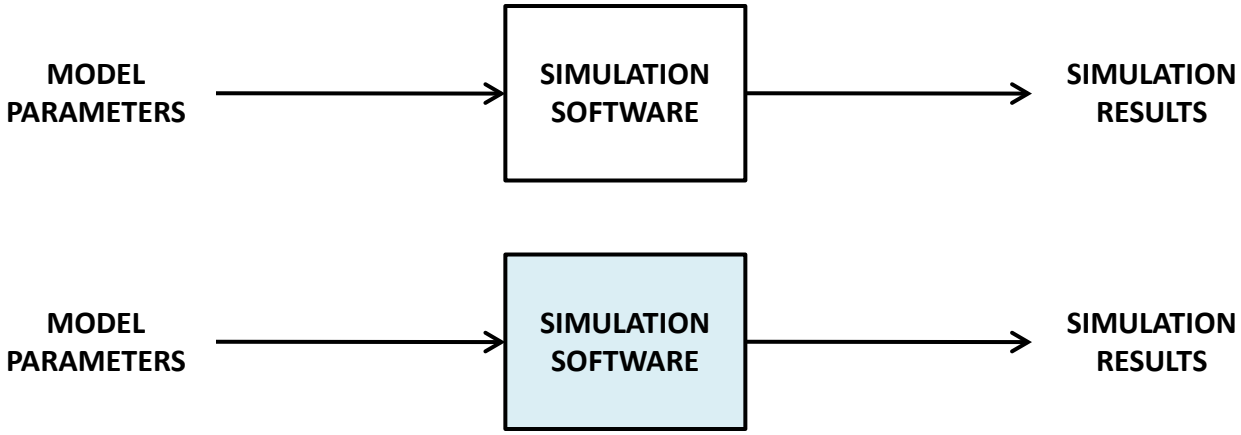


Simulation Use



Traditional Simulation Development

Traditional Simulation Development



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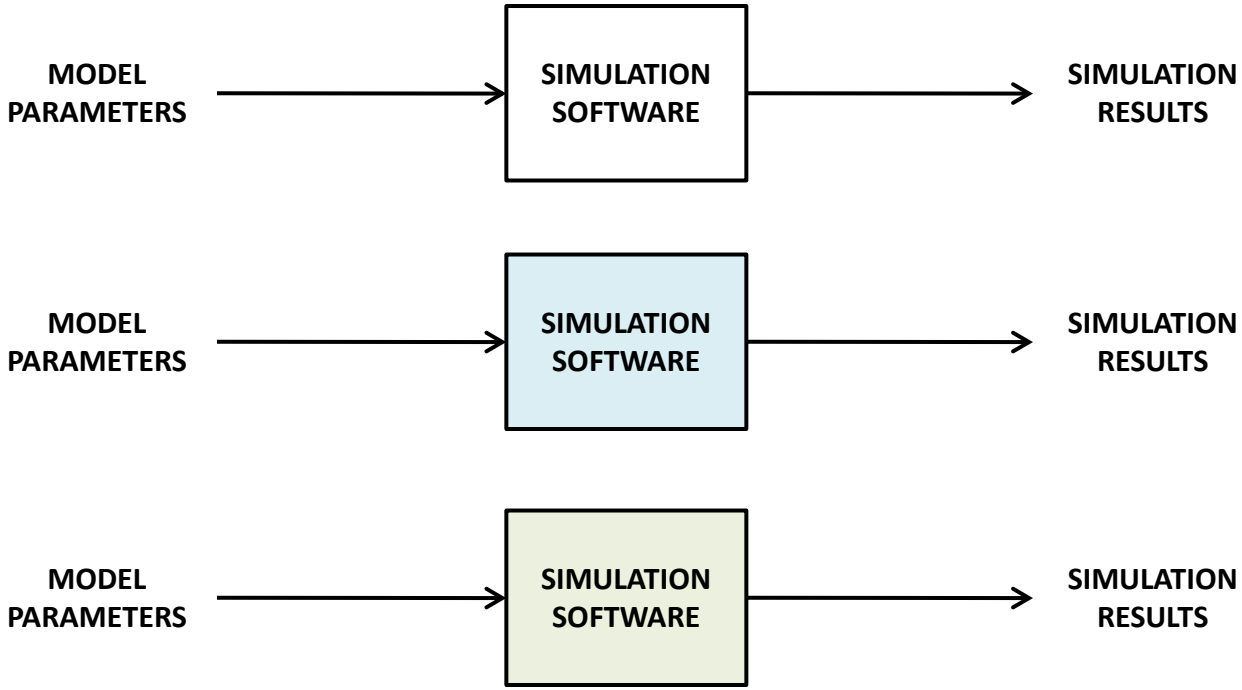
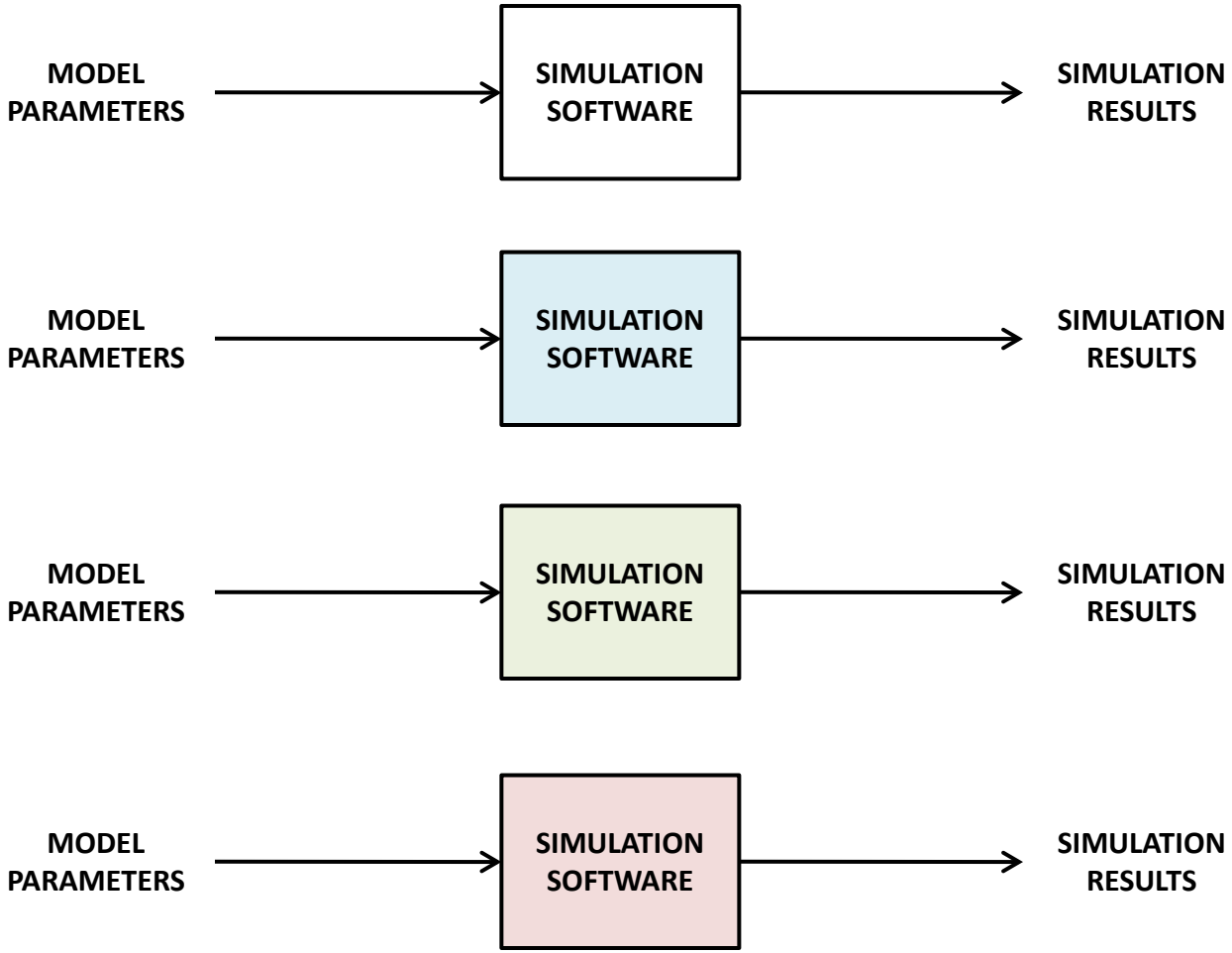
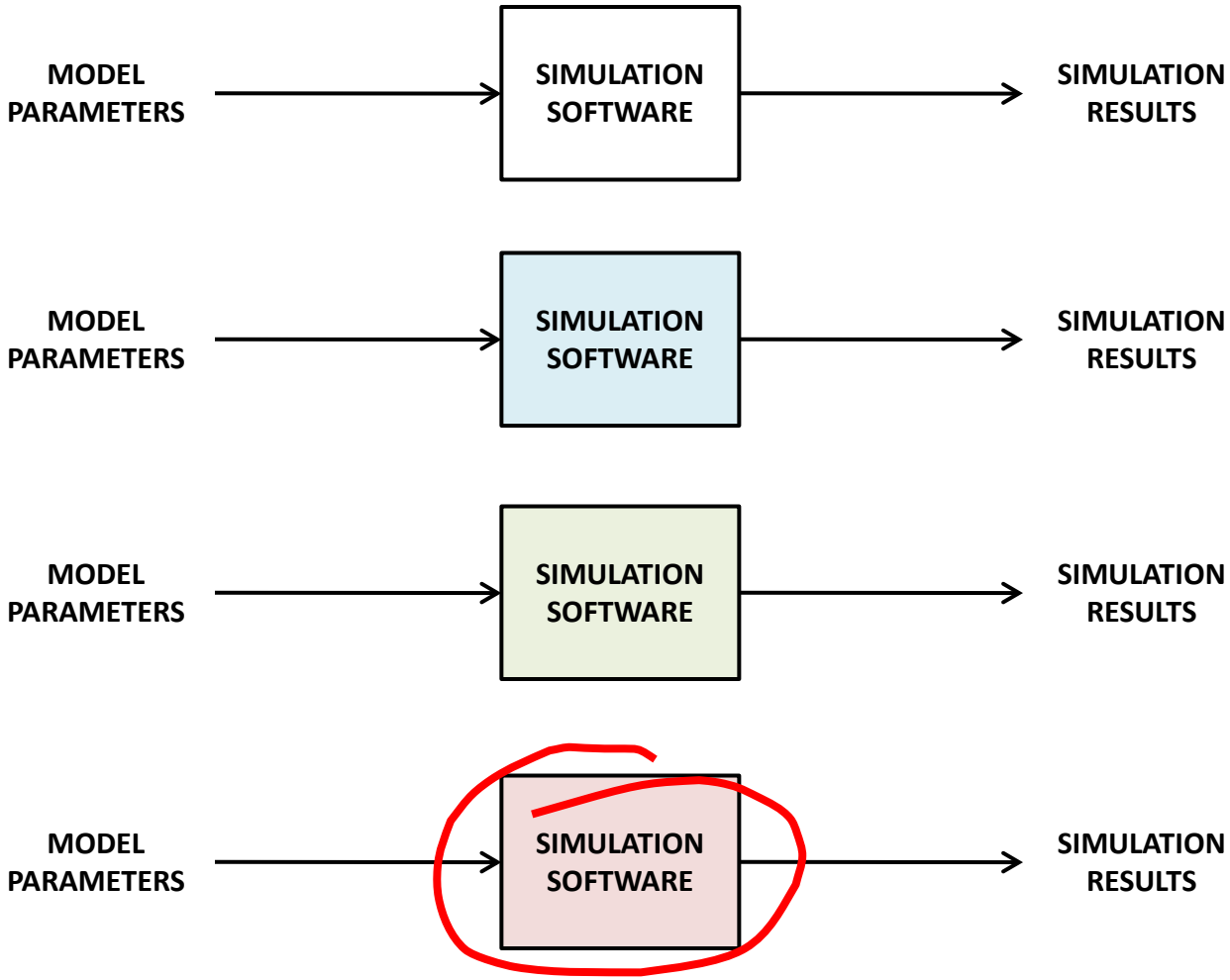


Traditional Simulation Development



Traditional Simulation Development



Outdoor Climate Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

Outdoor Climate Simulation

```
start_time = 4014
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weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

MODEL PARAMETERS

Outdoor Climate Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

INITIAL STATE

Outdoor Climate Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

SIMULATION LOOP

Outdoor Climate Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

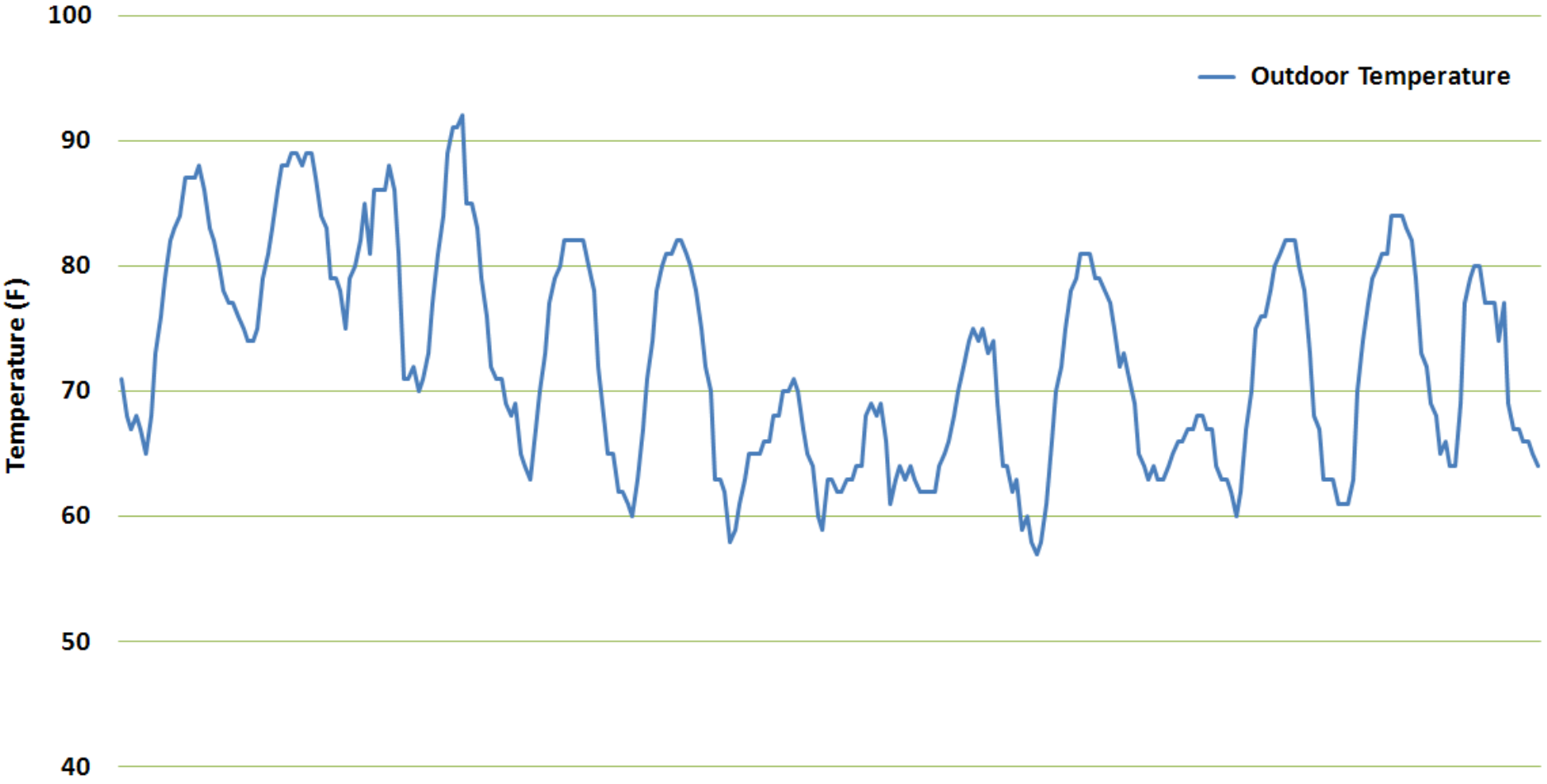
STATE TRANSITION

Outdoor Climate Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

SIMULATION OUTPUT

Outdoor Climate Simulation



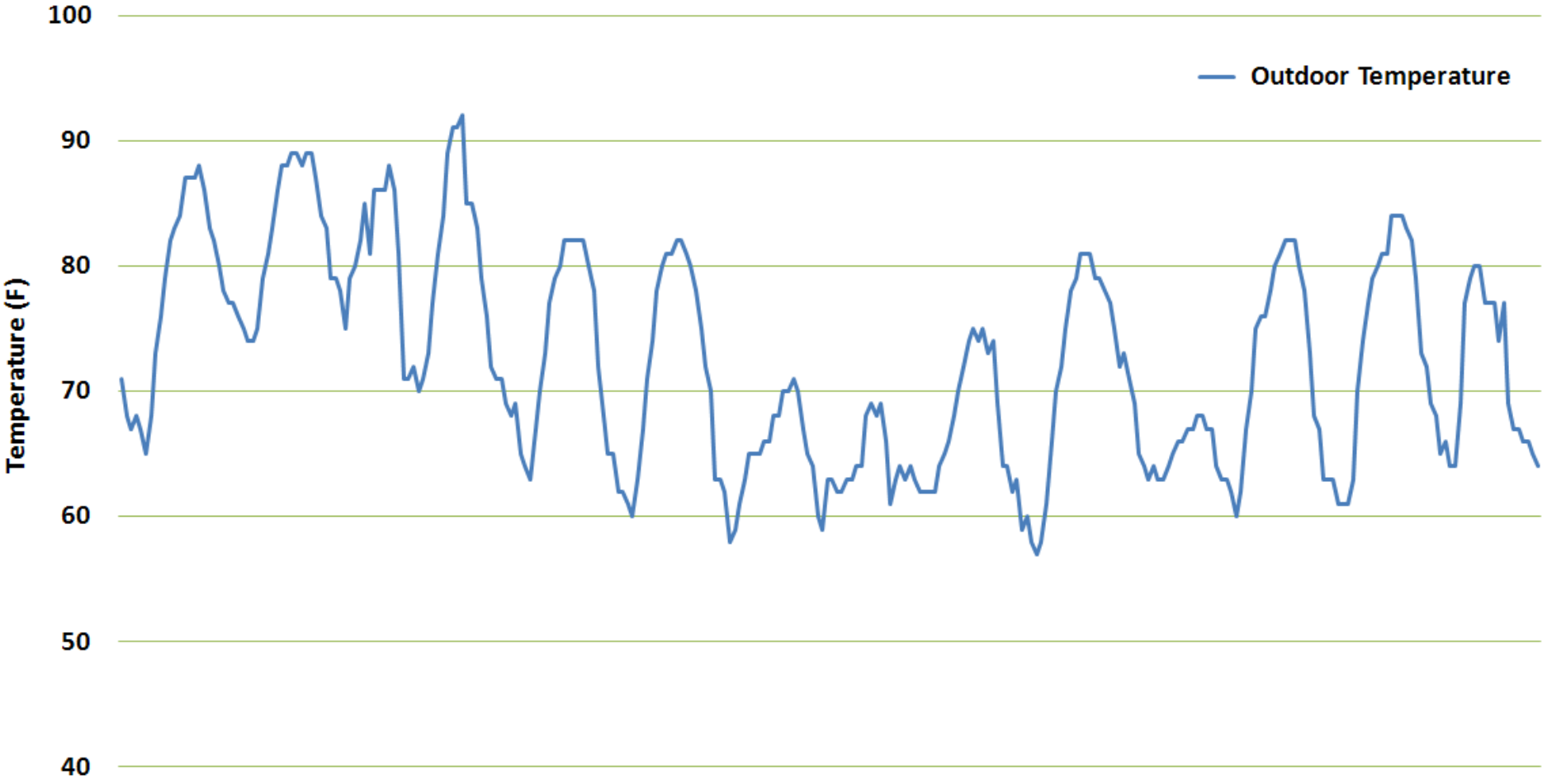
Outdoor Climate Simulation → Indoor Climate Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

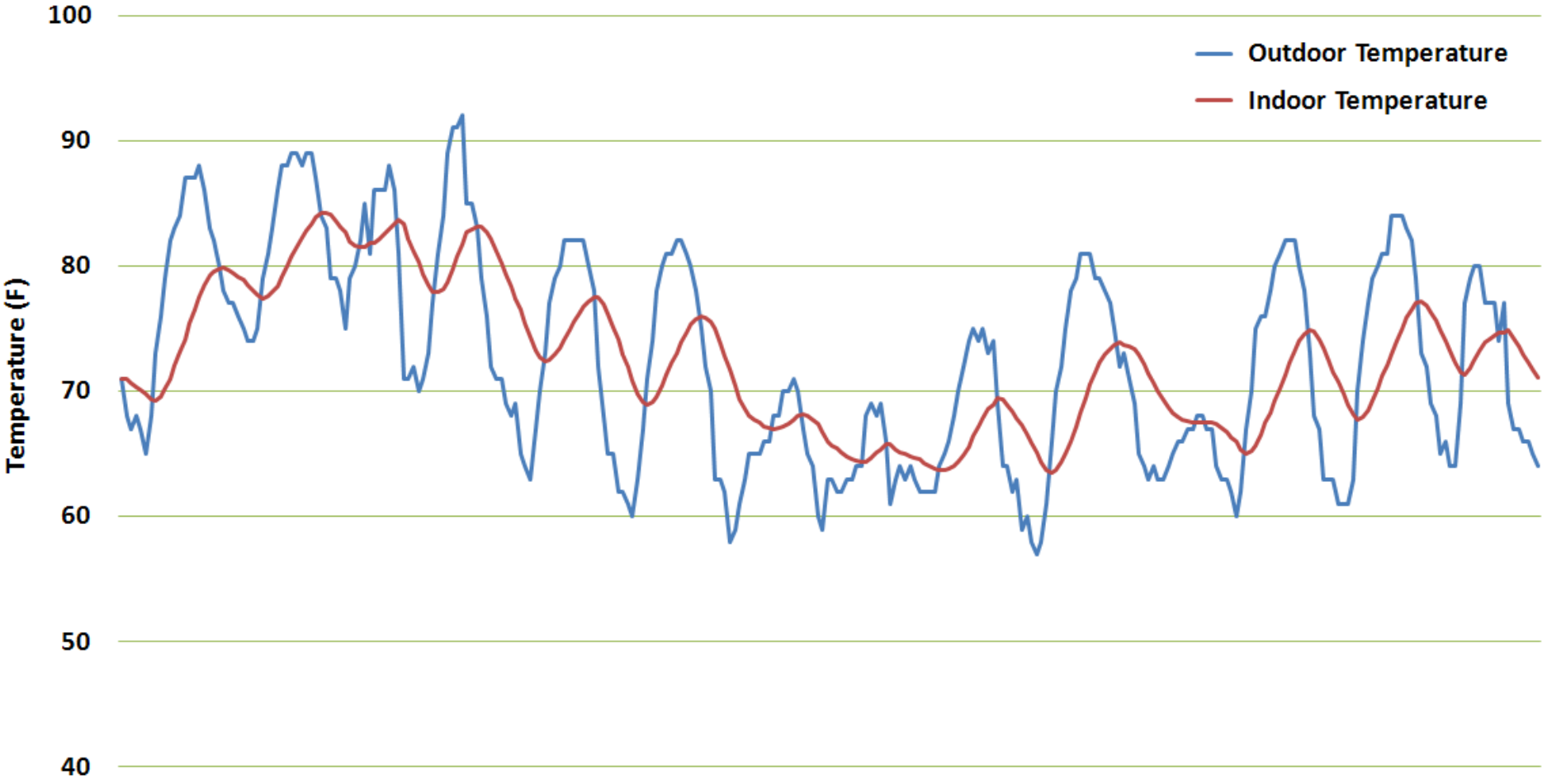
Outdoor Climate Simulation → Indoor Climate Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()
wall_rate = 0.1

time = start_time
outdoor_temperature = weather_data[int(start_time)]
indoor_temperature = weather_data[int(start_time)]
lower_transition_temperature = indoor_temperature - 1.0
upper_transition_temperature = indoor_temperature + 1.0

while time < end_time:

    outdoor_transition_time = int(time) + 1

    rate = wall_rate
    target_temperature = outdoor_temperature
    dT = target_temperature - indoor_temperature

    if dT < 0:
        transition_dT = lower_transition_temperature - indoor_temperature
    else:
        transition_dT = upper_transition_temperature - indoor_temperature
    if abs(dT) <= abs(transition_dT):
        indoor_transition_time = infty
    else:
        indoor_transition_time = time + (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

    if indoor_transition_time < outdoor_transition_time:
        if dT < 0:
            indoor_temperature = lower_transition_temperature
        else:
            indoor_temperature = upper_transition_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        time = indoor_transition_time
    else:
        dt = outdoor_transition_time - time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)
        time = outdoor_transition_time
        outdoor_temperature = weather_data[int(time)]
        output(time, ["outdoor_temperature", outdoor_temperature])
        output(time, ["indoor_temperature", indoor_temperature])
```

