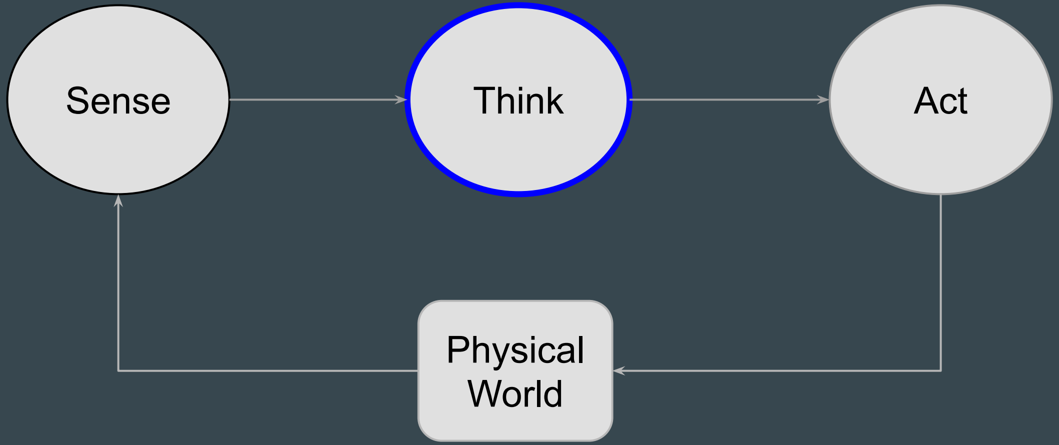
CS4501
Robotics for Soft Eng

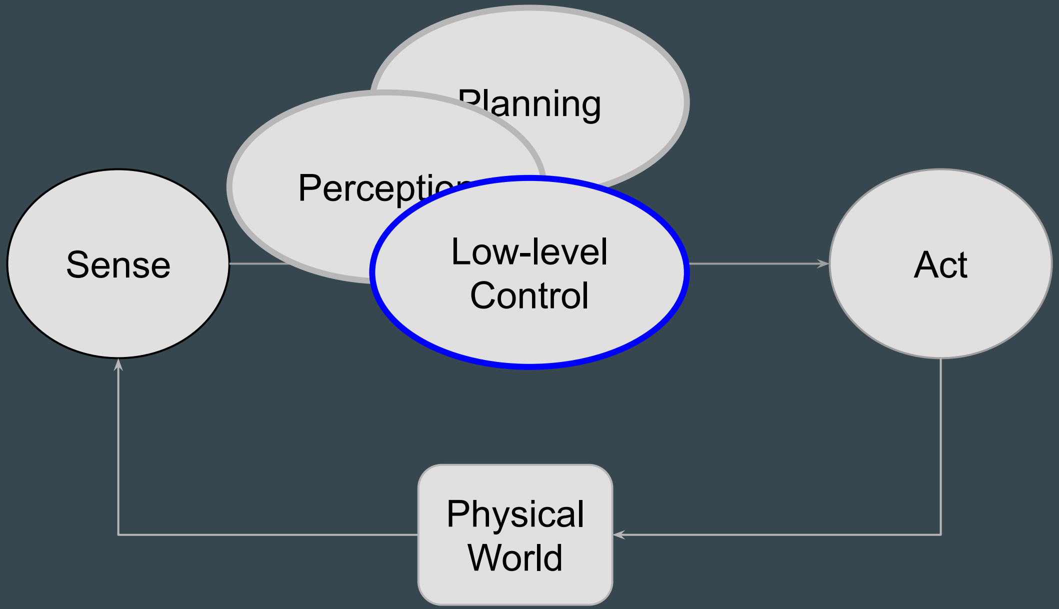
•••

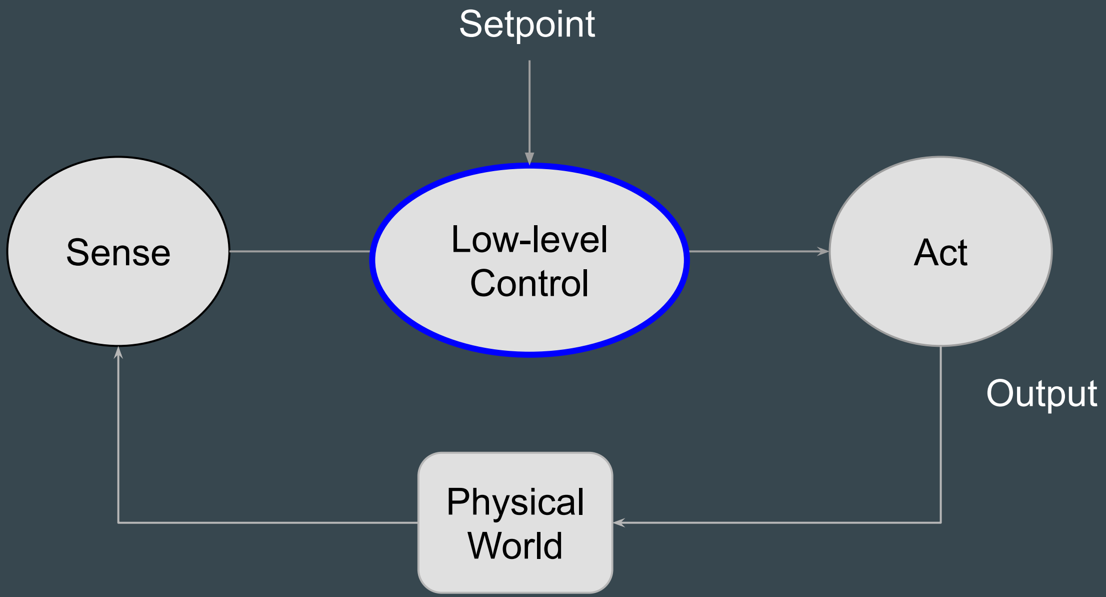
Control

Problem: Ride over straight line

- Sensors are noisy
  - Eyes, ears-balance, ...
- Actuators are noisy
  - Muscles, bike gears, breaks, ...
- Environment changes
  - Street, Grass, Rock, Mud, …