Outdoor Climate Simulation → Indoor Climate Simulation



Outdoor Climate Simulation → Indoor Climate Simulation



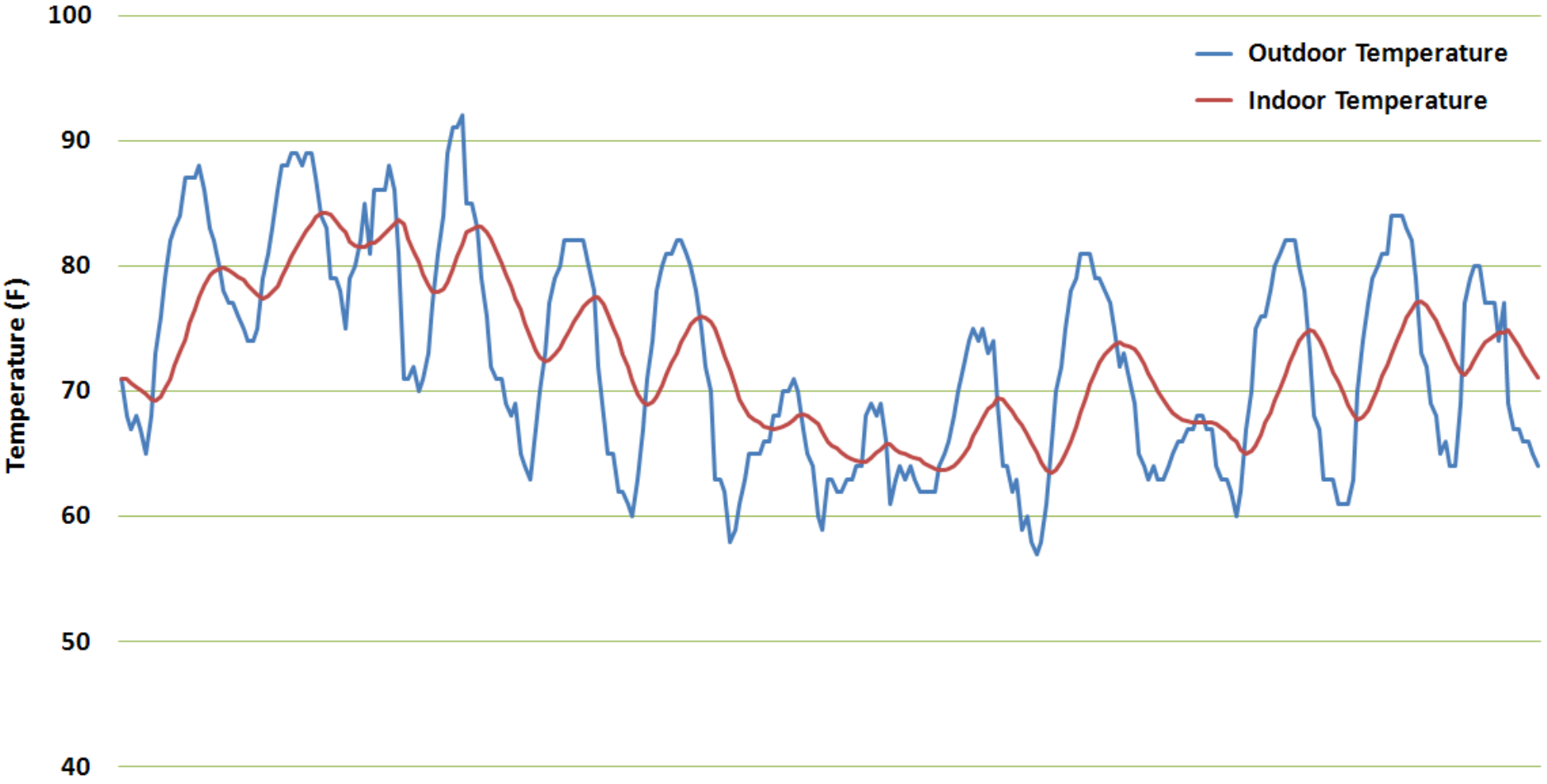
Indoor Climate Simulation → Heating System Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()
wall_rate = 0.1

time = start_time
outdoor_temperature = weather_data[int(start_time)]
indoor_temperature = weather_data[int(start_time)]
lower_transition_temperature = indoor_temperature - 1.0
upper_transition_temperature = indoor_temperature + 1.0

while time < end_time:

    outdoor_transition_time = int(time) + 1

    rate = wall_rate
    target_temperature = outdoor_temperature
    dT = target_temperature - indoor_temperature

    if dT < 0:
        transition_dT = lower_transition_temperature - indoor_temperature
    else:
        transition_dT = upper_transition_temperature - indoor_temperature
    if abs(dT) <= abs(transition_dT):
        indoor_transition_time = infty
    else:
        indoor_transition_time = time + (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

    if indoor_transition_time < outdoor_transition_time:
        if dT < 0:
            indoor_temperature = lower_transition_temperature
        else:
            indoor_temperature = upper_transition_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        time = indoor_transition_time
    else:
        dt = outdoor_transition_time - time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)
        time = outdoor_transition_time
        outdoor_temperature = weather_data[int(time)]
        output(time, ["outdoor_temperature", outdoor_temperature])
        output(time, ["indoor_temperature", indoor_temperature])
```

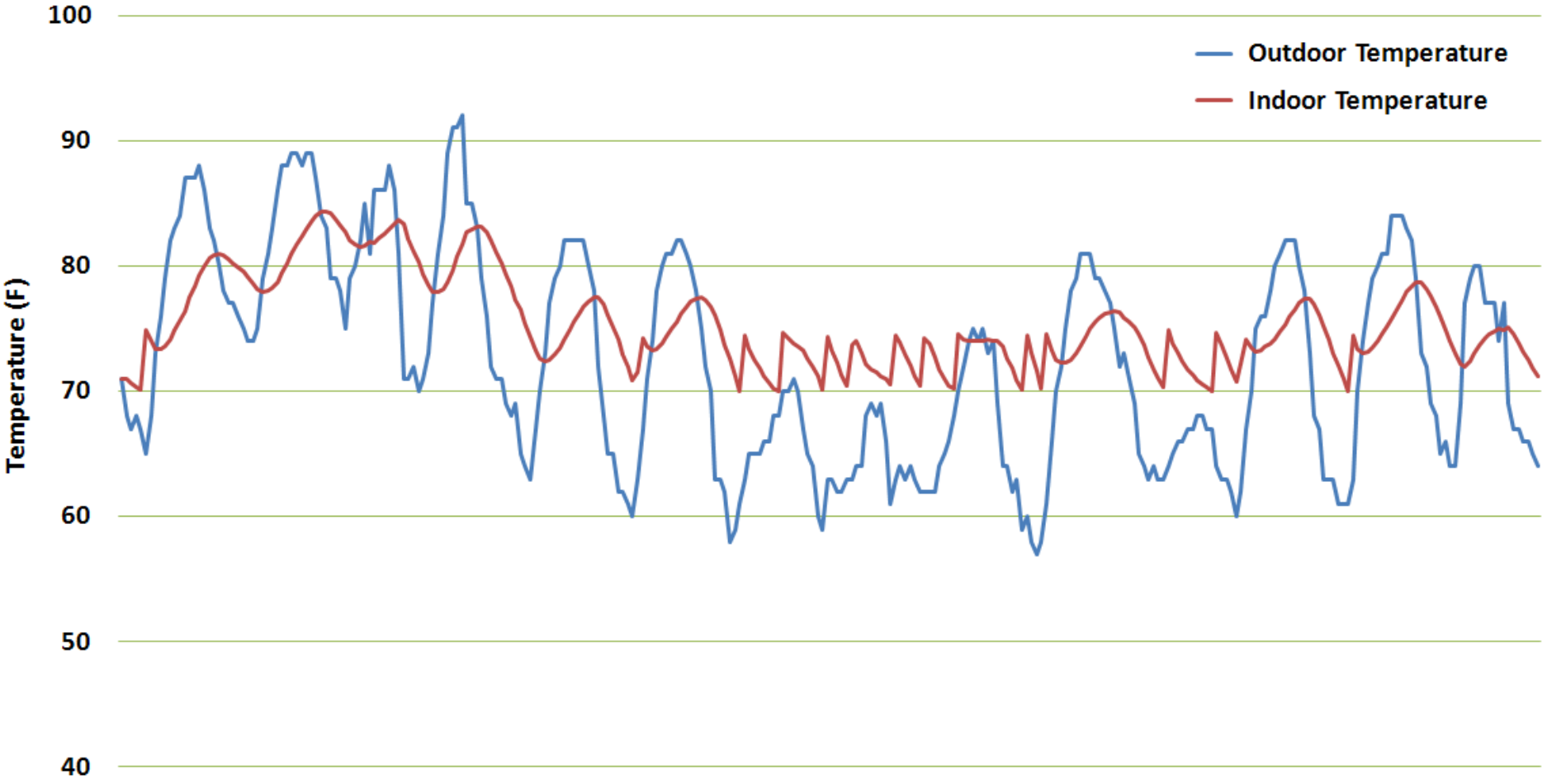
Indoor Climate Simulation → Heating System Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()
wall_rate = 0.1
heater_rate = 0.4
heater_temperature = 100
lower_sensor_threshold = 70
upper_sensor_threshold = 75

time = start_time
outdoor_temperature = weather_data[int(start_time)]
indoor_temperature = weather_data[int(start_time)]
lower_transition_temperature = indoor_temperature - 1.0
upper_transition_temperature = indoor_temperature + 1.0
heater_is_on = False

while time < end_time:

    outdoor_transition_time = int(time) + 1

    if heater_is_on:
        rate = wall_rate + heater_rate
        target_temperature = (wall_rate*outdoor_temperature + heater_rate*heater_temperature)/float(rate)
    else:
        rate = wall_rate
        target_temperature = outdoor_temperature
    dT = target_temperature - indoor_temperature

    if dT < 0:
        transition_dT = lower_transition_temperature - indoor_temperature
    else:
        transition_dT = upper_transition_temperature - indoor_temperature
    if abs(dT) <= abs(transition_dT):
        indoor_transition_time = infty
    else:
        indoor_transition_time = time + (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

    if indoor_transition_time < outdoor_transition_time:
        if dT < 0:
            indoor_temperature = lower_transition_temperature
        else:
            indoor_temperature = upper_transition_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        if indoor_temperature <= lower_sensor_threshold:
            heater_is_on = True
        elif indoor_temperature >= upper_sensor_threshold:
            heater_is_on = False
        time = indoor_transition_time
    else:
        dt = outdoor_transition_time - time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)
        time = outdoor_transition_time
        outdoor_temperature = weather_data[int(time)]
        output(time, ["outdoor_temperature", outdoor_temperature])
        output(time, ["indoor_temperature", indoor_temperature])
```

Indoor Climate Simulation → Heating System Simulation



Indoor Climate Simulation → Heating System Simulation



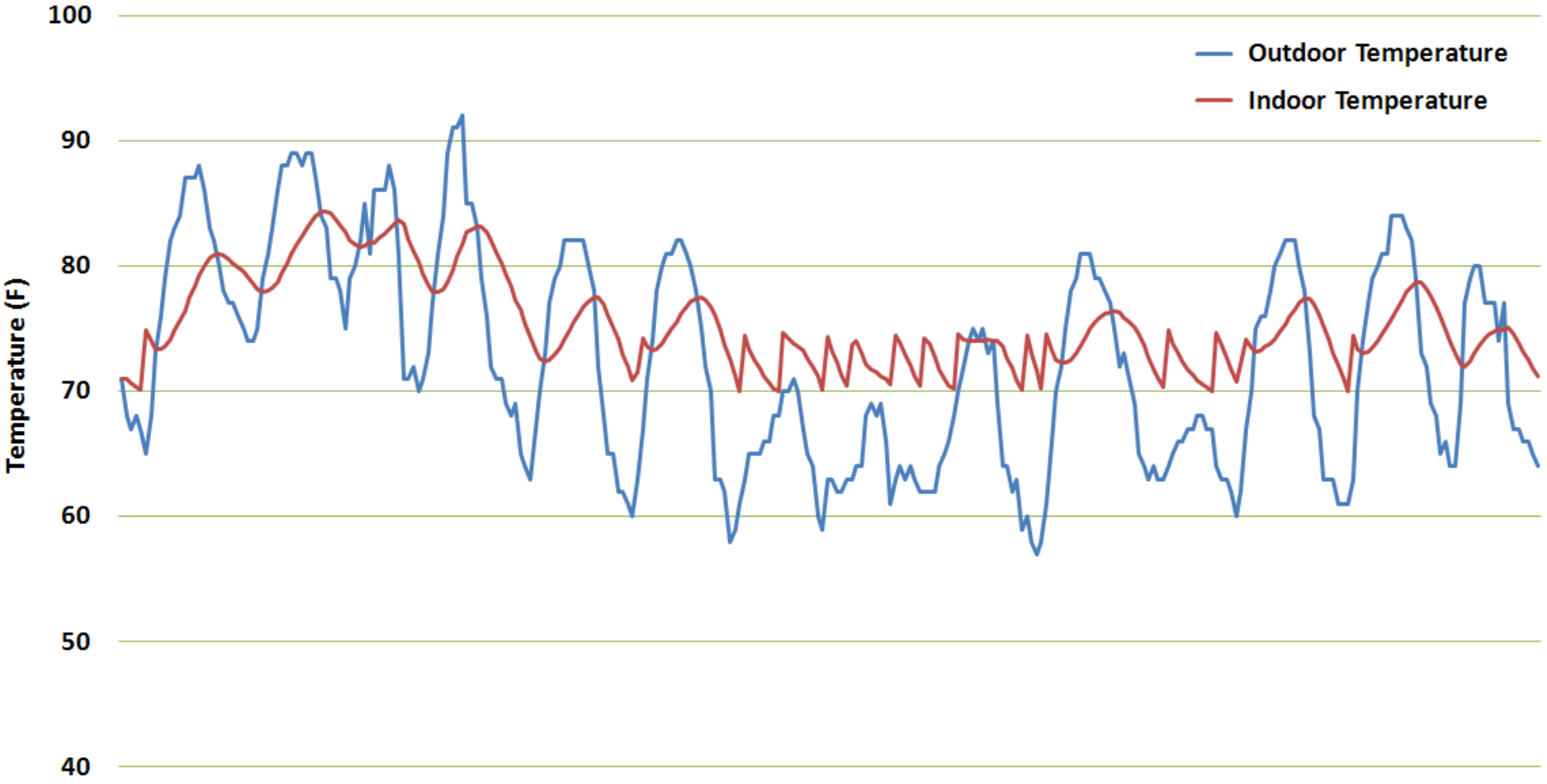
Heating System Simulation → Window Opening Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()
wall_rate = 0.1
heater_rate = 0.4
heater_temperature = 100
lower_sensor_threshold = 70
upper_sensor_threshold = 75

time = start_time
outdoor_temperature = weather_data[int(start_time)]
indoor_temperature = weather_data[int(start_time)]
lower_transition_temperature = indoor_temperature - 1.0
upper_transition_temperature = indoor_temperature + 1.0
heater_is_on = False

while time < end_time:

    outdoor_transition_time = int(time) + 1

    if heater_is_on:
        rate = wall_rate + heater_rate
        target_temperature = (wall_rate*outdoor_temperature + heater_rate*heater_temperature)/float(rate)
    else:
        rate = wall_rate
        target_temperature = outdoor_temperature
    dT = target_temperature - indoor_temperature

    if dT < 0:
        transition_dT = lower_transition_temperature - indoor_temperature
    else:
        transition_dT = upper_transition_temperature - indoor_temperature
    if abs(dT) <= abs(transition_dT):
        indoor_transition_time = infty
    else:
        indoor_transition_time = time + (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