Sense
Think
Act
Physical World


Planning
Perception
Sense
Low-level Control
Act
Physical World

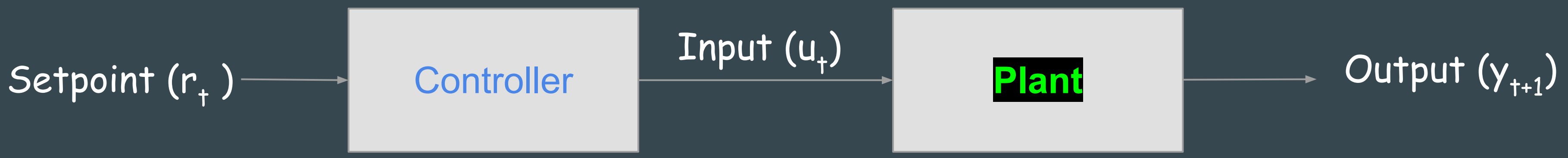


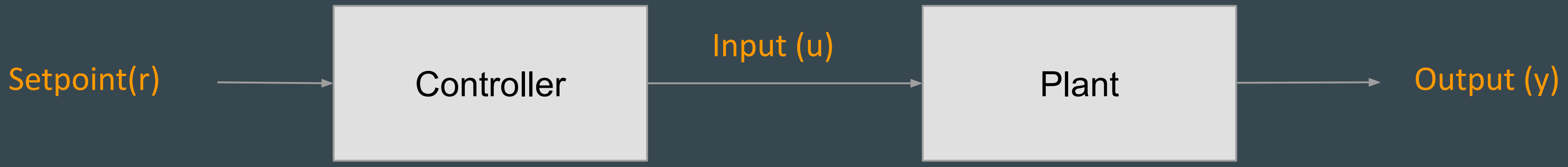
Goal of Controller

Sensed Output = Setpoint

- Controller aims to make *Sensed Output = Setpoint*

- Terms
  - Plant (system) with Inputs (u) and Outputs (y)
  - Setpoint (r)





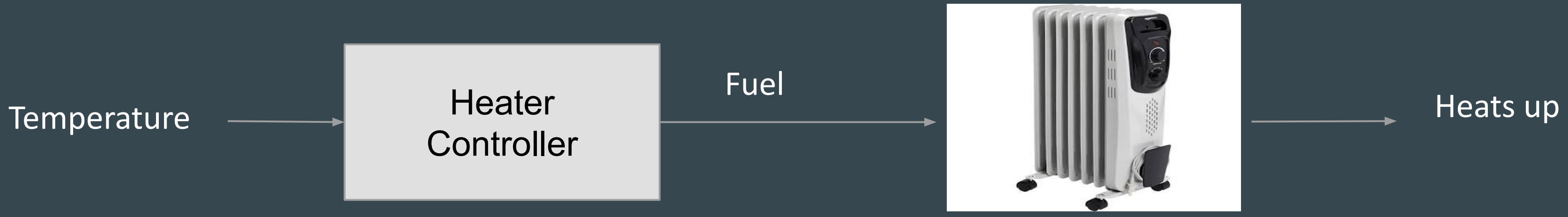
Setpoint(r)

Controller

Input (u)

Plant

Output (y)

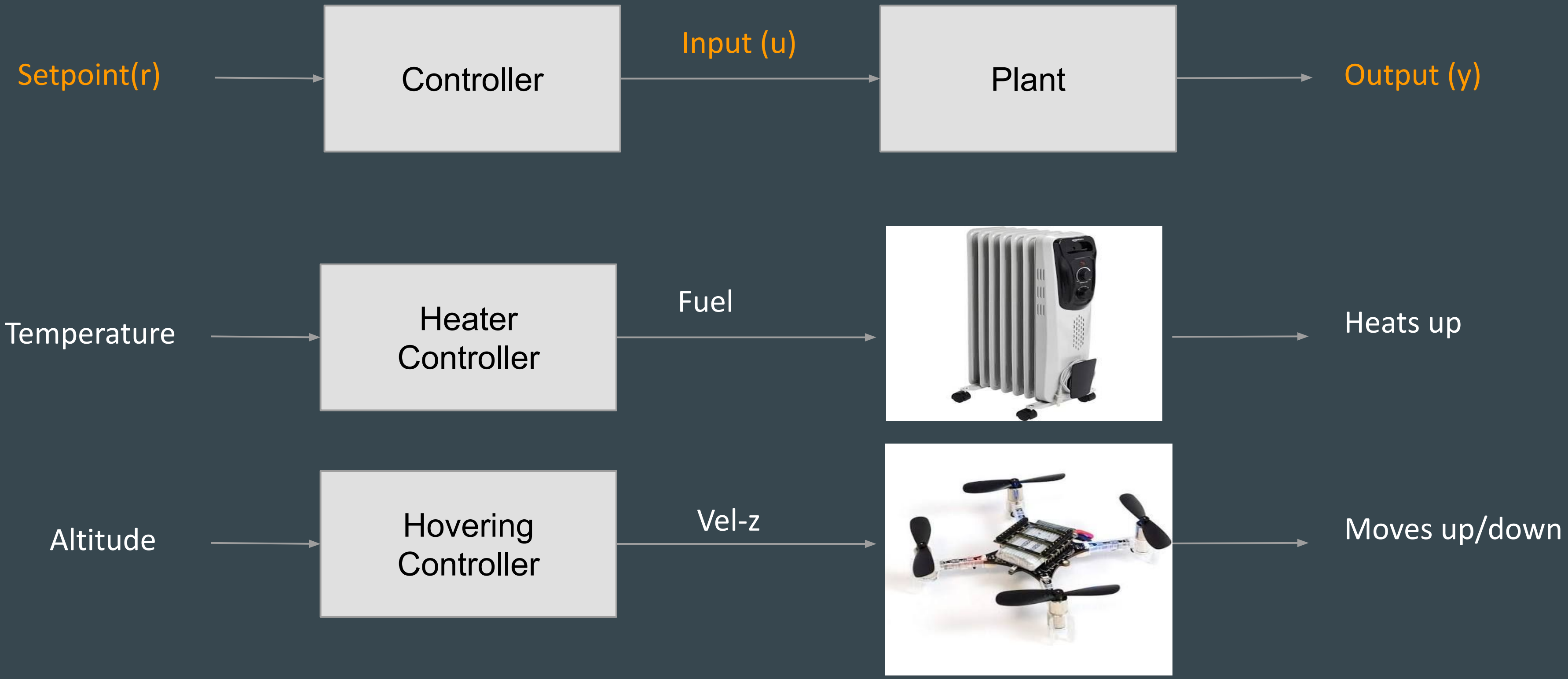


Temperature

Heater Controller

Fuel

Heats up



Setpoint(r)