    if indoor_transition_time < outdoor_transition_time:
        if dT < 0:
            indoor_temperature = lower_transition_temperature
        else:
            indoor_temperature = upper_transition_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        if indoor_temperature <= lower_sensor_threshold:
            heater_is_on = True
        elif indoor_temperature >= upper_sensor_threshold:
            heater_is_on = False
        time = indoor_transition_time
    else:
        dt = outdoor_transition_time - time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)
        time = outdoor_transition_time
        outdoor_temperature = weather_data[int(time)]
        output(time, ["outdoor_temperature", outdoor_temperature])
        output(time, ["indoor_temperature", indoor_temperature])
```

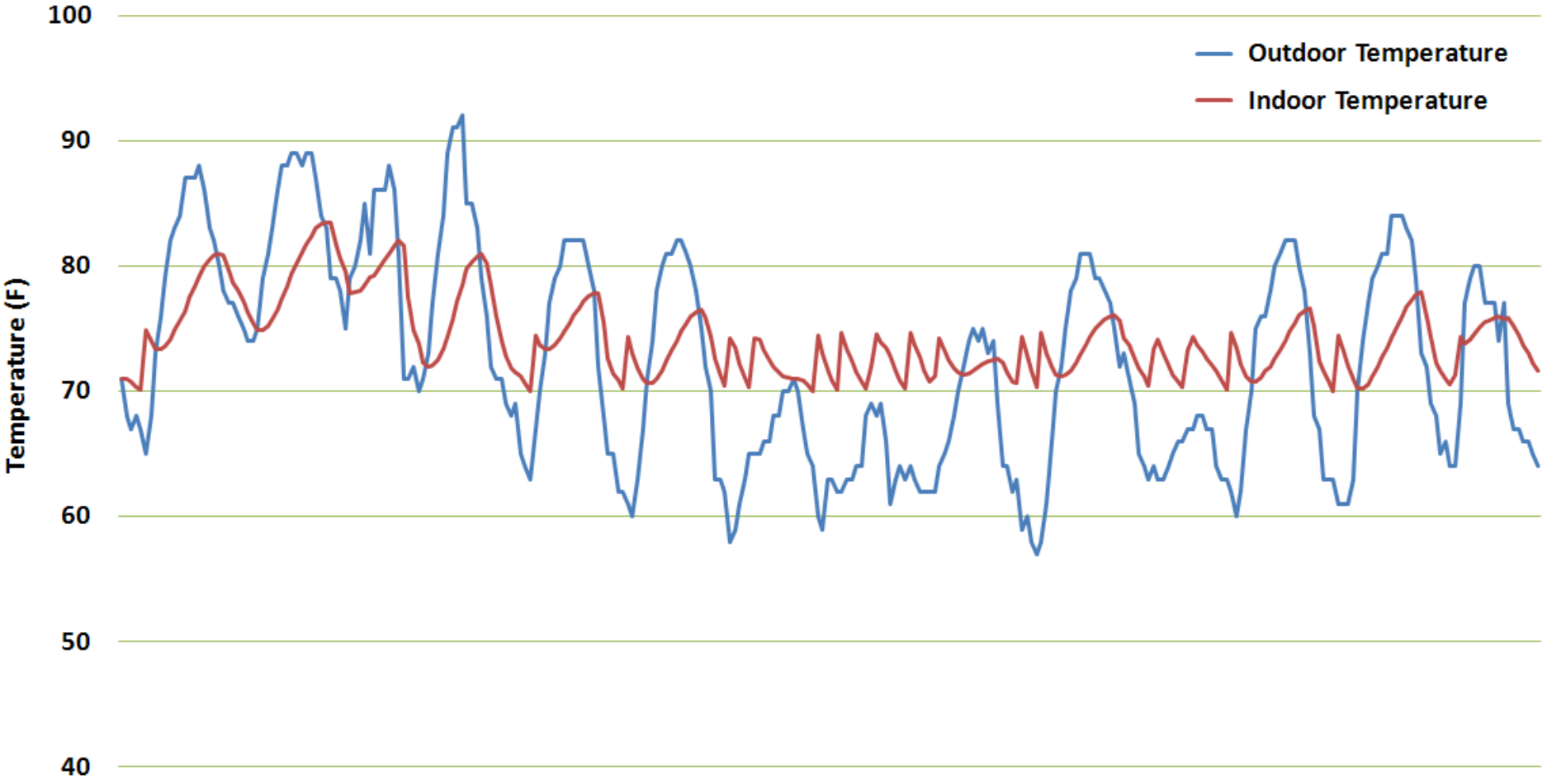
Heating System Simulation → Window Opening Simulation

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()
wall_rate = 0.1
heater_rate = 0.4
heater_temperature = 100
lower_sensor_threshold = 70
upper_sensor_threshold = 75
lower_occupant_threshold = 72
upper_occupant_threshold = 76
window_rate = 0.4

time = start_time
outdoor_temperature = weather_data[int(start_time)]
indoor_temperature = weather_data[int(start_time)]
lower_transition_temperature = indoor_temperature - 1.0
upper_transition_temperature = indoor_temperature + 1.0
heater_is_on = False
window_is_open = False
observed_temperature = weather_data[int(start_time)]

while time < end_time:

    outdoor_transition_time = int(time) + 1

    if window_is_open:
        envelope_rate = wall_rate + window_rate
    else:
        envelope_rate = wall_rate
    if heater_is_on:
        rate = envelope_rate + heater_rate
        target_temperature = (envelope_rate*outdoor_temperature + heater_rate*heater_temperature)/float(rate)
    else:
        rate = envelope_rate
        target_temperature = outdoor_temperature
    dT = target_temperature - indoor_temperature

    if dT < 0:
        transition_dT = lower_transition_temperature - indoor_temperature
    else:
        transition_dT = upper_transition_temperature - indoor_temperature
    if abs(dT) <= abs(transition_dT):
        indoor_transition_time = infty
    else:
        indoor_transition_time = time + (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

    if indoor_transition_time < outdoor_transition_time:
        if dT < 0:
            indoor_temperature = lower_transition_temperature
        else:
            indoor_temperature = upper_transition_temperature
        observed_temperature = indoor_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        if indoor_temperature <= lower_sensor_threshold:
            heater_is_on = True
        elif indoor_temperature >= upper_sensor_threshold:
            heater_is_on = False
        time = indoor_transition_time
    else:
        dt = outdoor_transition_time - time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)
        time = outdoor_transition_time
        outdoor_temperature = weather_data[int(time)]
        output(time, ["outdoor_temperature", outdoor_temperature])
        output(time, ["indoor_temperature", indoor_temperature])

    if observed_temperature >= max([outdoor_temperature, upper_occupant_threshold]):
        window_is_open = True
    if observed_temperature <= max([outdoor_temperature, lower_occupant_threshold]):
        window_is_open = False
```

Heating System Simulation → Window Opening Simulation



Heating System Simulation → Window Opening Simulation

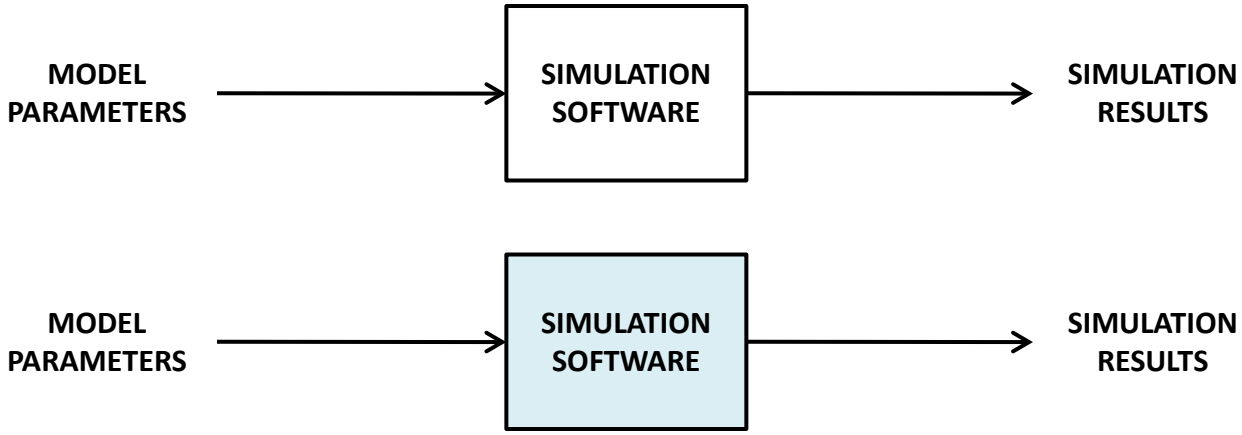


Traditional Simulation Code

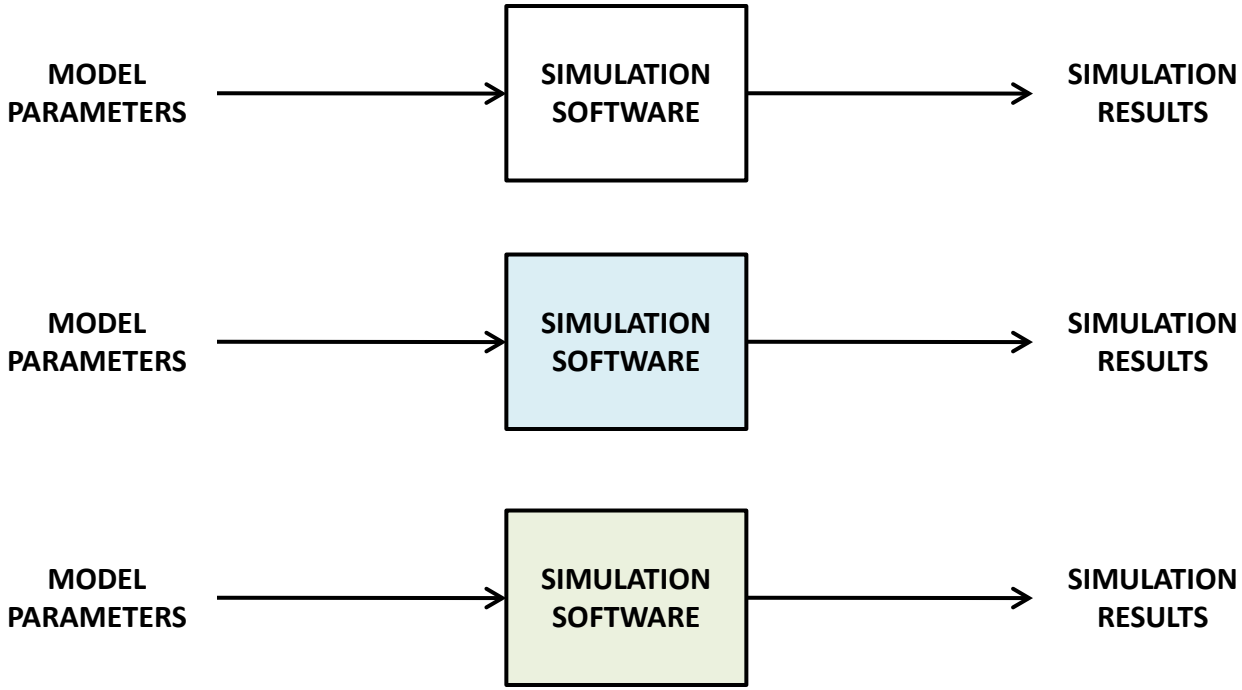
```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()
wall_rate = 0.1
heater_rate = 0.4
heater_temperature = 100
lower_sensor_threshold = 70
upper_sensor_threshold = 75
lower_occupant_threshold = 72
upper_occupant_threshold = 76
window_rate = 0.4

time = start_time
outdoor_temperature = weather_data[int(start_time)]
indoor_temperature = weather_data[int(start_time)]
lower_transition_temperature = indoor_temperature - 1.0
upper_transition_temperature = indoor_temperature + 1.0
heater_is_on = False
window_is_open = False
observed_temperature = weather_data[int(start_time)]

while time < end_time:

    outdoor_transition_time = int(time) + 1

    if window_is_open:
        envelope_rate = wall_rate + window_rate
    else:
        envelope_rate = wall_rate
    if heater_is_on:
        rate = envelope_rate + heater_rate
        target_temperature = (envelope_rate*outdoor_temperature + heater_rate*heater_temperature)/float(rate)
    else:
        rate = envelope_rate
        target_temperature = outdoor_temperature
    dT = target_temperature - indoor_temperature

    if dT < 0:
        transition_dT = lower_transition_temperature - indoor_temperature
    else:
        transition_dT = upper_transition_temperature - indoor_temperature
    if abs(dT) <= abs(transition_dT):
        indoor_transition_time = infty
    else:
        indoor_transition_time = time + (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

    if indoor_transition_time < outdoor_transition_time:
        if dT < 0:
            indoor_temperature = lower_transition_temperature
        else:
            indoor_temperature = upper_transition_temperature
        observed_temperature = indoor_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        if indoor_temperature <= lower_sensor_threshold:
            heater_is_on = True
        elif indoor_temperature >= upper_sensor_threshold:
            heater_is_on = False
        time = indoor_transition_time
    else:
        dt = outdoor_transition_time - time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)
        time = outdoor_transition_time
        outdoor_temperature = weather_data[int(time)]
        output(time, ["outdoor_temperature", outdoor_temperature])
        output(time, ["indoor_temperature", indoor_temperature])

    if observed_temperature >= max([outdoor_temperature, upper_occupant_threshold]):
        window_is_open = True
    if observed_temperature <= max([outdoor_temperature, lower_occupant_threshold]):
        window_is_open = False
```

Traditional Simulation Development

Traditional Simulation Development



Traditional Simulation Development



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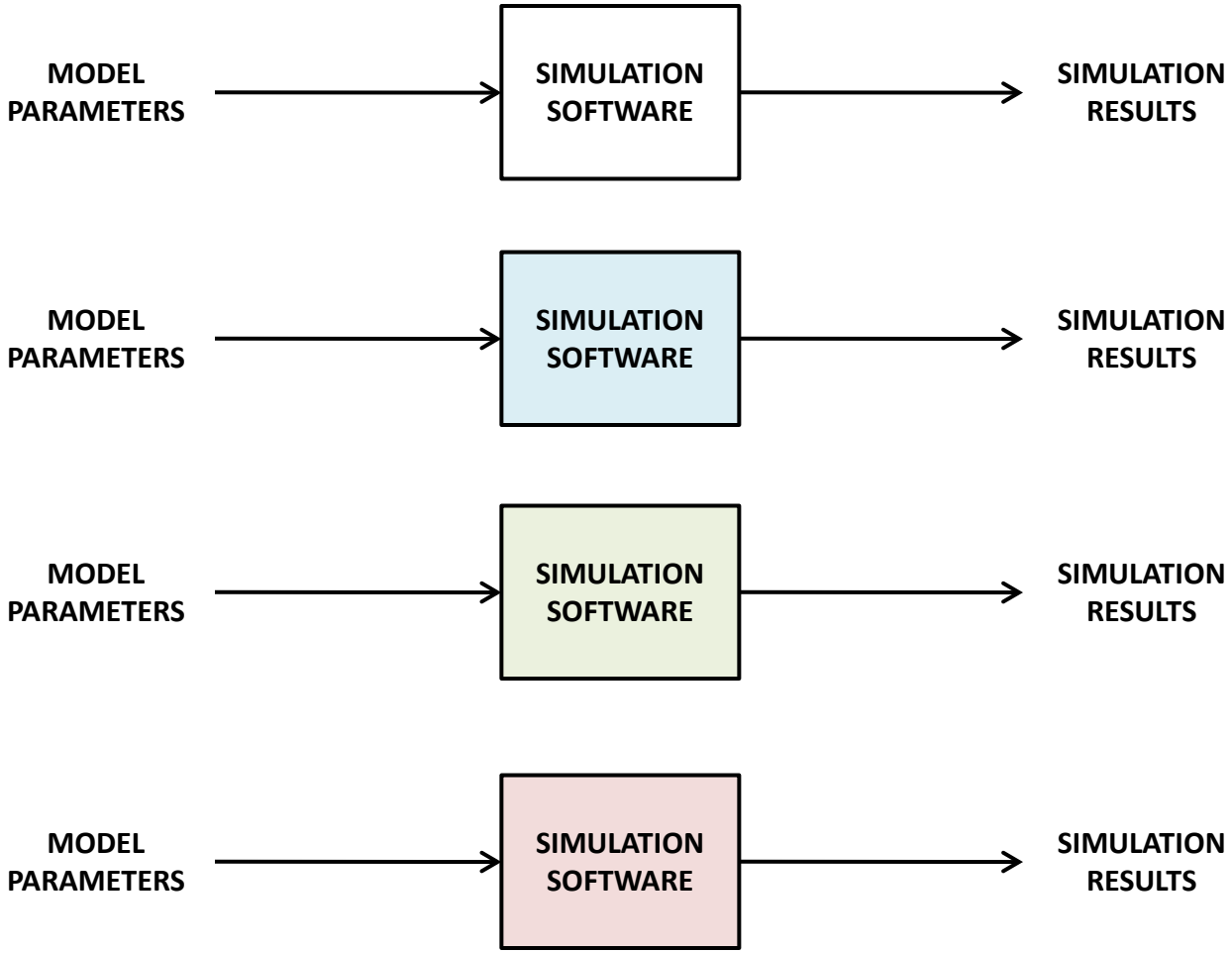
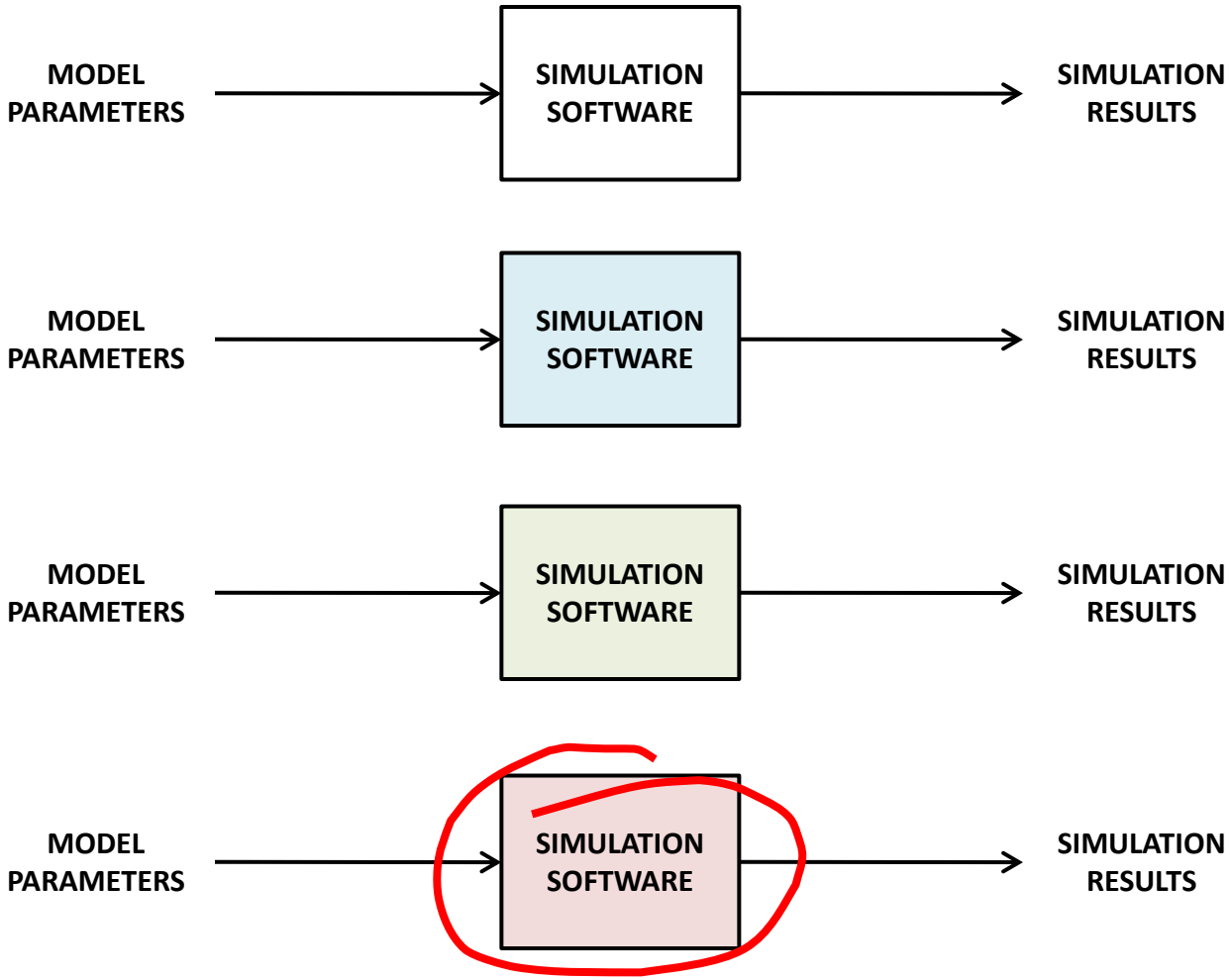
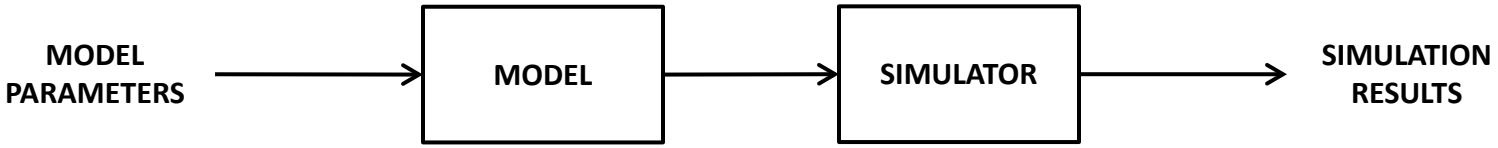