Controller

Input (u)

Plant

Output (y)

Temperature

Heater Controller

Fuel

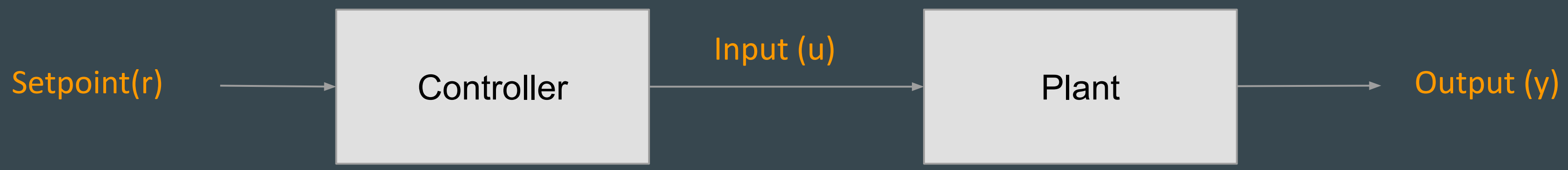
Heats up

Altitude

Hovering Controller

Vel-z

Moves up/down



Setpoint(r) → Controller → Input (u) → Plant → Output (y)

Temperature → Heater Controller → Fuel →

→ Heats up

Altitude → Hovering Controller → Vel-z →

→ Moves up/down

Steering Angle → Turning Controller → Torque →

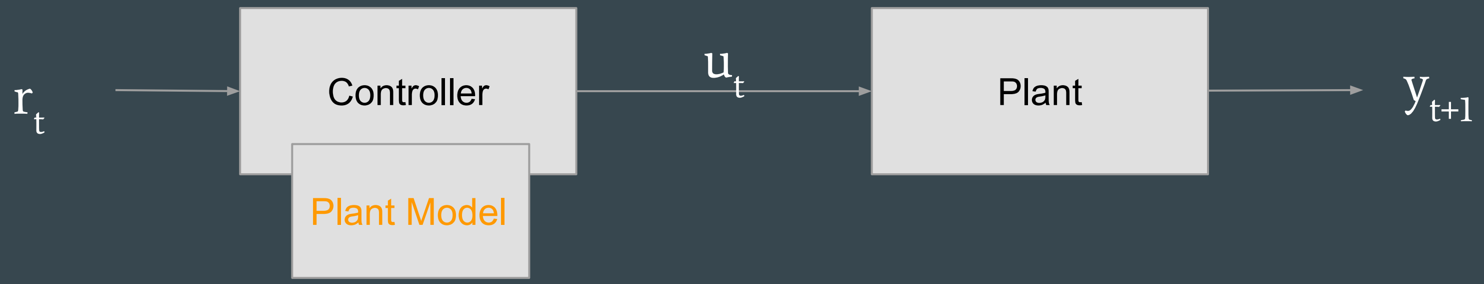
→ Turns

Setpoint(r)	Controller	Input (u)	Plant	Output (y)
Temperature	Heater Controller	Fuel		Heats up
Altitude	Hovering Controller	Vel-z		Moves up/down
Steering Angle	Turning Controller	Torque		Turns

r, u, y can all be in different units

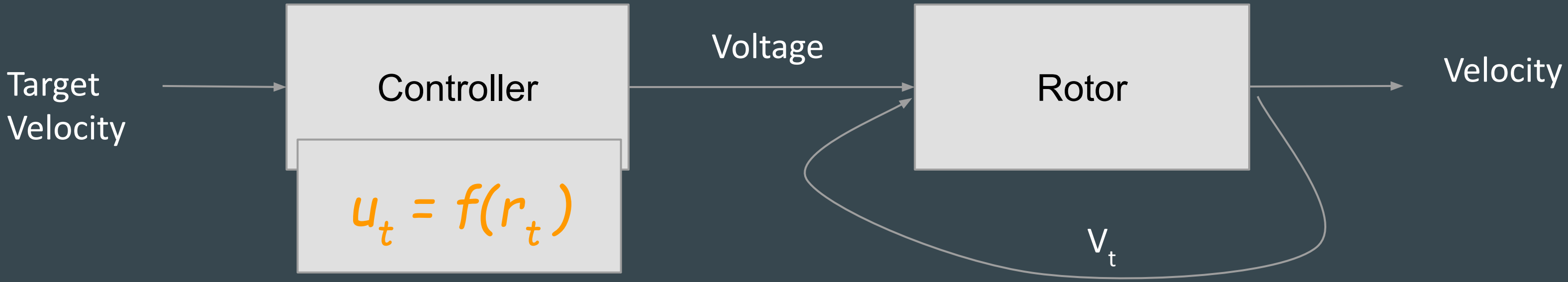
Families of controllers

Open-loop controller



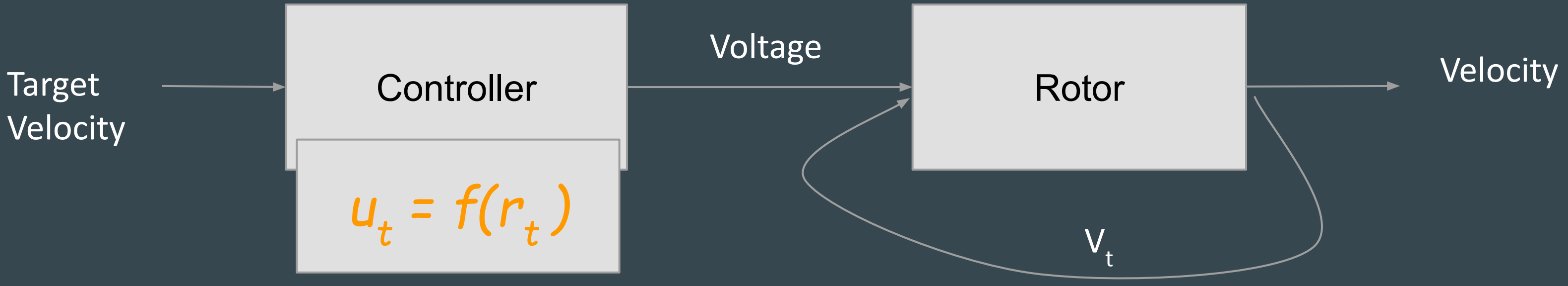
- Assumes we have a Good Model of the Plant
- Computes u_t input to plant given r_t: $u_t = F(r_t)$

Open-Loop Controller Example



- Computes input to plant based on model

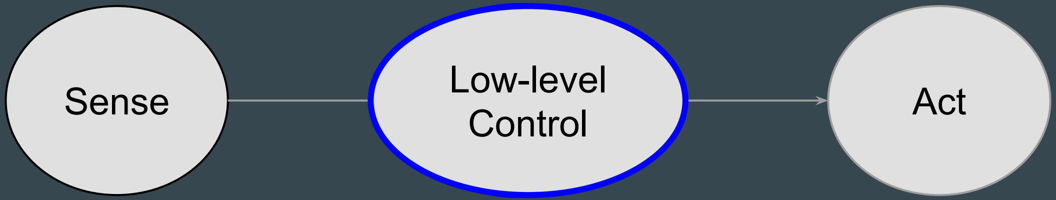
Open-Loop Controller Example



- Computes input to plant based on model
- Assumes we have a Good Model of Drone Rotor: $Voltage_t = f(TargetVel_t)$

Open-Loop Controller

- Good enough to keep temperature steady with expected air volume/flow
- Not as good if there is variation in air flow or air volume



Open-Loop Controller

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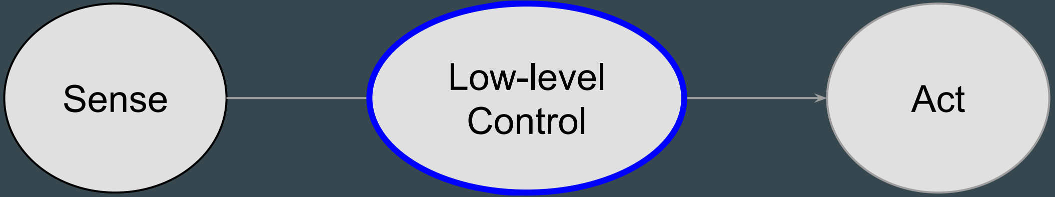


Sense

Low-level Control

Act

- Good enough for rpm on motors, drone on the ground, no propellers
- Not as good with propellers due to their differences
- Pretty bad when flying due to variations in angle, pressure, drafts, …

Open-Loop Controller - Self test

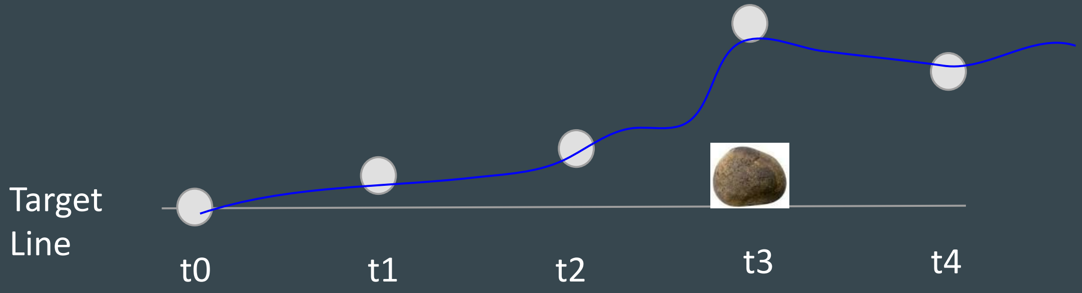
- Eyes closed
- Rotate 5 times in place
- Iterate
    - Walk 3 steps, rotate 90

Open-Loop Controller Example

- Drive over a straight line

Open-Loop Controller (less ideal) Example

- Drive over straight line
- Open-loop ≈ close your eyes (no feedback)
  - Small errors will accumulate over time
  - Wheel may be a bit crooked
  - Disturbances (hitting a rock) may cause drastic changes



Target Line

t0

t1

t2

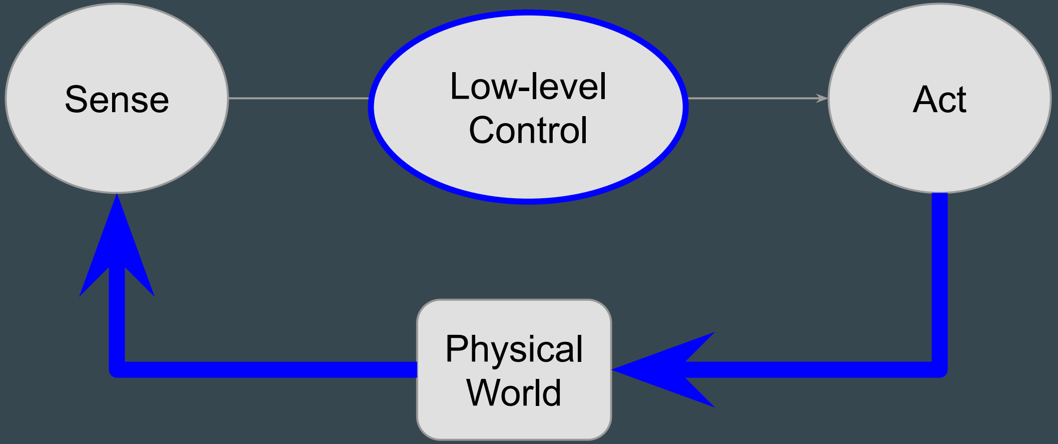
t3

t4

Limitations of Open-Loop Controller

- Performance depends on model/s
  - Fidelity in capturing relationships between input and output
  - Robustness to environment variations
  - Generalizability to other plants

- Good-enough Models may be difficult or impossible to derive


Sense
Low-level Control
Act
Physical World

Close-Loop Controller

- Incorporates feedback to the Controller
  - Knows impacts of actions
  - Diffs setpoint and sensed output
  - Aims to make that difference zero

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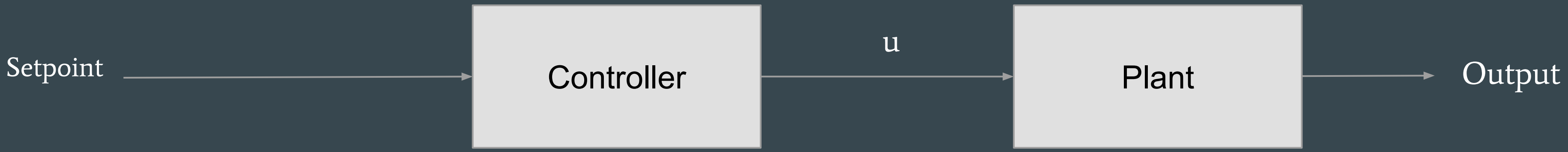