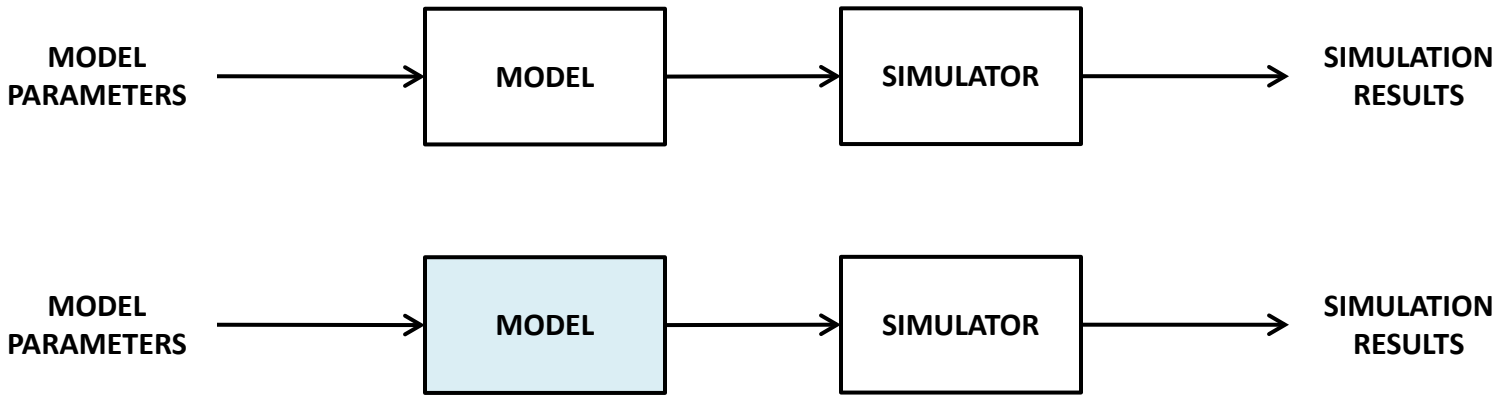
Traditional Simulation Development



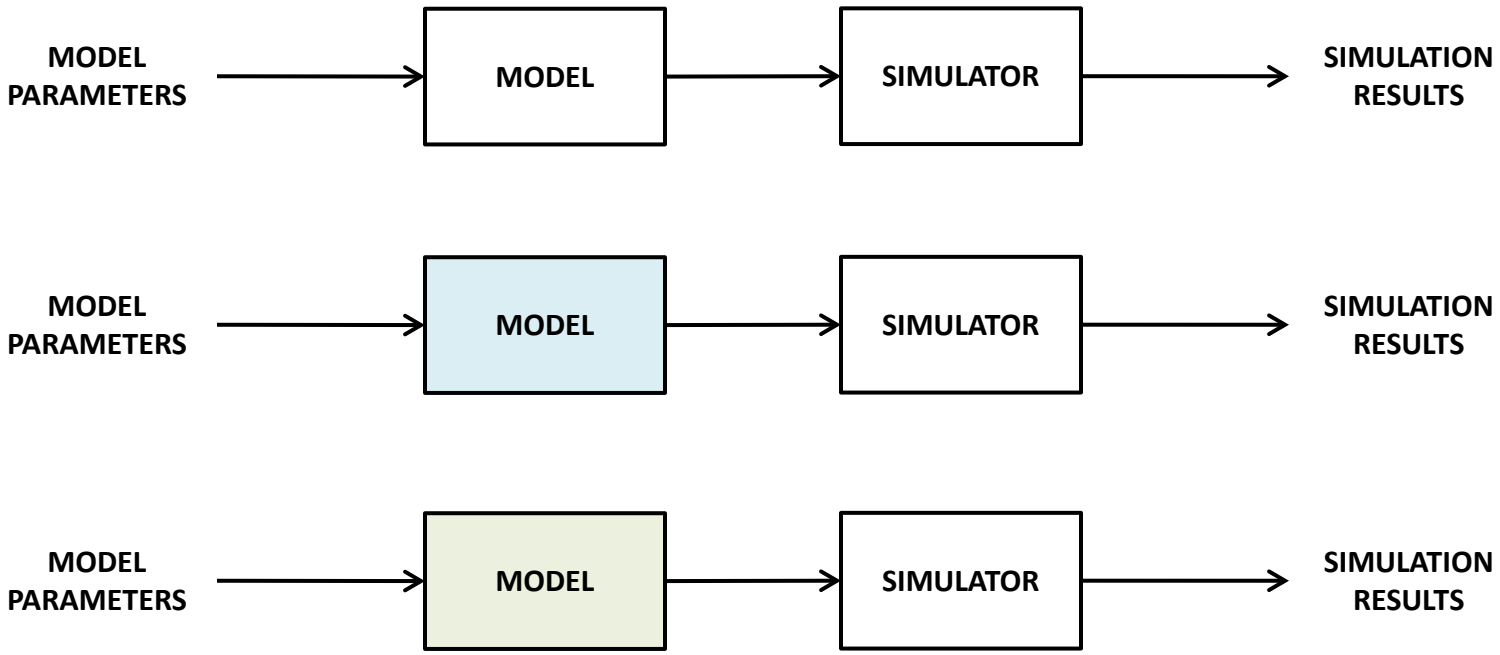
DEVS Model Development



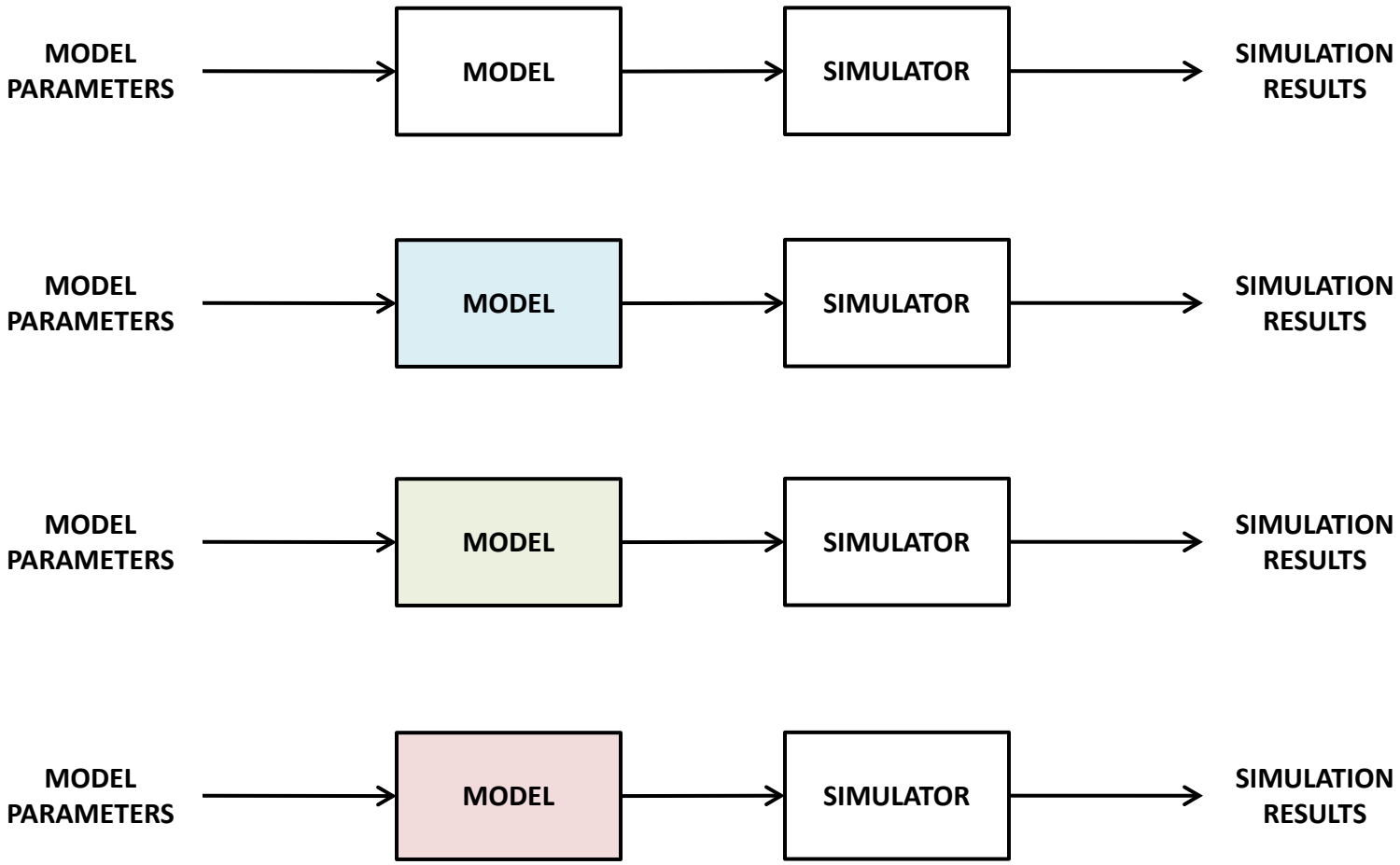
DEVS Model Development



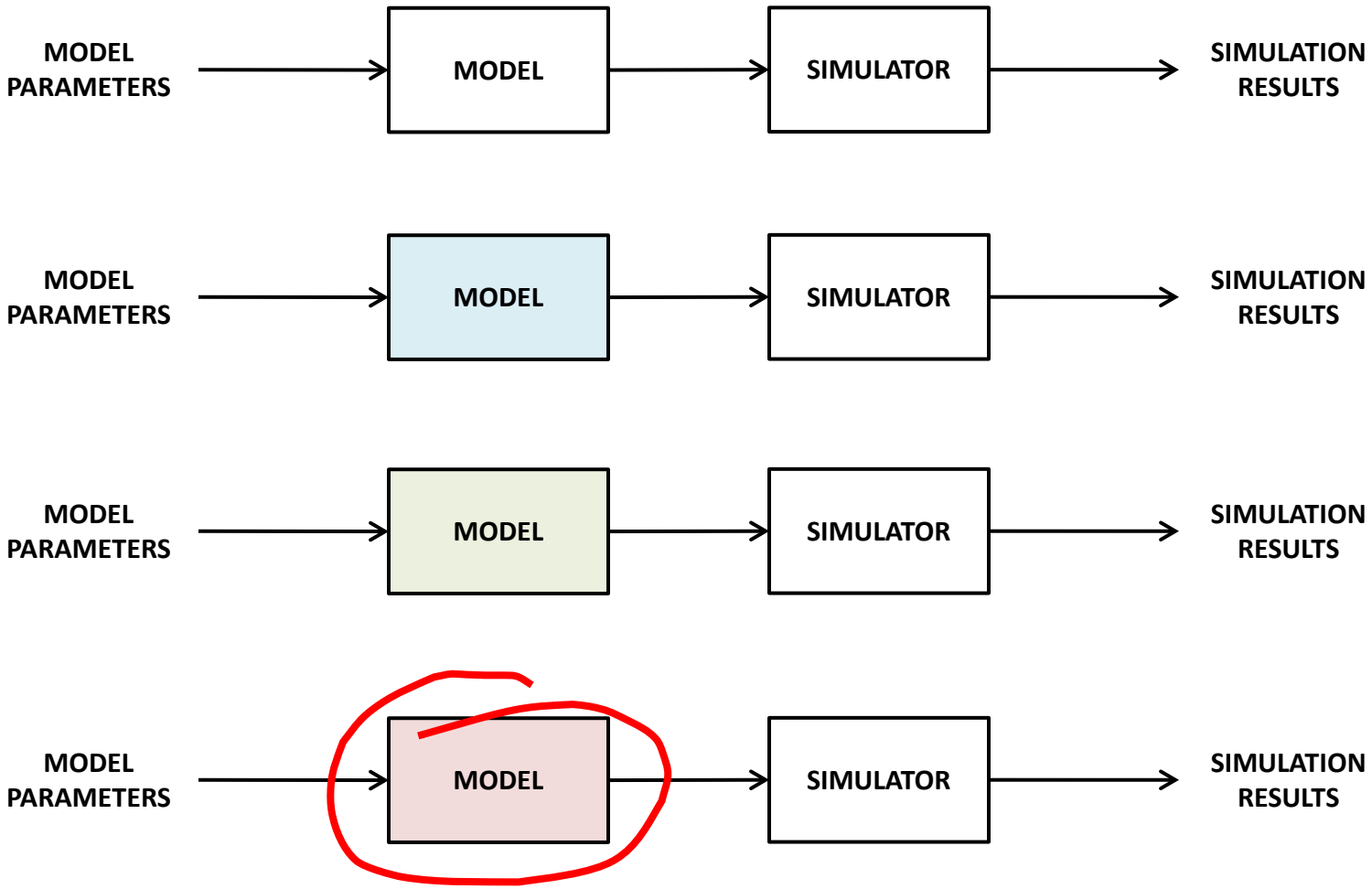
DEVS Model Development



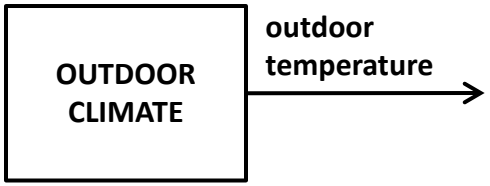
DEVS Model Development



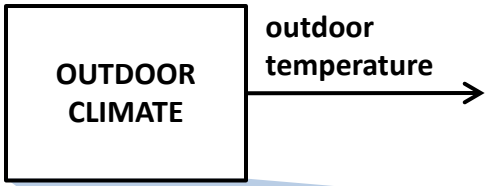
DEVS Model Development



Outdoor Climate Model



Outdoor Climate Model




```
def OUTDOOR_CLIMATE(start_time, end_time, weather_data):

    def initialize():
        time = start_time
        outdoor_temperature = weather_data[int(start_time)]
        state = [time, outdoor_temperature]
        return state

    def external_transition(state, elapsed_time, input_value):
        pass

    def internal_transition(state):
        [time, outdoor_temperature] = state
        time = time + 1
        outdoor_temperature = weather_data[int(time)]
        state = [time, outdoor_temperature]
        output_values = [["outdoor_temperature", outdoor_temperature]]
        return [state, output_values]

    def time_advance(state):
        [time, outdoor_temperature] = state
        if time < end_time:
            remaining_time = 1
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

Outdoor Climate Model

Traditional Simulation Code:

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()

time = start_time
outdoor_temperature = weather_data[int(start_time)]

while time < end_time:
    time = time + 1
    outdoor_temperature = weather_data[int(time)]
    output(time, ["outdoor_temperature", outdoor_temperature])
```

DEVS Model Code:

```
def OUTDOOR_CLIMATE(start_time, end_time, weather_data):

    def initialize():
        time = start_time
        outdoor_temperature = weather_data[int(start_time)]
        state = [time, outdoor_temperature]
        return state

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DEVS Model Code:

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        outdoor_temperature = weather_data[int(time)]
        state = [time, outdoor_temperature]
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        [time, outdoor_temperature] = state
        time = time + 1
        outdoor_temperature = weather_data[int(time)]
        state = [time, outdoor_temperature]
        output_values = [["outdoor_temperature", outdoor_temperature]]
        return [state, output_values]

    def time_advance(state):
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    def initialize():
        time = start_time
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        state = [time, outdoor_temperature]
        return state

    def external_transition(state, elapsed_time, input_value):
        pass

    def internal_transition(state):
        [time, outdoor_temperature] = state
        time = time + 1
        outdoor_temperature = weather_data[int(time)]
        state = [time, outdoor_temperature]
        output_values = [["outdoor_temperature", outdoor_temperature]]
        return [state, output_values]

    def time_advance(state):
        [time, outdoor_temperature] = state
        if time < end_time:
            remaining_time = 1
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```
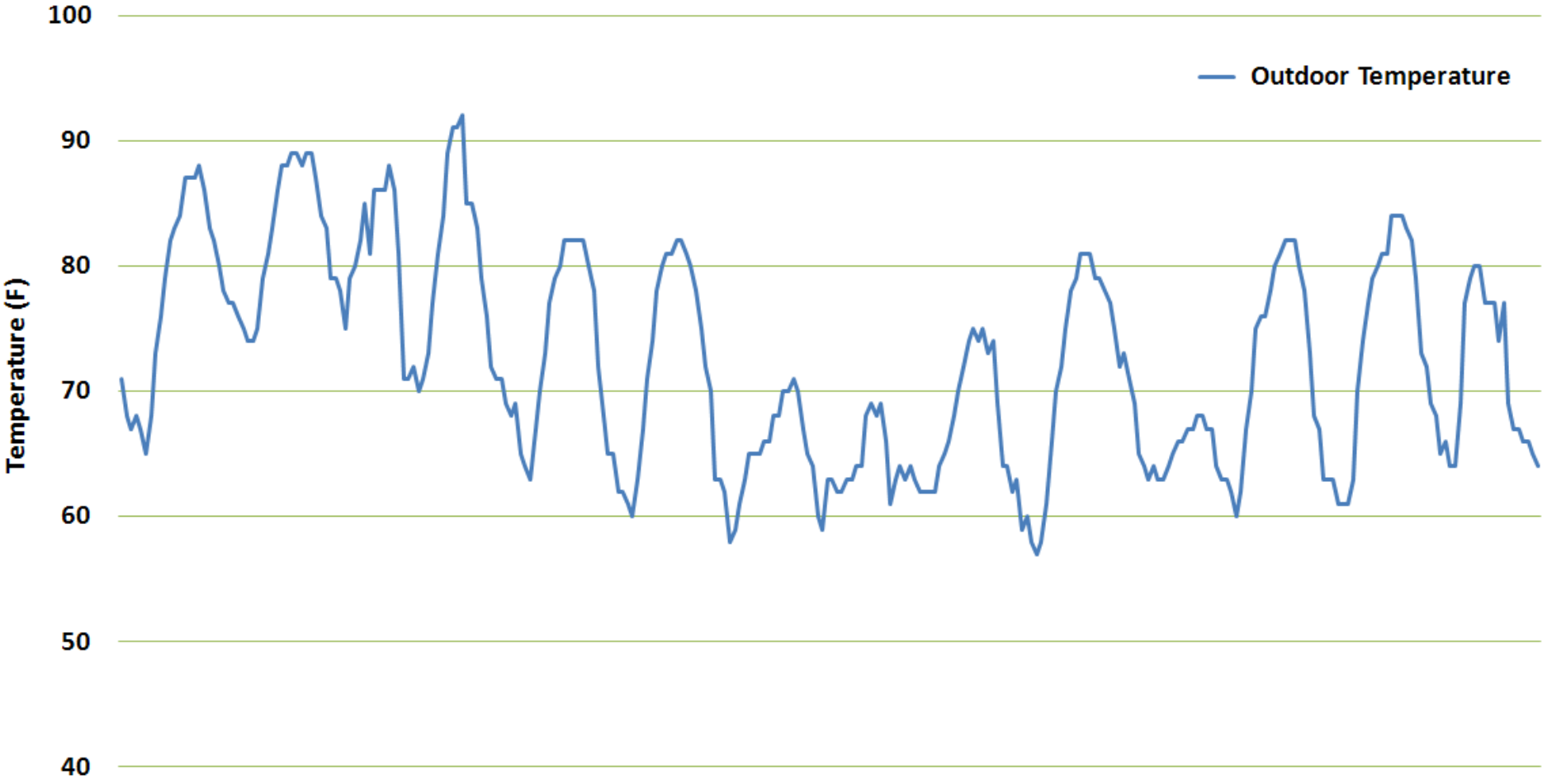
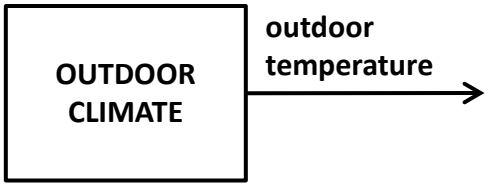
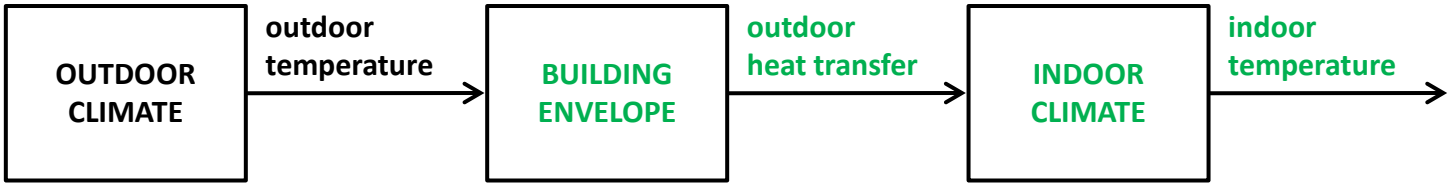

DEVS Simulation Output



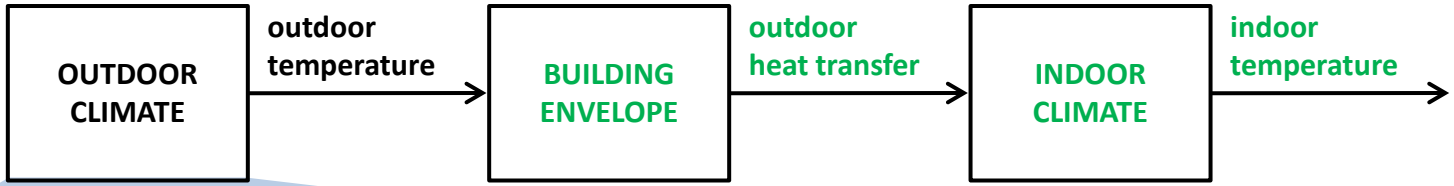
Outdoor Climate Model → Indoor Climate Model



Outdoor Climate Model → Indoor Climate Model



Outdoor Climate Model → Indoor Climate Model

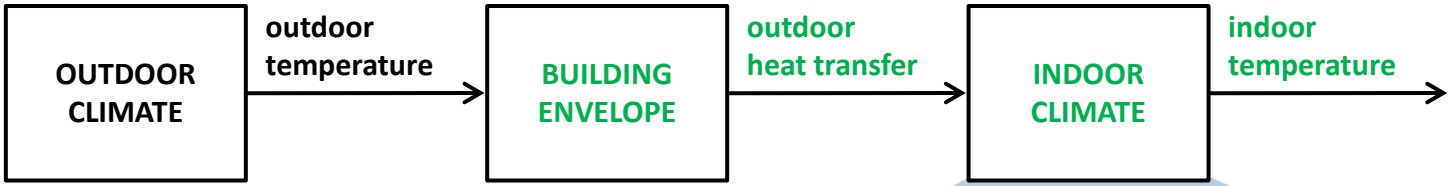