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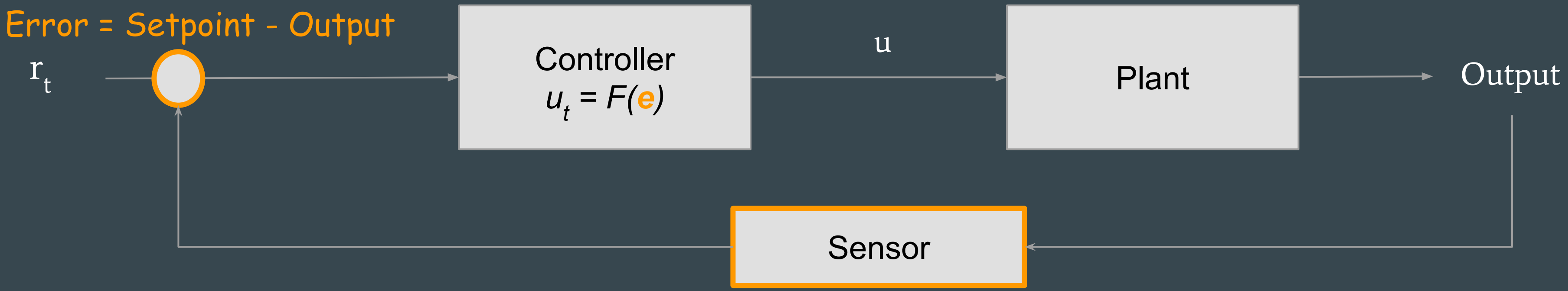

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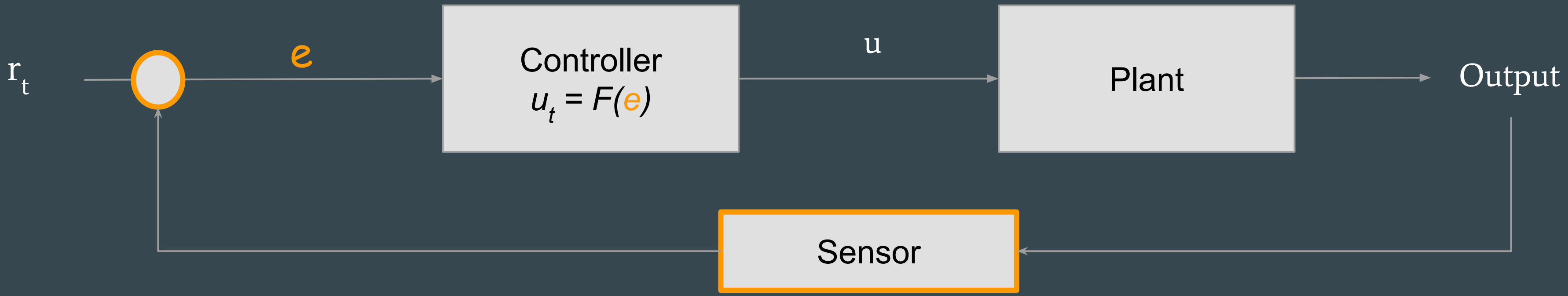

Close-Loop Controller: Bang-Bang

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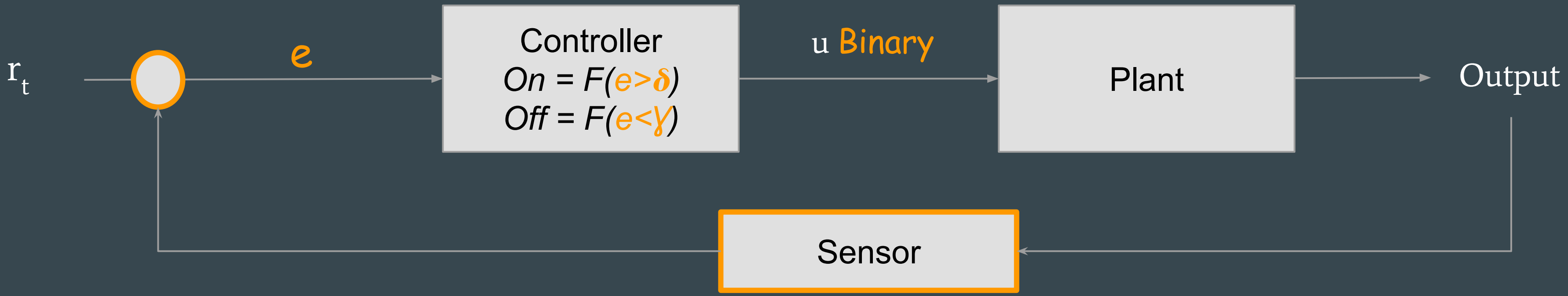