```
def OUTDOOR_CLIMATE(start_time, end_time, weather_data):

    def initialize():
        time = start_time
        outdoor_temperature = weather_data[int(start_time)]
        state = [time, outdoor_temperature]
        return state

    def external_transition(state, elapsed_time, input_value):
        pass

    def internal_transition(state):
        [time, outdoor_temperature] = state
        time = time + 1
        outdoor_temperature = weather_data[int(time)]
        state = [time, outdoor_temperature]
        output_values = [["outdoor_temperature", outdoor_temperature]]
        return [state, output_values]

    def time_advance(state):
        [time, outdoor_temperature] = state
        if time < end_time:
            remaining_time = 1
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

Outdoor Climate Model → Indoor Climate Model

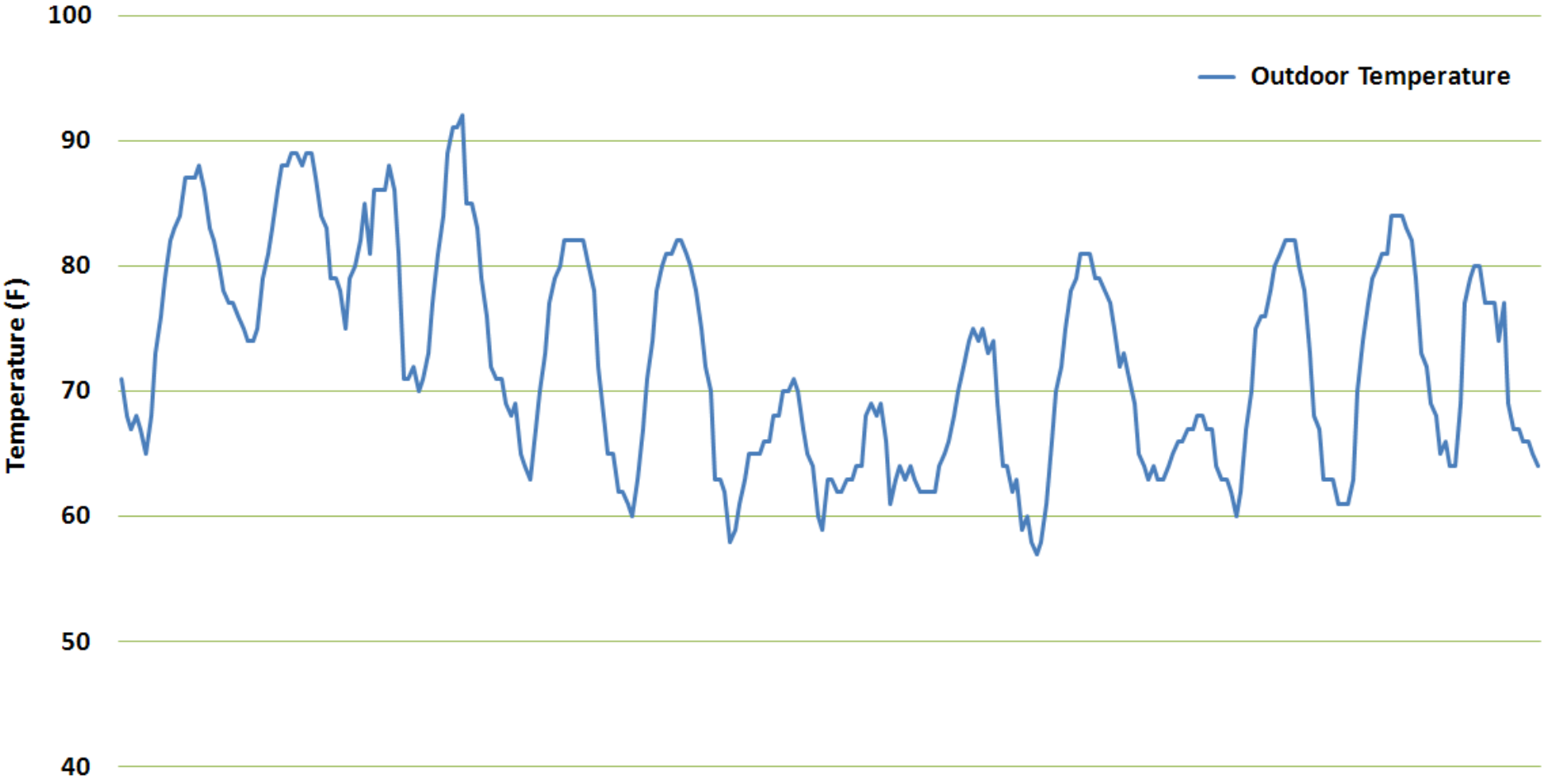

```
def BUILDING_ENVELOPE(wall_rate):

    def initialize(initial_temperature):
        state_has_changed = False
        outdoor_temperature = initial_temperature
        state = [state_has_changed, outdoor_temperature]
        return state

    def external_transition(state, elapsed_time, input_value):
        state_has_changed = True
        [port, outdoor_temperature] = input_value
        state = [state_has_changed, outdoor_temperature]
        return state

    def internal_transition(state):
        [state_has_changed, outdoor_temperature] = state
        state_has_changed = False
        state = [state_has_changed, outdoor_temperature]
        output_values = [["outdoor_heat_transfer", [outdoor_temperature, wall_rate]]]
        return [state, output_values]

    def time_advance(state):
        [state_has_changed, outdoor_temperature] = state
        if state_has_changed:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

Outdoor Climate Model → Indoor Climate Model

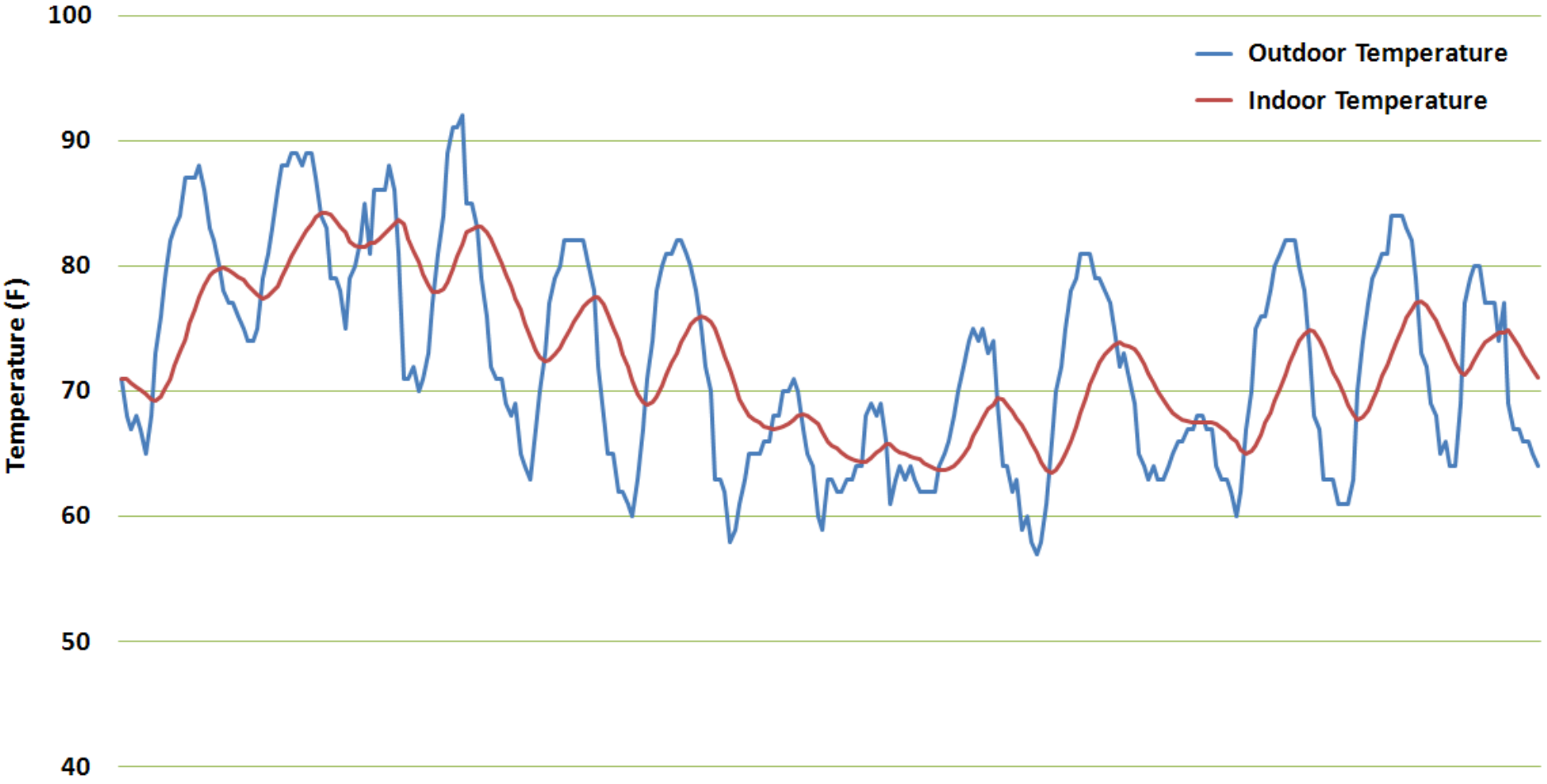



```
def INDOOR_CLIMATE():

    def initialize(initial_temperature, initial_rate):
        indoor_temperature = initial_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        outdoor_temperature = initial_temperature
        envelope_rate = initial_rate
        rate = initial_rate
        target_temperature = initial_temperature
        dT = 0
        indoor_transition_remaining_time = infty
        outdoor_has_changed = False
        state = [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
                 outdoor_temperature, envelope_rate, rate, target_temperature, dT,
                 indoor_transition_remaining_time, outdoor_has_changed]
        return state

    def external_transition(state, elapsed_time, input_value):
        [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
         outdoor_temperature, envelope_rate, rate, target_temperature, dT,
         indoor_transition_remaining_time, outdoor_has_changed] = state

        dt = elapsed_time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)

        [port, message] = input_value
        if port == "outdoor_heat_transfer":
            [new_outdoor_temperature, new_envelope_rate] = message
            if new_envelope_rate == envelope_rate or not (new_outdoor_temperature == outdoor_temperature):
                outdoor_has_changed = True
            outdoor_temperature = new_outdoor_temperature
            envelope_rate = new_envelope_rate

        rate = envelope_rate
        target_temperature = outdoor_temperature
        dT = target_temperature - indoor_temperature

        if dT < 0:
            transition_dT = lower_transition_temperature - indoor_temperature
        else:
            transition_dT = upper_transition_temperature - indoor_temperature
        if abs(dT) <= abs(transition_dT):
            indoor_transition_remaining_time = infty
        else:
            indoor_transition_remaining_time = (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

        state = [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
                 outdoor_temperature, envelope_rate, rate, target_temperature, dT,
                 indoor_transition_remaining_time, outdoor_has_changed]
        return state

    def internal_transition(state):
        [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
         outdoor_temperature, envelope_rate, rate, target_temperature, dT,
         indoor_transition_remaining_time, outdoor_has_changed] = state

        if outdoor_has_changed:
            outdoor_has_changed = False
            output_values = [["indoor_temperature", indoor_temperature]]
        else:
            if dT < 0:
                indoor_temperature = lower_transition_temperature
            else:
                indoor_temperature = upper_transition_temperature
            lower_transition_temperature = indoor_temperature - 1.0
            upper_transition_temperature = indoor_temperature + 1.0
            dT = target_temperature - indoor_temperature

            if dT < 0:
                transition_dT = lower_transition_temperature - indoor_temperature
            else:
                transition_dT = upper_transition_temperature - indoor_temperature
            if abs(dT) <= abs(transition_dT):
                indoor_transition_remaining_time = infty
            else:
                indoor_transition_remaining_time = (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

            output_values = [["indoor_temperature_transition", indoor_temperature]]

        state = [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
                 outdoor_temperature, envelope_rate, rate, target_temperature, dT,
                 indoor_transition_remaining_time, outdoor_has_changed]
        return [state, output_values]

    def time_advance(state):
        [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
         outdoor_temperature, envelope_rate, rate, target_temperature, dT,
         indoor_transition_remaining_time, outdoor_has_changed] = state
        if outdoor_has_changed:
            remaining_time = 0
        else:
            remaining_time = indoor_transition_remaining_time
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

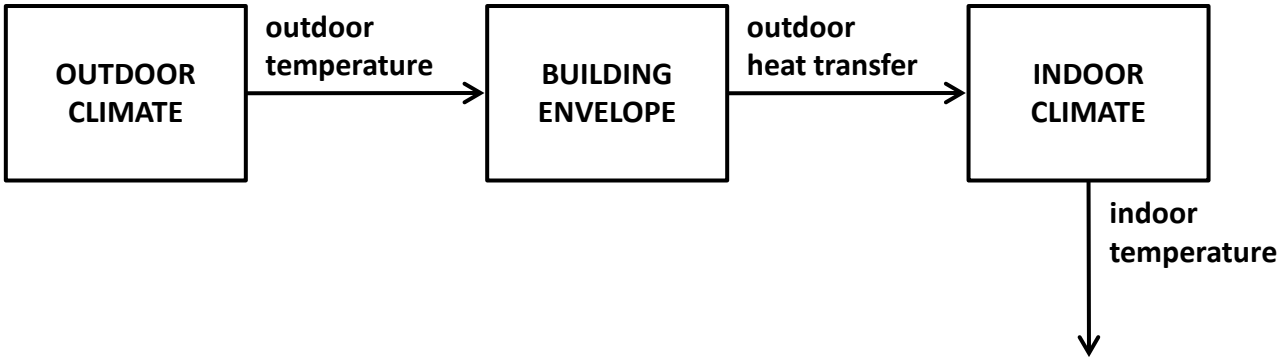
DEVS Simulation Output



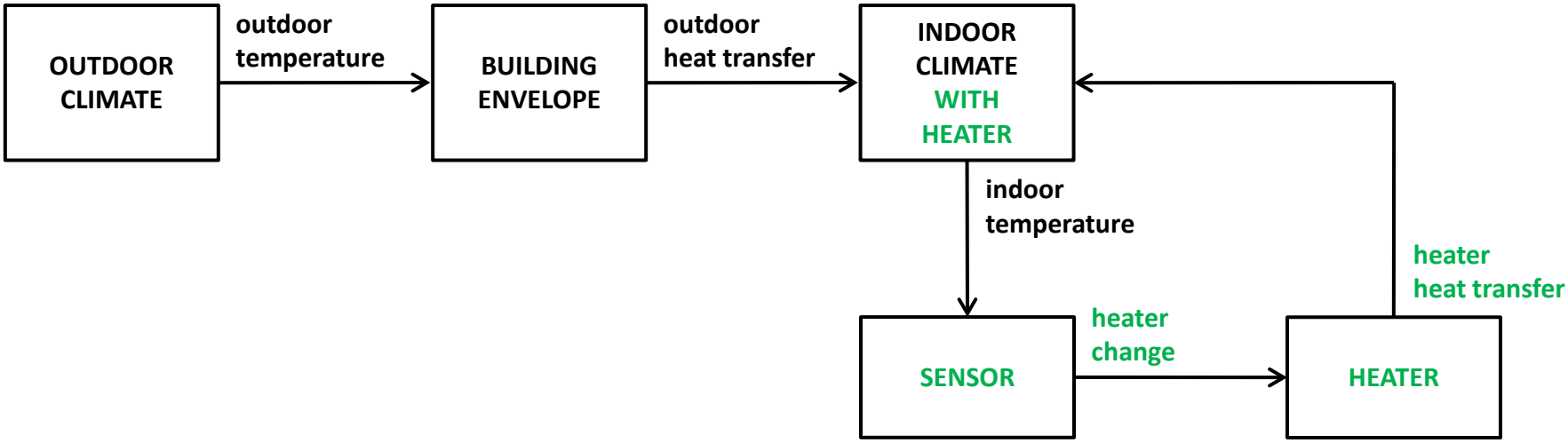
DEVS Simulation Output



Indoor Climate Model → Heating System Model



Indoor Climate Model → Heating System Model



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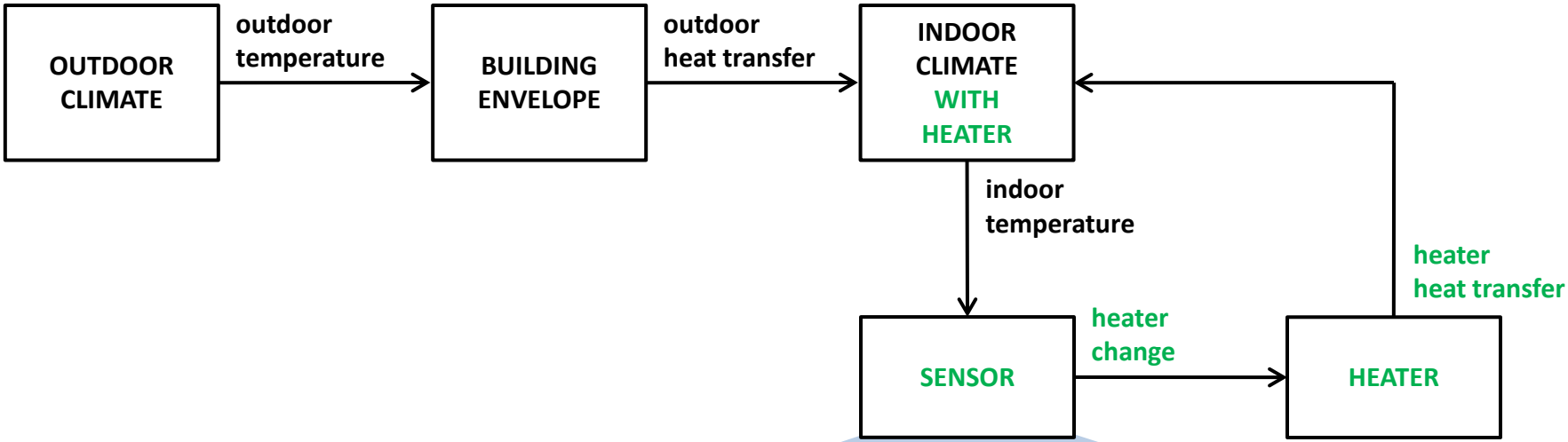
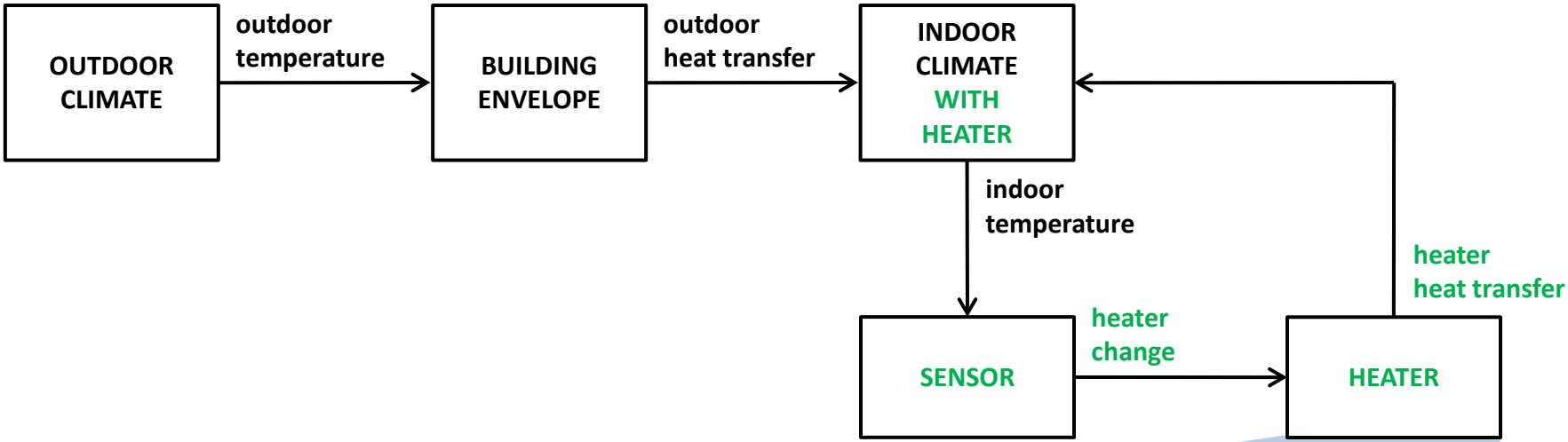