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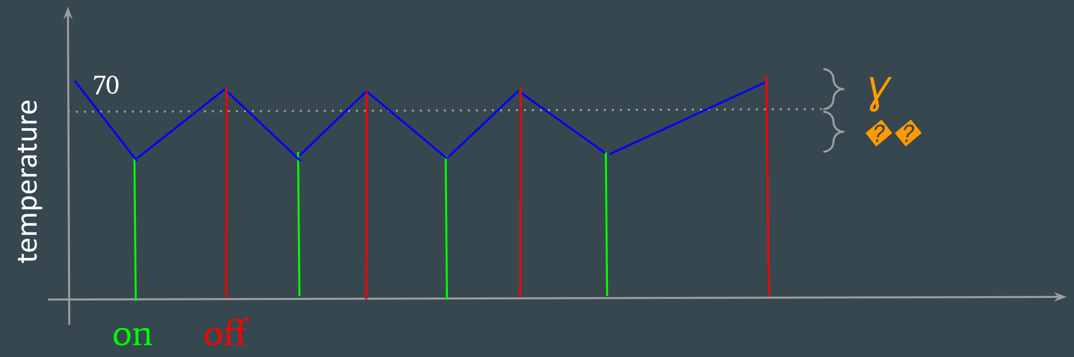
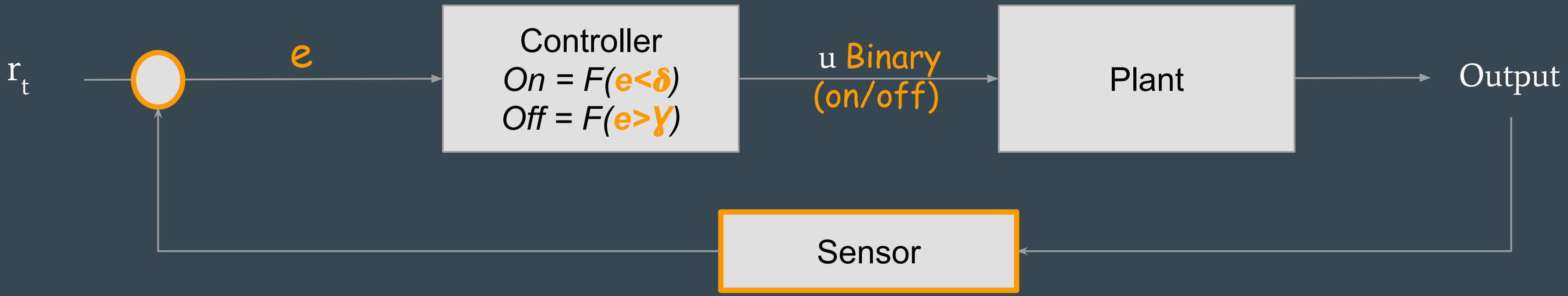
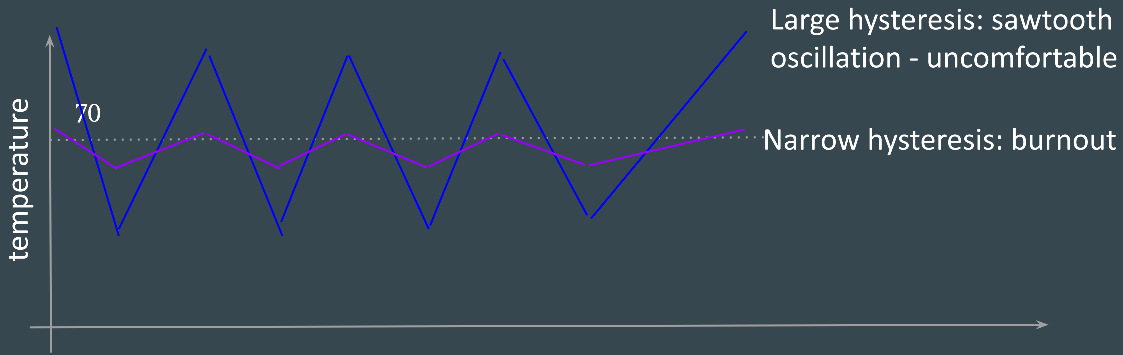


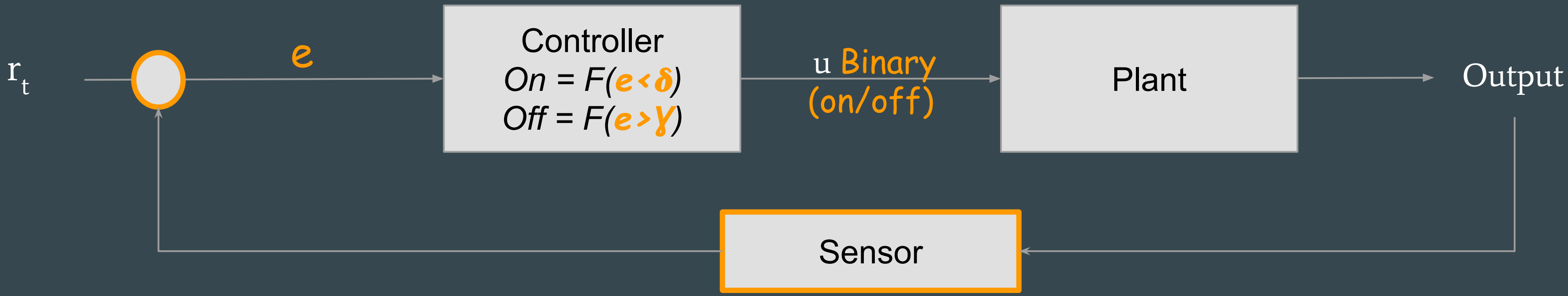


Close-Loop Controller: Bang-Bang



Large hysteresis: sawtooth oscillation - uncomfortable

Narrow hysteresis: burnout



r_t

e

Controller

On = $F(e<\delta)$

Off = $F(e>\gamma)$

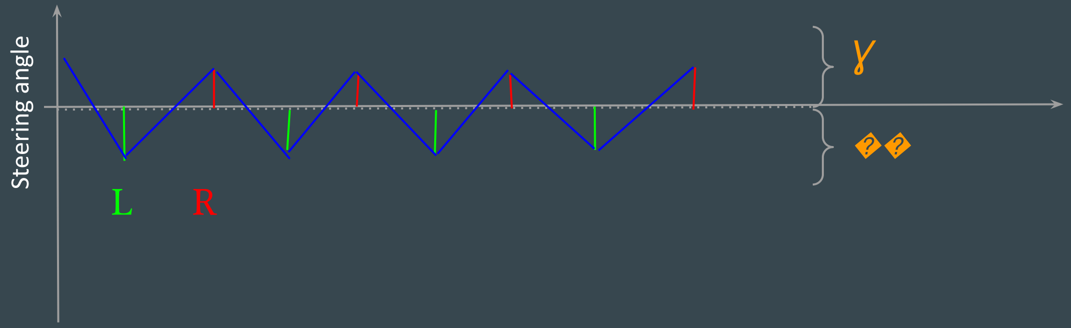
u Binary (on/off)