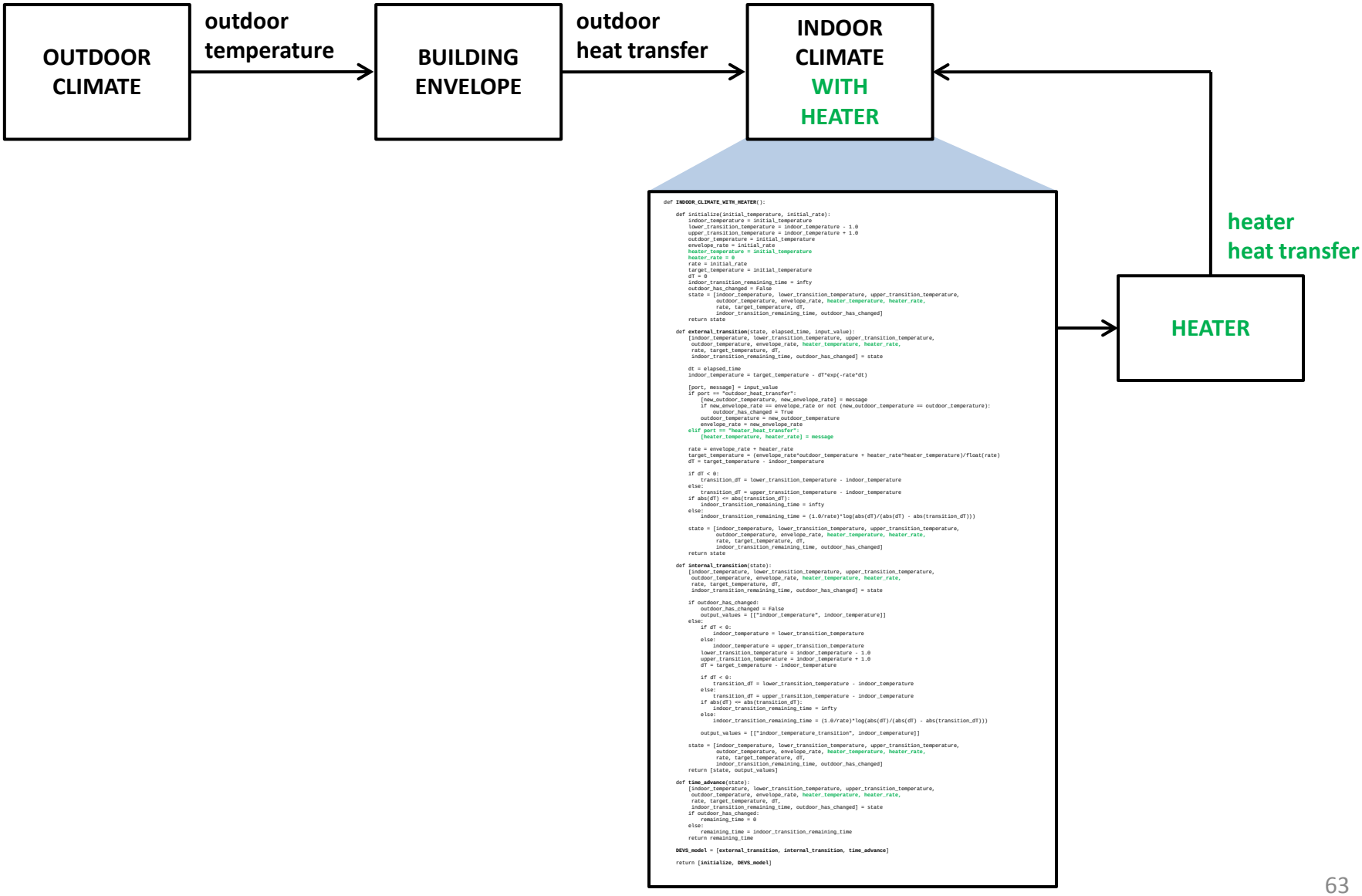

```
def SENSOR(lower_sensor_threshold, upper_sensor_threshold):

    def initialize():
        heater_should_change = False
        heater_should_be_on = False
        state = [heater_should_change, heater_should_be_on]
        return state

    def external_transition(state, elapsed_time, input_value):
        [heater_should_change, heater_should_be_on] = state
        [port, indoor_temperature] = input_value
        if (not heater_should_be_on) and indoor_temperature <= lower_sensor_threshold:
            heater_should_change = True
            heater_should_be_on = True
        elif heater_should_be_on and indoor_temperature >= upper_sensor_threshold:
            heater_should_change = True
            heater_should_be_on = False
        state = [heater_should_change, heater_should_be_on]
        return state

    def internal_transition(state):
        [heater_should_change, heater_should_be_on] = state
        heater_should_change = False
        state = [heater_should_change, heater_should_be_on]
        output_values = [["heater_change", heater_should_be_on]]
        return [state, output_values]

    def time_advance(state):
        [heater_should_change, heater_should_be_on] = state
        if heater_should_change:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

Indoor Climate Model → Heating System Model



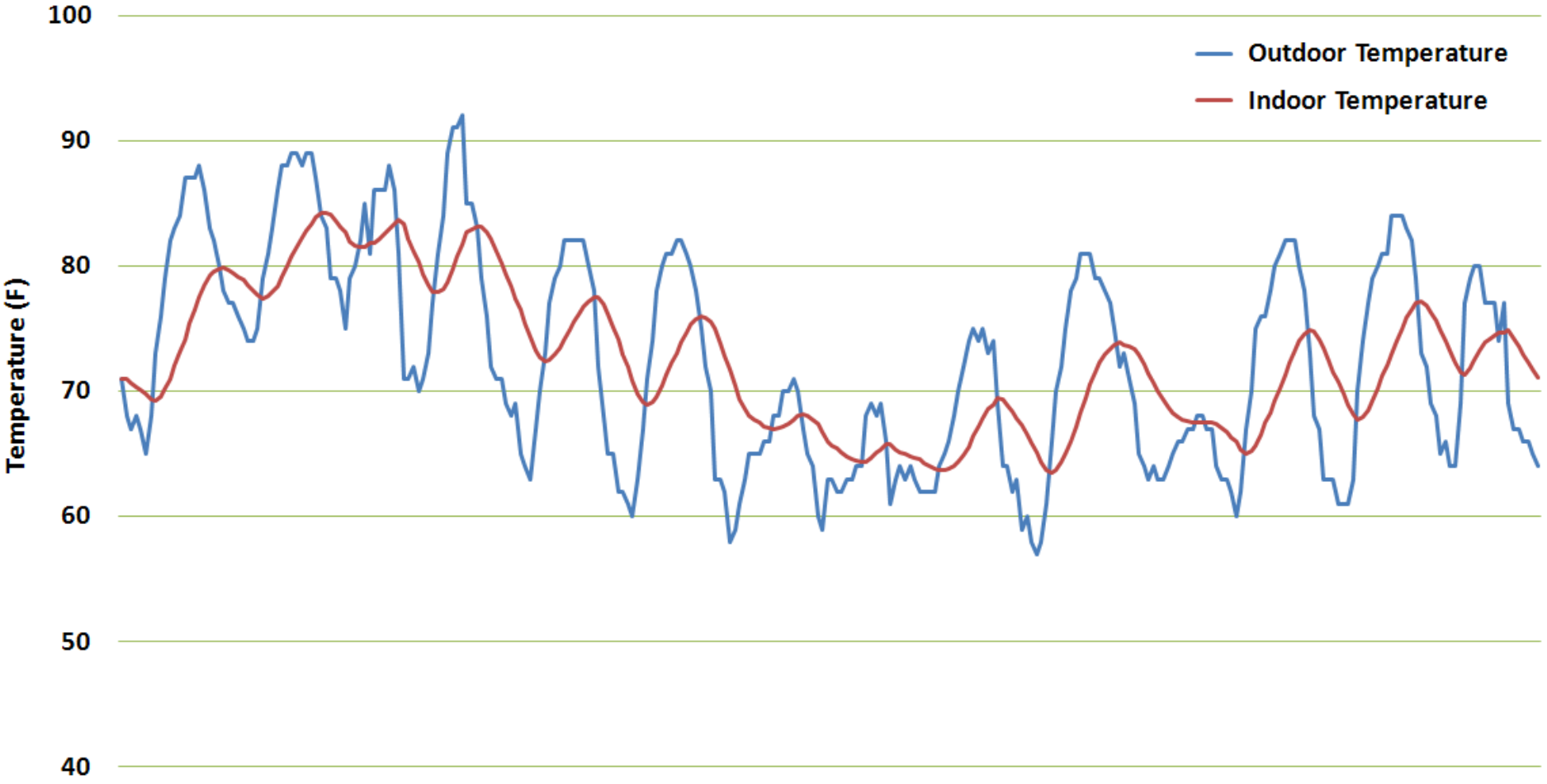

```
def HEATER(heater_temperature, heater_rate):

    def initialize():
        heater_has_changed = False
        heater_is_on = False
        state = [heater_has_changed, heater_is_on]
        return state

    def external_transition(state, elapsed_time, input_value):
        [heater_has_changed, heater_is_on] = state
        heater_has_changed = True
        [port, heater_is_on] = input_value
        state = [heater_has_changed, heater_is_on]
        return state

    def internal_transition(state):
        [heater_has_changed, heater_is_on] = state
        heater_has_changed = False
        state = [heater_has_changed, heater_is_on]
        if heater_is_on:
            rate = heater_rate
        else:
            rate = 0
        output_values = [["heater_heat_transfer", [heater_temperature, rate]]]
        return [state, output_values]

    def time_advance(state):
        [heater_has_changed, heater_is_on] = state
        if heater_has_changed:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

Indoor Climate Model → Heating System Model

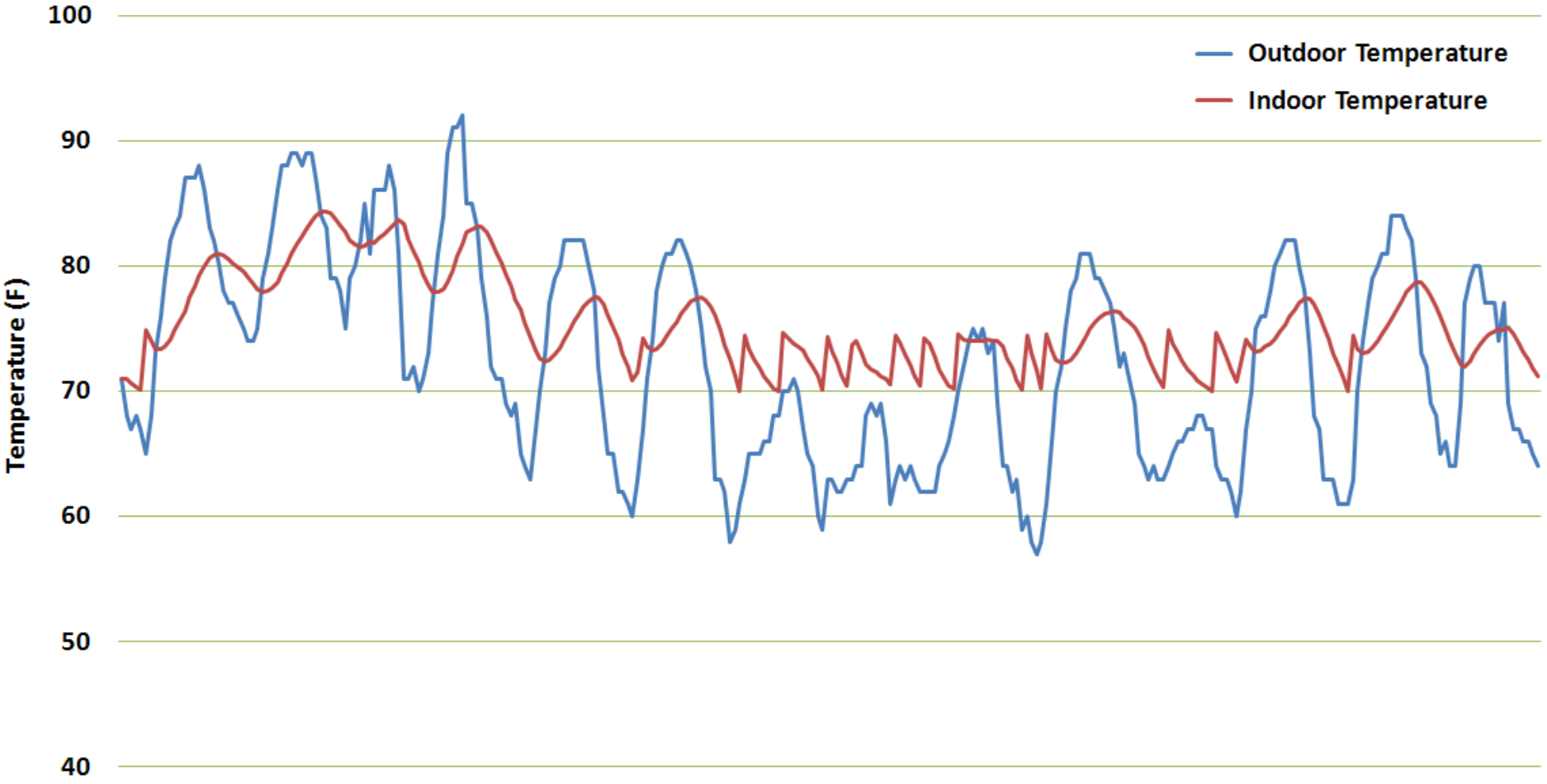



```
def INDOOR_CLIMATE_WITH_HEATER():

    def initialize(initial_temperature, initial_rate):
        indoor_temperature = initial_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        outdoor_temperature = initial_temperature
        envelope_rate = initial_rate
        heater_temperature = initial_temperature
        heater_rate = 0
        rate = initial_rate
        target_temperature = initial_temperature
        dT = 0
        indoor_transition_remaining_time = infty
        outdoor_has_changed = False
        state = [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
                 outdoor_temperature, envelope_rate, heater_temperature, heater_rate,
                 rate, target_temperature, dT,
                 indoor_transition_remaining_time, outdoor_has_changed]
        return state

    def external_transition(state, elapsed_time, input_value):
        [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
         outdoor_temperature, envelope_rate, heater_temperature, heater_rate,
         rate, target_temperature, dT,
         indoor_transition_remaining_time, outdoor_has_changed] = state

        dt = elapsed_time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)

        [port, message] = input_value
        if port == "outdoor_heat_transfer":
            [new_outdoor_temperature, new_envelope_rate] = message
            if new_envelope_rate == envelope_rate or not (new_outdoor_temperature == outdoor_temperature):
                outdoor_has_changed = True
            outdoor_temperature = new_outdoor_temperature
            envelope_rate = new_envelope_rate
        elif port == "heater_heat_transfer":
            [heater_temperature, heater_rate] = message

        rate = envelope_rate + heater_rate
        target_temperature = (envelope_rate*outdoor_temperature + heater_rate*heater_temperature)/float(rate)
        dT = target_temperature - indoor_temperature

        if dT < 0:
            transition_dT = lower_transition_temperature - indoor_temperature
        else:
            transition_dT = upper_transition_temperature - indoor_temperature
        if abs(dT) <= abs(transition_dT):
            indoor_transition_remaining_time = infty
        else:
            indoor_transition_remaining_time = (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

        state = [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
                 outdoor_temperature, envelope_rate, heater_temperature, heater_rate,
                 rate, target_temperature, dT,
                 indoor_transition_remaining_time, outdoor_has_changed]
        return state

    def internal_transition(state):
        [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
         outdoor_temperature, envelope_rate, heater_temperature, heater_rate,
         rate, target_temperature, dT,
         indoor_transition_remaining_time, outdoor_has_changed] = state

        if outdoor_has_changed:
            outdoor_has_changed = False
            output_values = [["indoor_temperature", indoor_temperature]]
        else:
            if dT < 0:
                indoor_temperature = lower_transition_temperature
            else:
                indoor_temperature = upper_transition_temperature
            lower_transition_temperature = indoor_temperature - 1.0
            upper_transition_temperature = indoor_temperature + 1.0
            dT = target_temperature - indoor_temperature

            if dT < 0:
                transition_dT = lower_transition_temperature - indoor_temperature
            else:
                transition_dT = upper_transition_temperature - indoor_temperature
            if abs(dT) <= abs(transition_dT):
                indoor_transition_remaining_time = infty
            else:
                indoor_transition_remaining_time = (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

            output_values = [["indoor_temperature_transition", indoor_temperature]]

        state = [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
                 outdoor_temperature, envelope_rate, heater_temperature, heater_rate,
                 rate, target_temperature, dT,
                 indoor_transition_remaining_time, outdoor_has_changed]
        return [state, output_values]

    def time_advance(state):
        [indoor_temperature, lower_transition_temperature, upper_transition_temperature,
         outdoor_temperature, envelope_rate, heater_temperature, heater_rate,
         rate, target_temperature, dT,
         indoor_transition_remaining_time, outdoor_has_changed] = state
        if outdoor_has_changed:
            remaining_time = 0
        else:
            remaining_time = indoor_transition_remaining_time
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

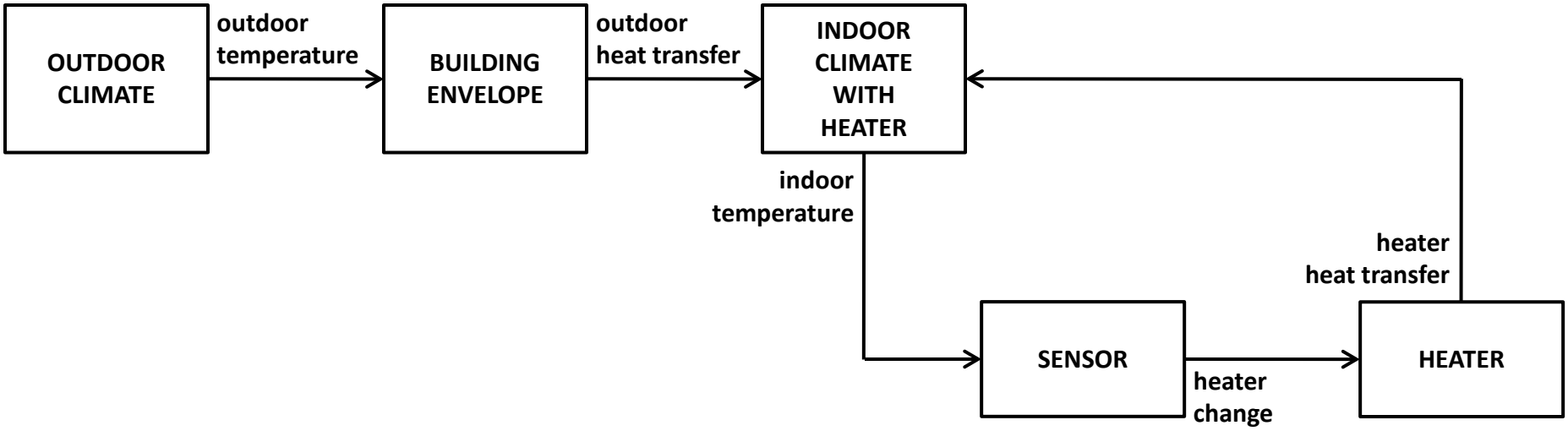
DEVS Simulation Output



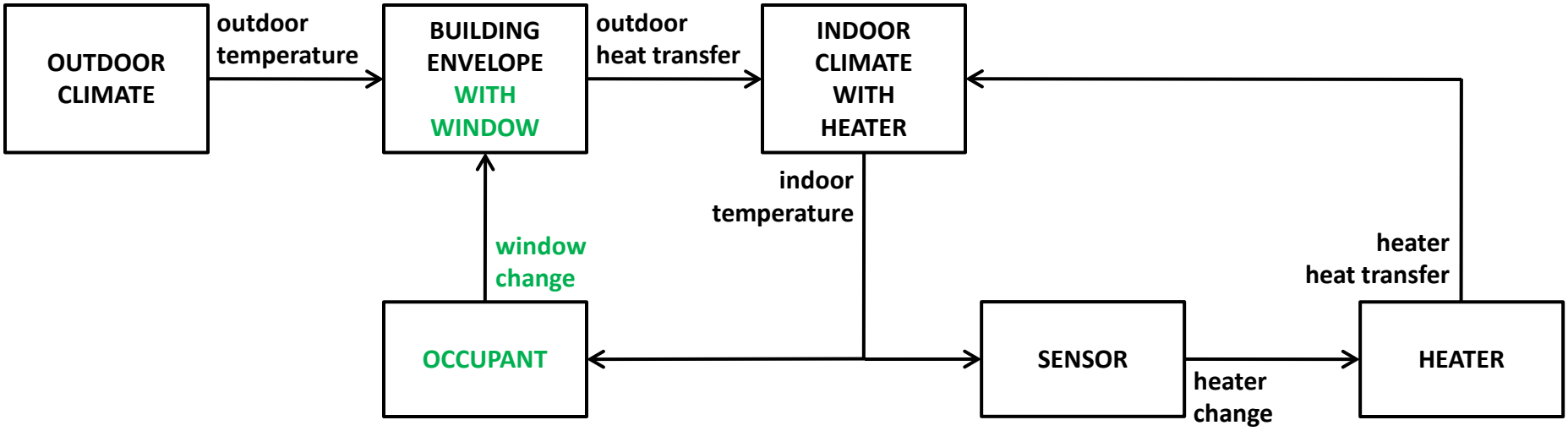
DEVS Simulation Output



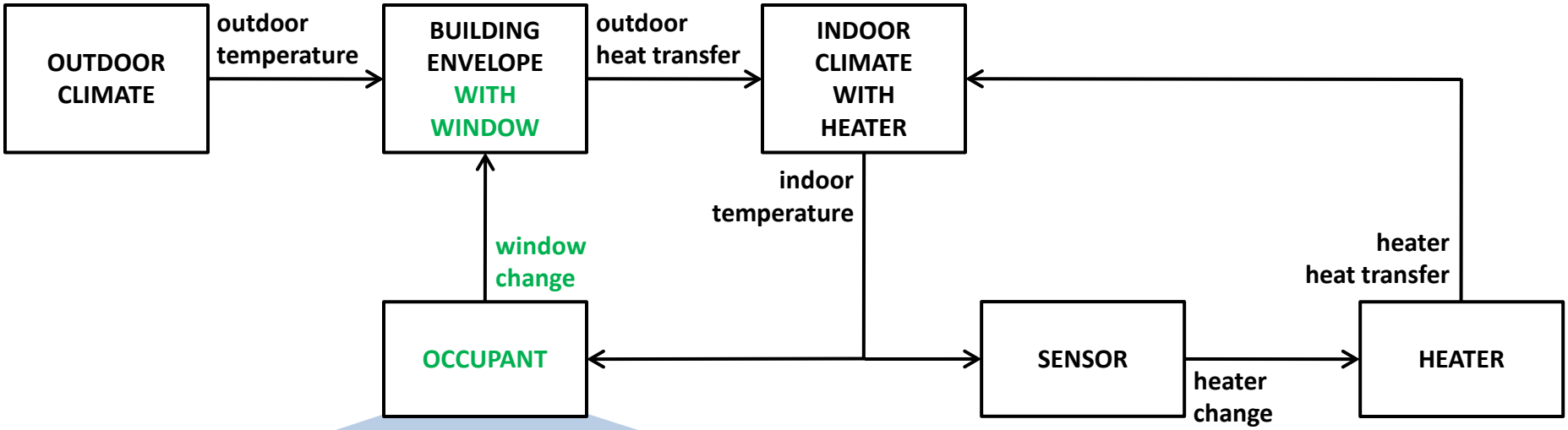
Heating System Model → Window Opening Model



Heating System Model → Window Opening Model

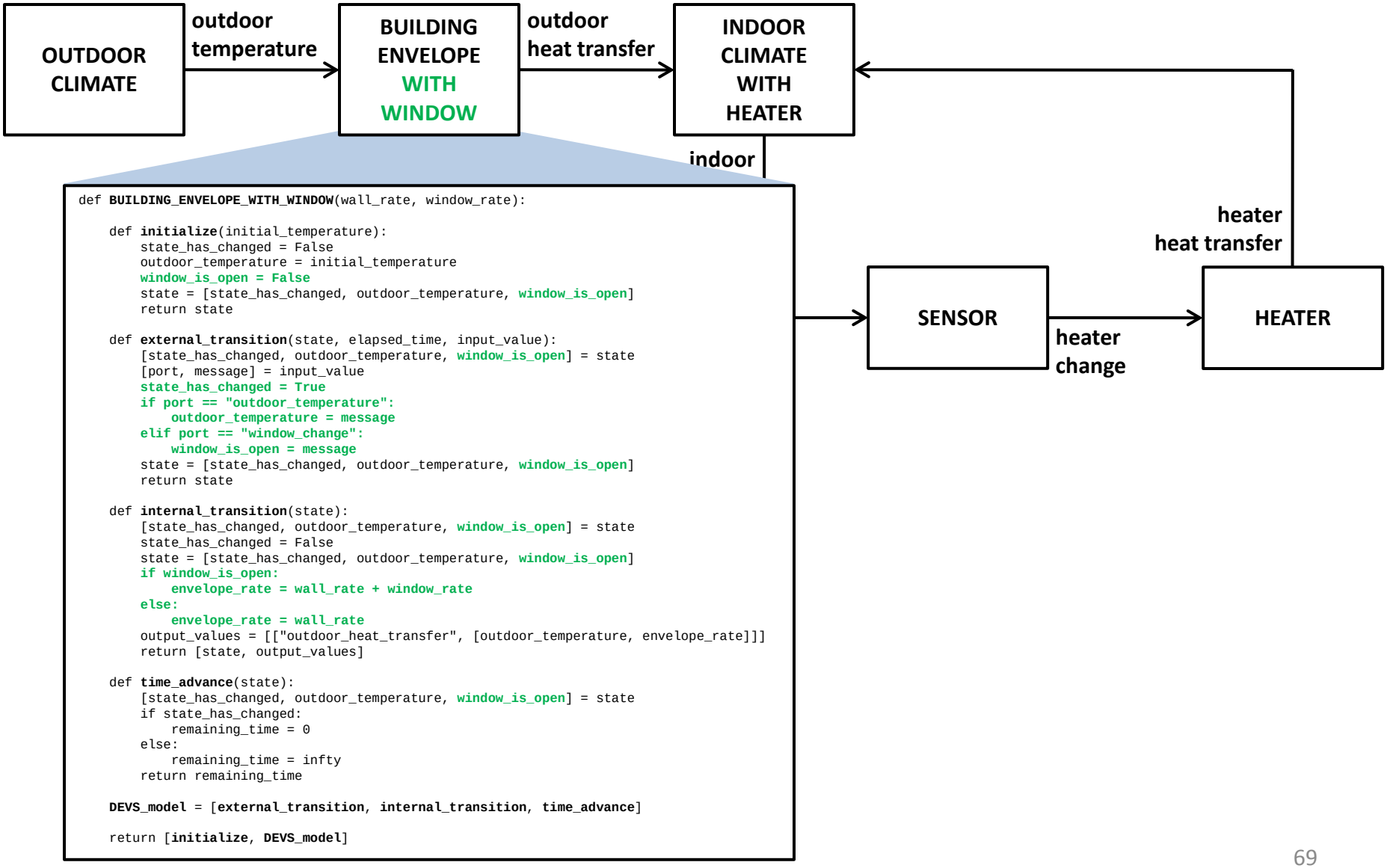


Heating System Model → Window Opening Model



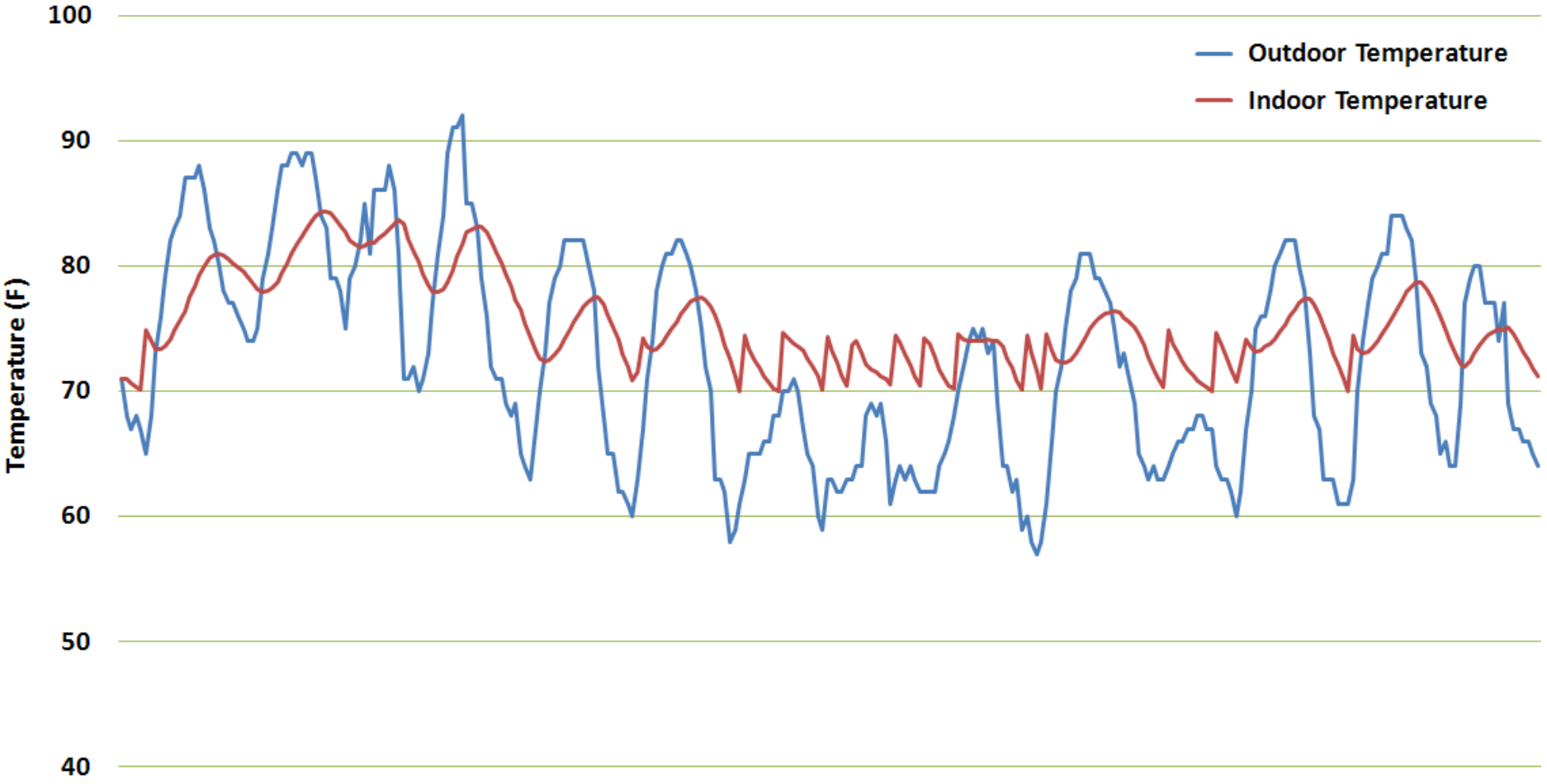

```
def OCCUPANT(lower_sensor_threshold, upper_sensor_threshold):

    def initialize(initial_temperature):
        window_should_change = False
        window_should_be_open = False
        outdoor_temperature = initial_temperature
        indoor_temperature = initial_temperature
        state = [window_should_change, window_should_be_open,
                 outdoor_temperature, indoor_temperature]
        return state

    def external_transition(state, elapsed_time, input_value):
        [window_should_change, window_should_be_open,
         outdoor_temperature, indoor_temperature] = state
        [port, input_temperature] = input_value
        if port == "outdoor_temperature":
            outdoor_temperature = input_temperature
        elif port == "indoor_temperature_transition":
            indoor_temperature = input_temperature
        if (not window_should_be_open) and indoor_temperature >= max([outdoor_temperature, upper_sensor_threshold]):
            window_should_change = True
            window_should_be_open = True
        elif window_should_be_open and indoor_temperature <= max([outdoor_temperature, lower_sensor_threshold]):
            window_should_change = True
            window_should_be_open = False
        state = [window_should_change, window_should_be_open,
                 outdoor_temperature, indoor_temperature]
        return state

    def internal_transition(state):
        [window_should_change, window_should_be_open,
         outdoor_temperature, indoor_temperature] = state
        window_should_change = False
        state = [window_should_change, window_should_be_open,
                 outdoor_temperature, indoor_temperature]
        output_values = [["window_change", window_should_be_open]]
        return [state, output_values]

    def time_advance(state):
        [window_should_change, window_should_be_open,
         outdoor_temperature, indoor_temperature] = state
        if window_should_change:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

Heating System Model → Window Opening Model

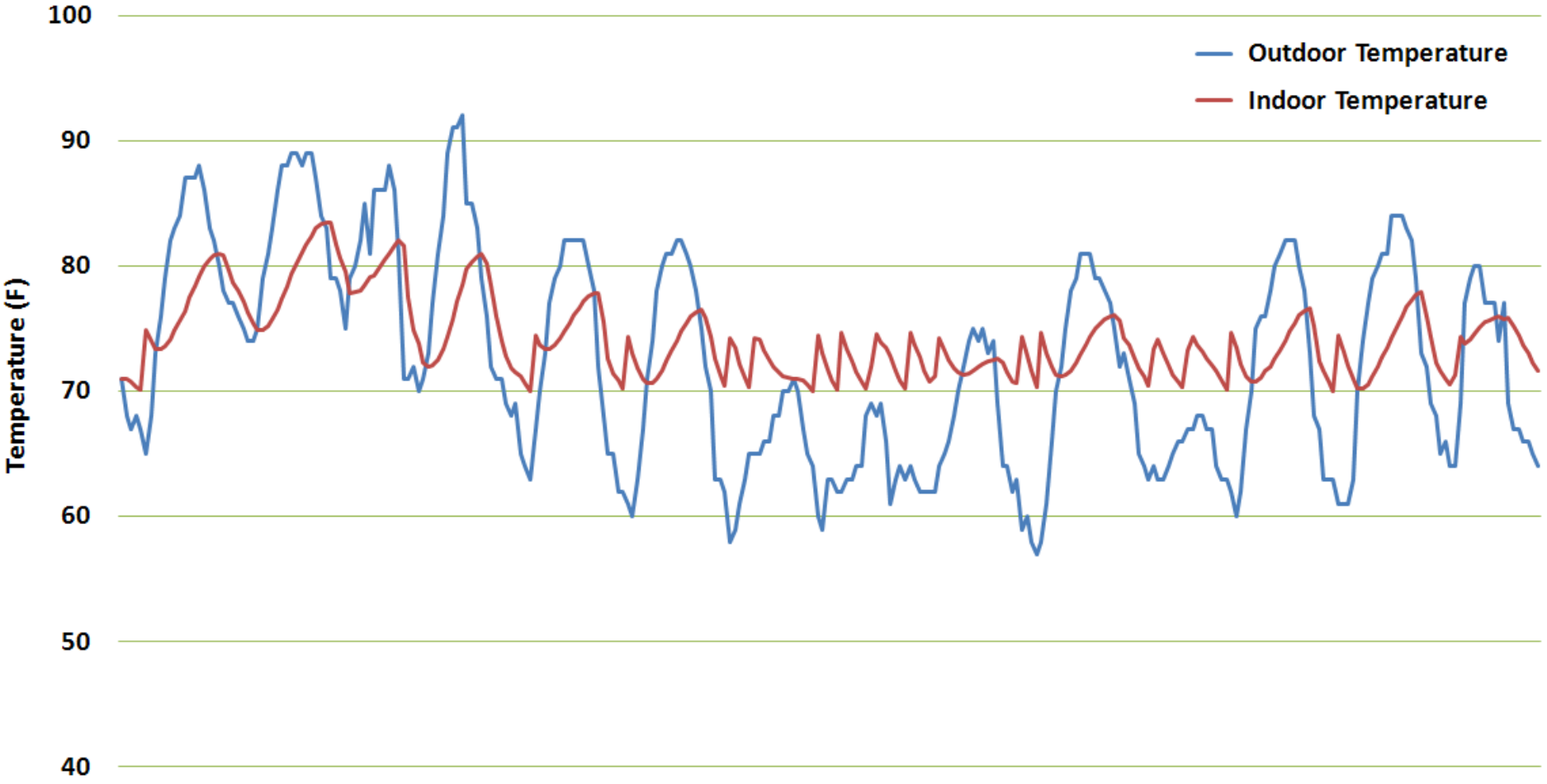



```
def BUILDING_ENVELOPE_WITH_WINDOW(wall_rate, window_rate):

    def initialize(initial_temperature):
        state_has_changed = False
        outdoor_temperature = initial_temperature
        window_is_open = False
        state = [state_has_changed, outdoor_temperature, window_is_open]
        return state

    def external_transition(state, elapsed_time, input_value):
        [state_has_changed, outdoor_temperature, window_is_open] = state
        [port, message] = input_value
        state_has_changed = True
        if port == "outdoor_temperature":
            outdoor_temperature = message
        elif port == "window_change":
            window_is_open = message
        state = [state_has_changed, outdoor_temperature, window_is_open]
        return state

    def internal_transition(state):
        [state_has_changed, outdoor_temperature, window_is_open] = state
        state_has_changed = False
        state = [state_has_changed, outdoor_temperature, window_is_open]
        if window_is_open:
            envelope_rate = wall_rate + window_rate
        else:
            envelope_rate = wall_rate
        output_values = [["outdoor_heat_transfer", [outdoor_temperature, envelope_rate]]]
        return [state, output_values]

    def time_advance(state):
        [state_has_changed, outdoor_temperature, window_is_open] = state
        if state_has_changed:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

DEVS Simulation Output



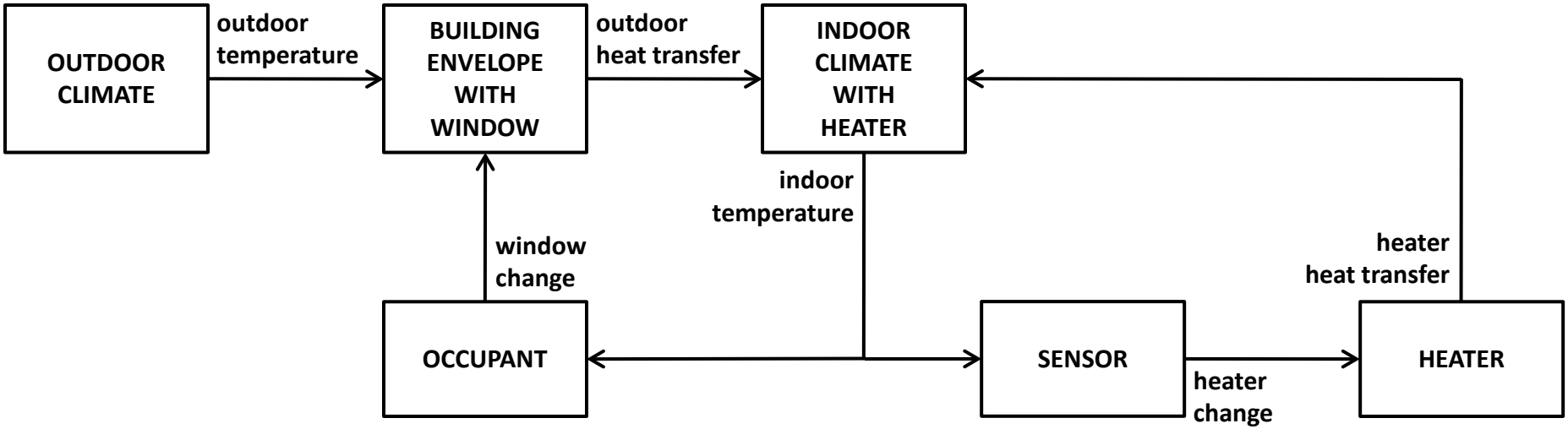
DEVS Simulation Output



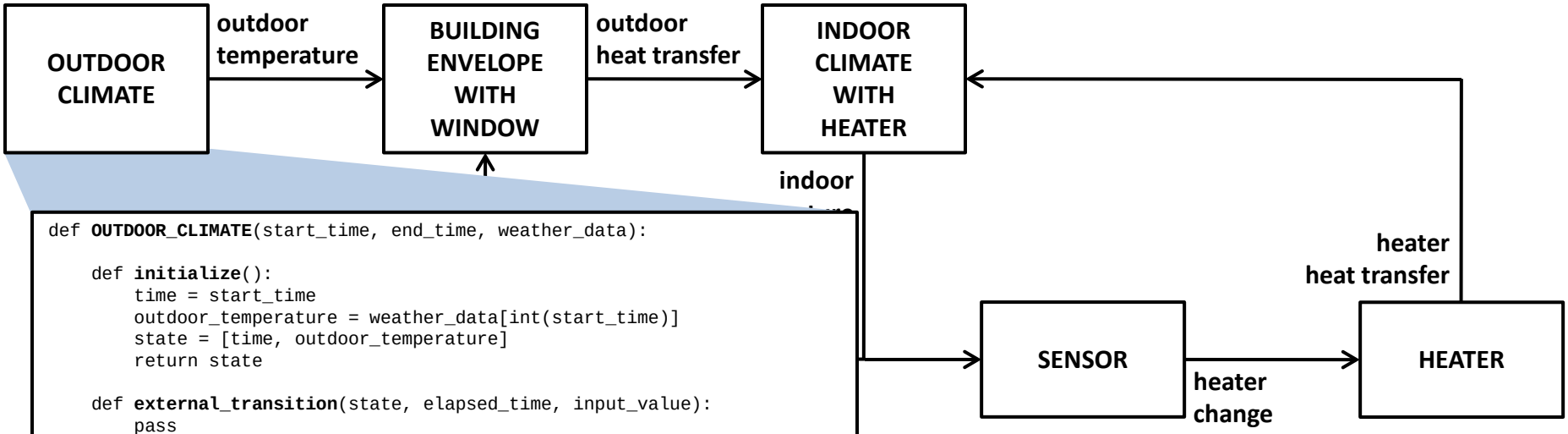
Traditional Simulation Code