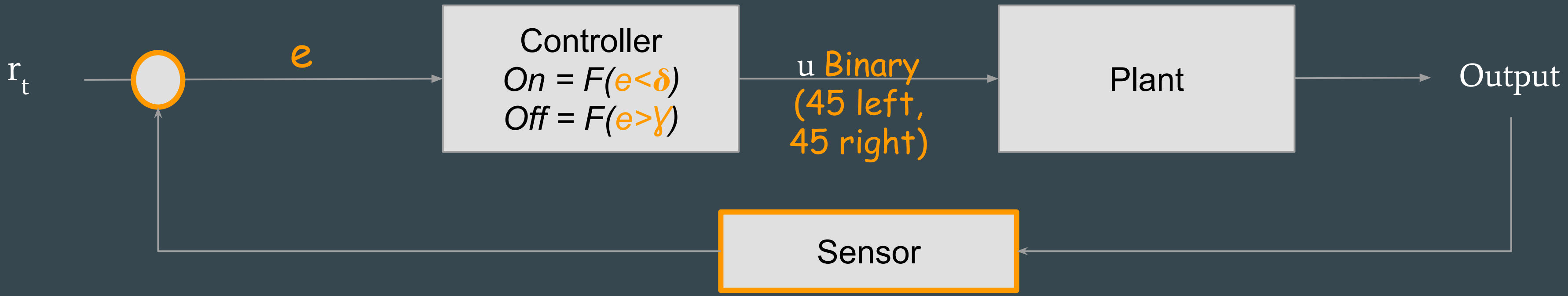
Plant

Output

Sensor

Close-Loop Controller: Bang-Bang





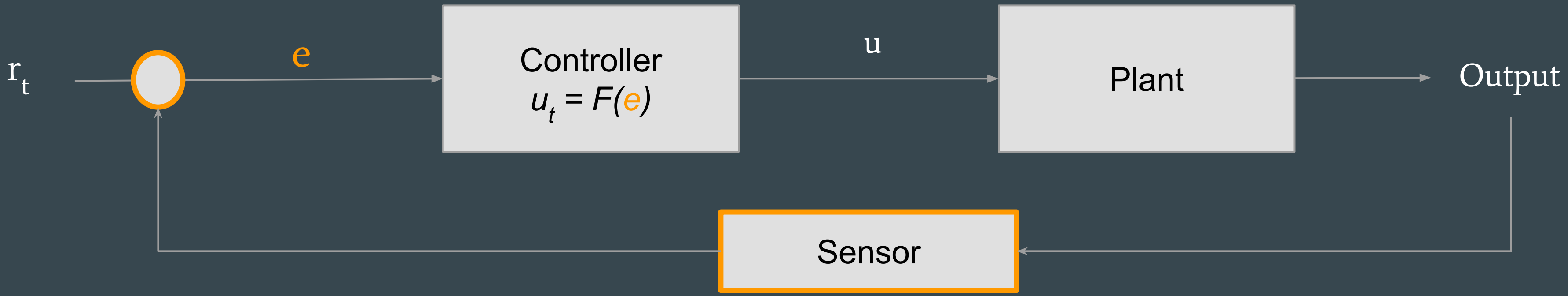
Close-Loop Controller: Proportional

- Objective: adjust based on magnitude of error

$$F(e) = K_p\,(e_t)$$
$$= K_p\,(r_t - o_t)$$

- Example

$$= 0.5\,(\text{Setpoint} - V_t)$$



Close-Loop Controller: Proportional Example

- Drive over straight line
- Process
  - Observe line
  - Compute wheel misalignment
  - Change steering angle proportional to misalignment

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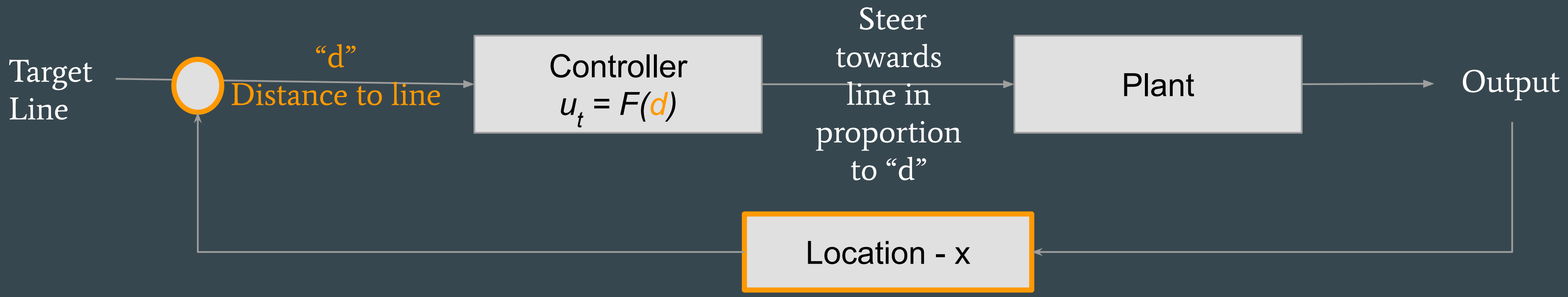

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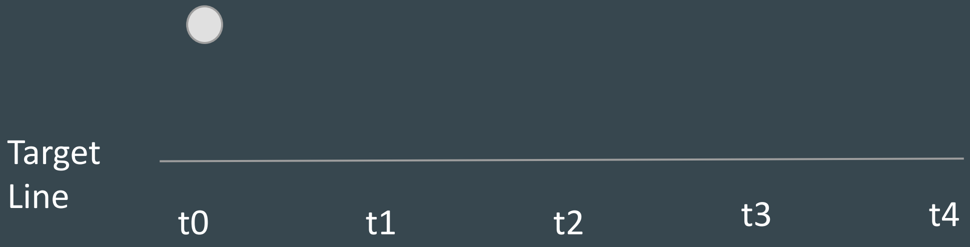
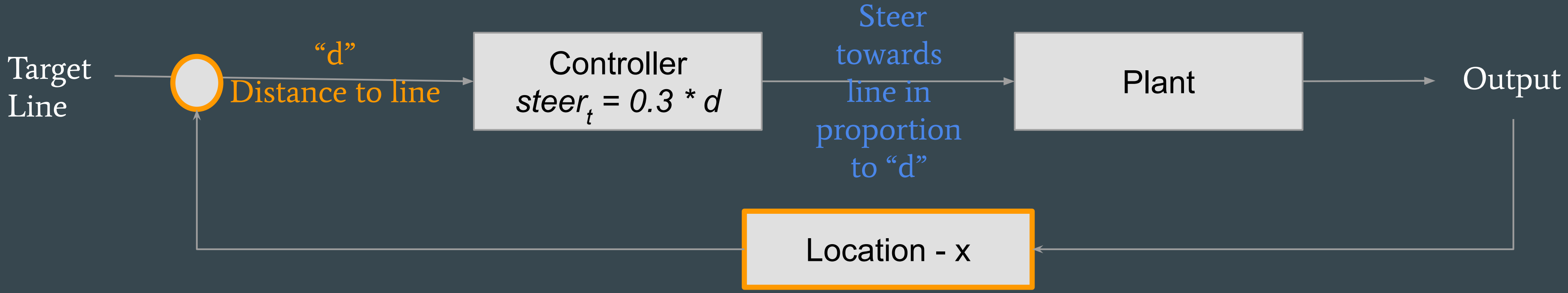