```
start_time = 4014
end_time = 4306
weather_data = read_weather_from_file()
wall_rate = 0.1
heater_rate = 0.4
heater_temperature = 100
lower_sensor_threshold = 70
upper_sensor_threshold = 75
lower_occupant_threshold = 72
upper_occupant_threshold = 76
window_rate = 0.4

time = start_time
outdoor_temperature = weather_data[int(start_time)]
indoor_temperature = weather_data[int(start_time)]
lower_transition_temperature = indoor_temperature - 1.0
upper_transition_temperature = indoor_temperature + 1.0
heater_is_on = False
window_is_open = False
observed_temperature = weather_data[int(start_time)]

while time < end_time:

    outdoor_transition_time = int(time) + 1

    if window_is_open:
        envelope_rate = wall_rate + window_rate
    else:
        envelope_rate = wall_rate
    if heater_is_on:
        rate = envelope_rate + heater_rate
        target_temperature = (envelope_rate*outdoor_temperature + heater_rate*heater_temperature)/float(rate)
    else:
        rate = envelope_rate
        target_temperature = outdoor_temperature
    dT = target_temperature - indoor_temperature

    if dT < 0:
        transition_dT = lower_transition_temperature - indoor_temperature
    else:
        transition_dT = upper_transition_temperature - indoor_temperature
    if abs(dT) <= abs(transition_dT):
        indoor_transition_time = infty
    else:
        indoor_transition_time = time + (1.0/rate)*log(abs(dT)/(abs(dT) - abs(transition_dT)))

    if indoor_transition_time < outdoor_transition_time:
        if dT < 0:
            indoor_temperature = lower_transition_temperature
        else:
            indoor_temperature = upper_transition_temperature
        observed_temperature = indoor_temperature
        lower_transition_temperature = indoor_temperature - 1.0
        upper_transition_temperature = indoor_temperature + 1.0
        if indoor_temperature <= lower_sensor_threshold:
            heater_is_on = True
        elif indoor_temperature >= upper_sensor_threshold:
            heater_is_on = False
        time = indoor_transition_time
    else:
        dt = outdoor_transition_time - time
        indoor_temperature = target_temperature - dT*exp(-rate*dt)
        time = outdoor_transition_time
        outdoor_temperature = weather_data[int(time)]
        output(time, ["outdoor_temperature", outdoor_temperature])
        output(time, ["indoor_temperature", indoor_temperature])

    if observed_temperature >= max([outdoor_temperature, upper_occupant_threshold]):
        window_is_open = True
    if observed_temperature <= max([outdoor_temperature, lower_occupant_threshold]):
        window_is_open = False
```

DEVS Model Code

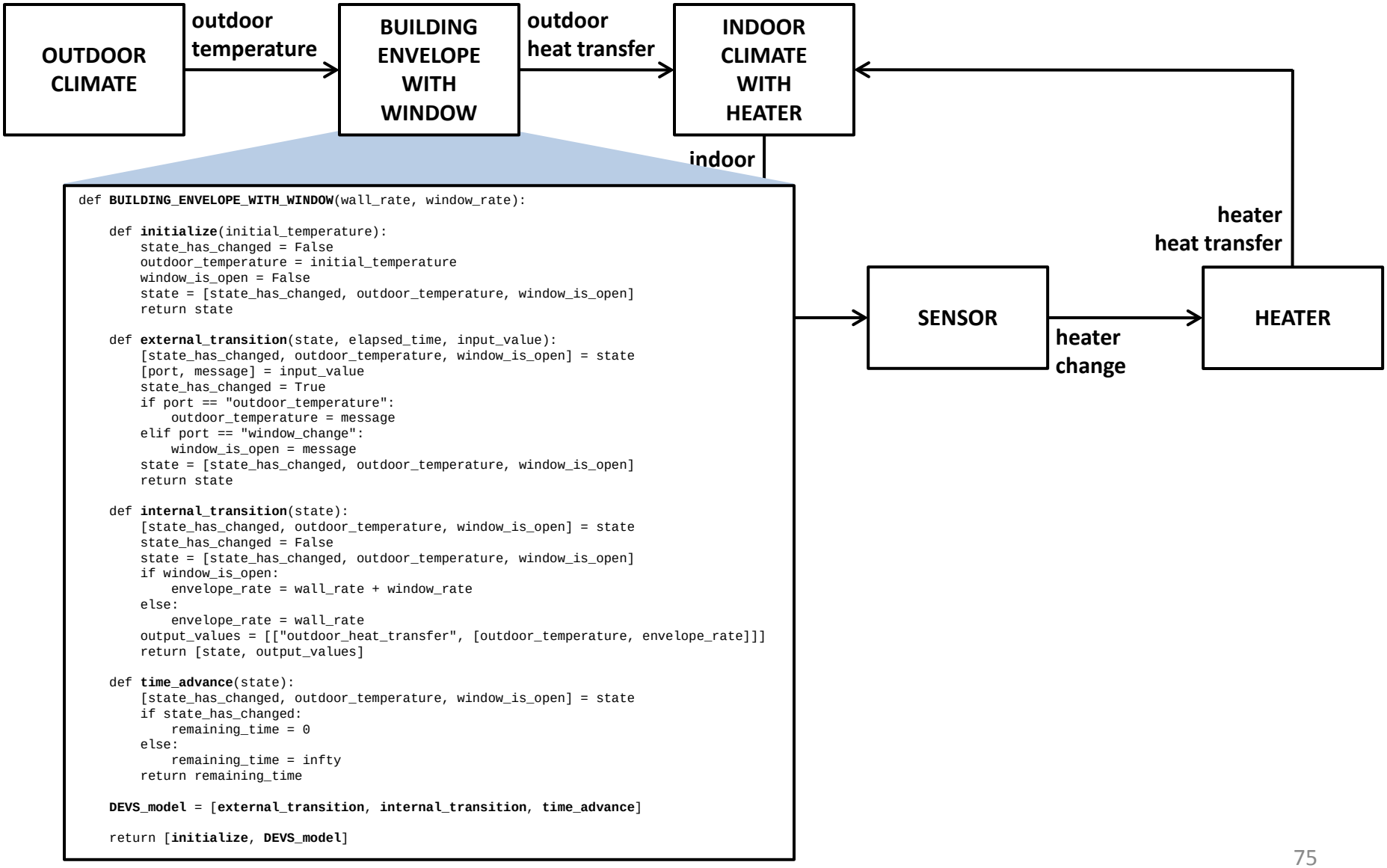


DEVS Model Code



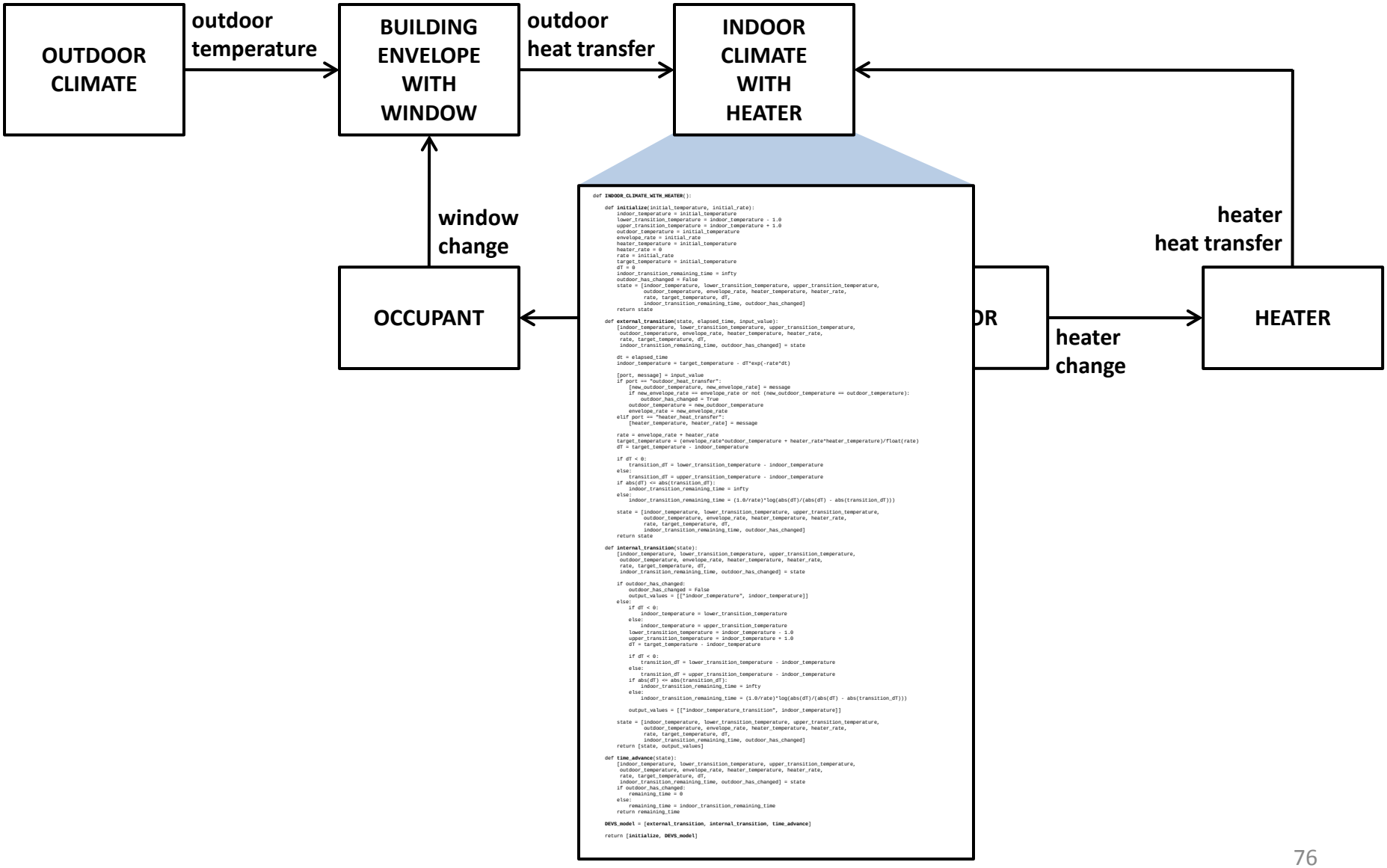

```
def OUTDOOR_CLIMATE(start_time, end_time, weather_data):

    def initialize():
        time = start_time
        outdoor_temperature = weather_data[int(start_time)]
        state = [time, outdoor_temperature]
        return state

    def external_transition(state, elapsed_time, input_value):
        pass

    def internal_transition(state):
        [time, outdoor_temperature] = state
        time = time + 1
        outdoor_temperature = weather_data[int(time)]
        state = [time, outdoor_temperature]
        output_values = [["outdoor_temperature", outdoor_temperature]]
        return [state, output_values]

    def time_advance(state):
        [time, outdoor_temperature] = state
        if time < end_time:
            remaining_time = 1
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

DEVS Model Code

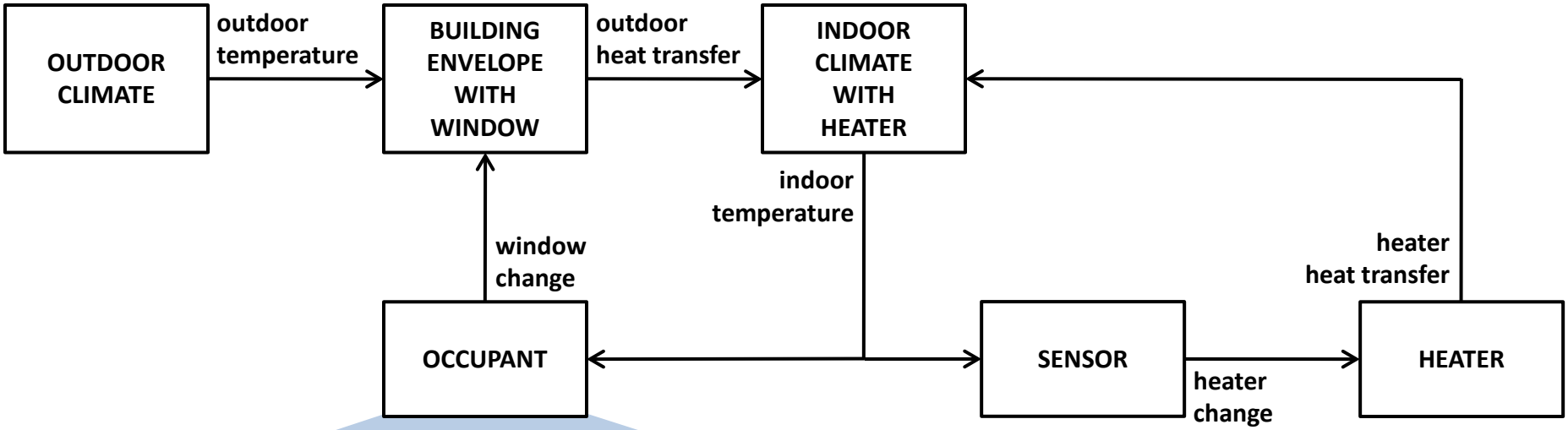



```
def BUILDING_ENVELOPE_WITH_WINDOW(wall_rate, window_rate):

    def initialize(initial_temperature):
        state_has_changed = False
        outdoor_temperature = initial_temperature
        window_is_open = False
        state = [state_has_changed, outdoor_temperature, window_is_open]
        return state

    def external_transition(state, elapsed_time, input_value):
        [state_has_changed, outdoor_temperature, window_is_open] = state
        [port, message] = input_value
        state_has_changed = True
        if port == "outdoor_temperature":
            outdoor_temperature = message
        elif port == "window_change":
            window_is_open = message
        state = [state_has_changed, outdoor_temperature, window_is_open]
        return state

    def internal_transition(state):
        [state_has_changed, outdoor_temperature, window_is_open] = state
        state_has_changed = False
        state = [state_has_changed, outdoor_temperature, window_is_open]
        if window_is_open:
            envelope_rate = wall_rate + window_rate
        else:
            envelope_rate = wall_rate
        output_values = [["outdoor_heat_transfer", [outdoor_temperature, envelope_rate]]]
        return [state, output_values]

    def time_advance(state):
        [state_has_changed, outdoor_temperature, window_is_open] = state
        if state_has_changed:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

DEVS Model Code

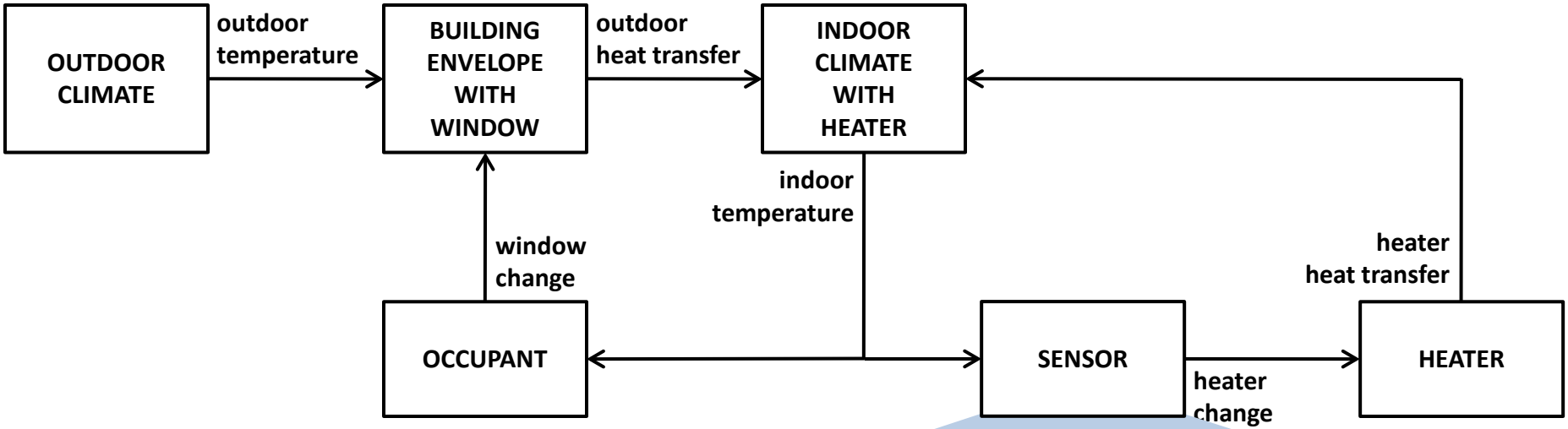


DEVS Model Code



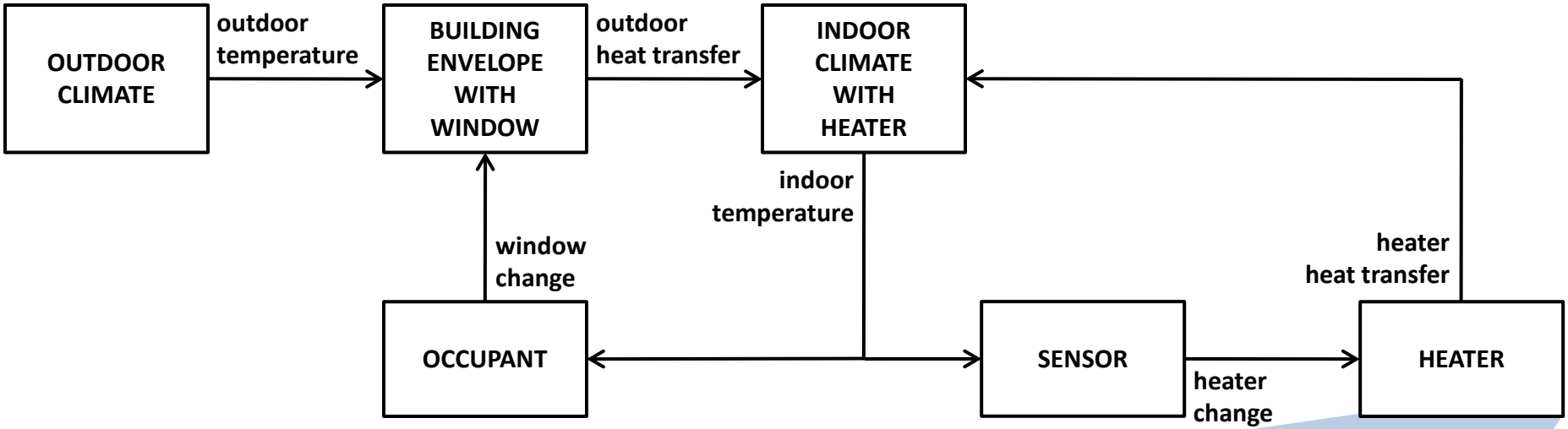

```
def OCCUPANT(lower_sensor_threshold, upper_sensor_threshold):

    def initialize(initial_temperature):
        window_should_change = False
        window_should_be_open = False
        outdoor_temperature = initial_temperature
        indoor_temperature = initial_temperature
        state = [window_should_change, window_should_be_open,
                 outdoor_temperature, indoor_temperature]
        return state

    def external_transition(state, elapsed_time, input_value):
        [window_should_change, window_should_be_open,
         outdoor_temperature, indoor_temperature] = state
        [port, input_temperature] = input_value
        if port == "outdoor_temperature":
            outdoor_temperature = input_temperature
        elif port == "indoor_temperature_transition":
            indoor_temperature = input_temperature
        if (not window_should_be_open) and indoor_temperature >= max([outdoor_temperature, upper_sensor_threshold]):
            window_should_change = True
            window_should_be_open = True
        elif window_should_be_open and indoor_temperature <= max([outdoor_temperature, lower_sensor_threshold]):
            window_should_change = True
            window_should_be_open = False
        state = [window_should_change, window_should_be_open,
                 outdoor_temperature, indoor_temperature]
        return state

    def internal_transition(state):
        [window_should_change, window_should_be_open,
         outdoor_temperature, indoor_temperature] = state
        window_should_change = False
        state = [window_should_change, window_should_be_open,
                 outdoor_temperature, indoor_temperature]
        output_values = [["window_change", window_should_be_open]]
        return [state, output_values]

    def time_advance(state):
        [window_should_change, window_should_be_open,
         outdoor_temperature, indoor_temperature] = state
        if window_should_change:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

DEVS Model Code




```
def SENSOR(lower_sensor_threshold, upper_sensor_threshold):

    def initialize():
        heater_should_change = False
        heater_should_be_on = False
        state = [heater_should_change, heater_should_be_on]
        return state

    def external_transition(state, elapsed_time, input_value):
        [heater_should_change, heater_should_be_on] = state
        [port, indoor_temperature] = input_value
        if (not heater_should_be_on) and indoor_temperature <= lower_sensor_threshold:
            heater_should_change = True
            heater_should_be_on = True
        elif heater_should_be_on and indoor_temperature >= upper_sensor_threshold:
            heater_should_change = True
            heater_should_be_on = False
        state = [heater_should_change, heater_should_be_on]
        return state

    def internal_transition(state):
        [heater_should_change, heater_should_be_on] = state
        heater_should_change = False
        state = [heater_should_change, heater_should_be_on]
        output_values = [["heater_change", heater_should_be_on]]
        return [state, output_values]

    def time_advance(state):
        [heater_should_change, heater_should_be_on] = state
        if heater_should_change:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

DEVS Model Code




```
def HEATER(heater_temperature, heater_rate):

    def initialize():
        heater_has_changed = False
        heater_is_on = False
        state = [heater_has_changed, heater_is_on]
        return state

    def external_transition(state, elapsed_time, input_value):
        [heater_has_changed, heater_is_on] = state
        heater_has_changed = True
        [port, heater_is_on] = input_value
        state = [heater_has_changed, heater_is_on]
        return state

    def internal_transition(state):
        [heater_has_changed, heater_is_on] = state
        heater_has_changed = False
        state = [heater_has_changed, heater_is_on]
        if heater_is_on:
            rate = heater_rate
        else:
            rate = 0
        output_values = [["heater_heat_transfer", [heater_temperature, rate]]]
        return [state, output_values]

    def time_advance(state):
        [heater_has_changed, heater_is_on] = state
        if heater_has_changed:
            remaining_time = 0
        else:
            remaining_time = infty
        return remaining_time

    DEVS_model = [external_transition, internal_transition, time_advance]

    return [initialize, DEVS_model]
```

Introducing DEVS for Collaborative Building Simulation Development

Rhys Goldstein and Azam Khan

Autodesk Research