Target Line

"d"

Distance to line

Controller

$steer_t = 0.3 * d$

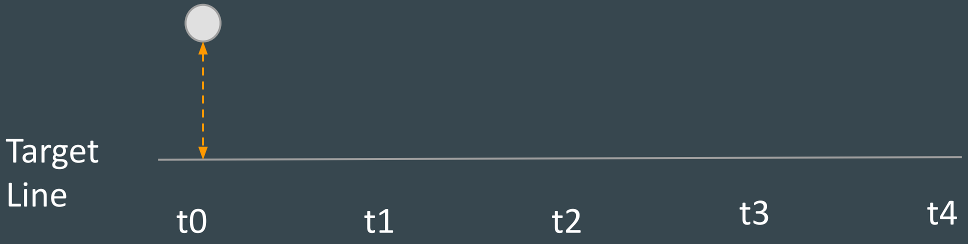
Steer towards line in proportion to "d"

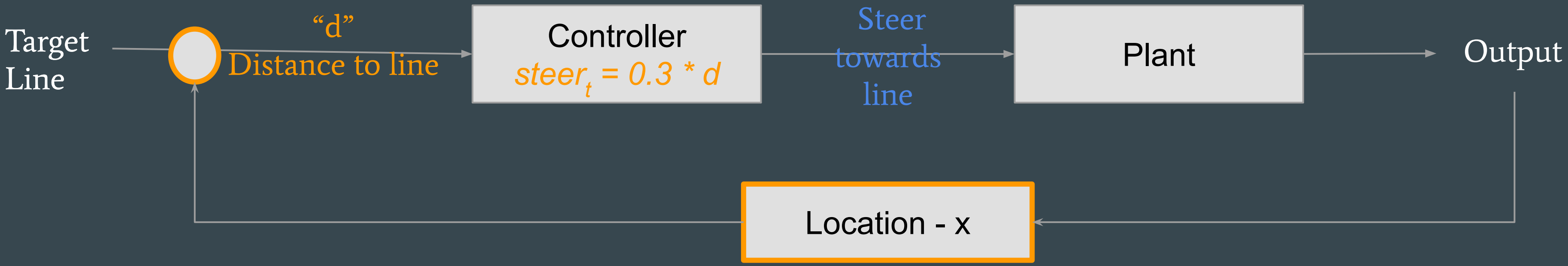
Plant

Output

Location - x

Close-Loop Controller: Proportional Example





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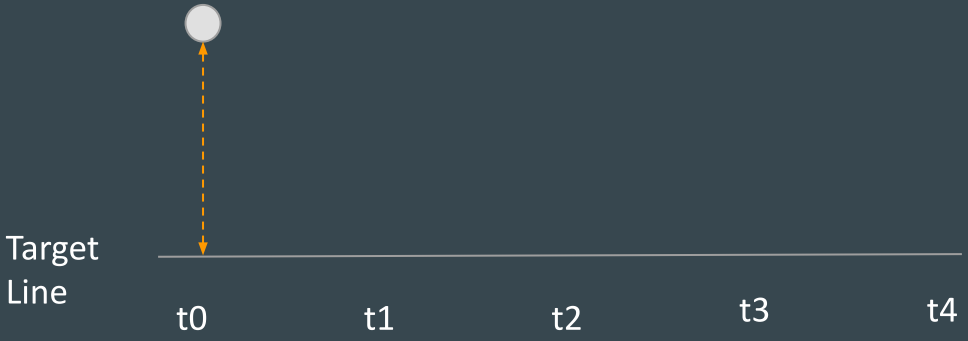

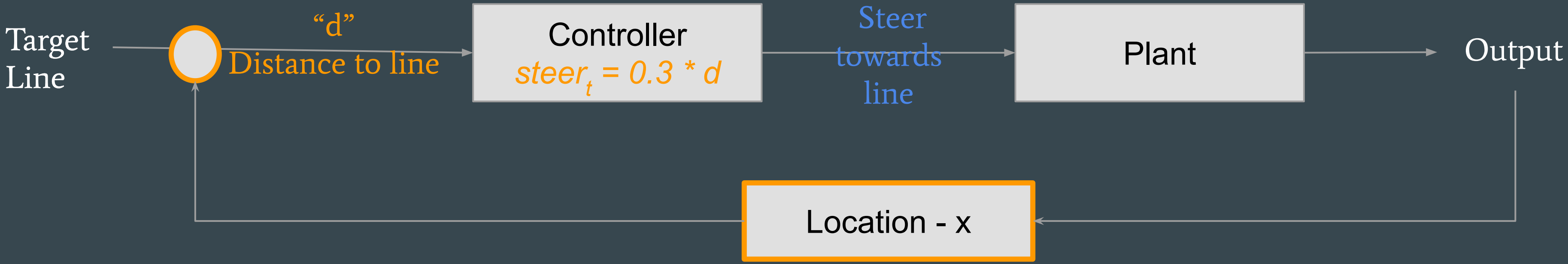

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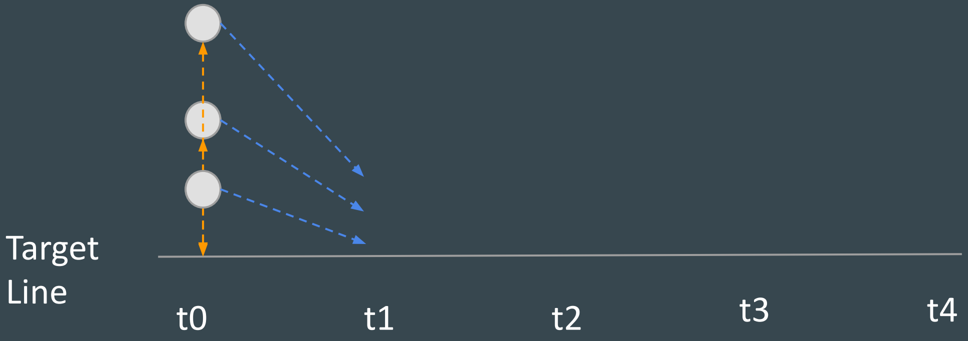

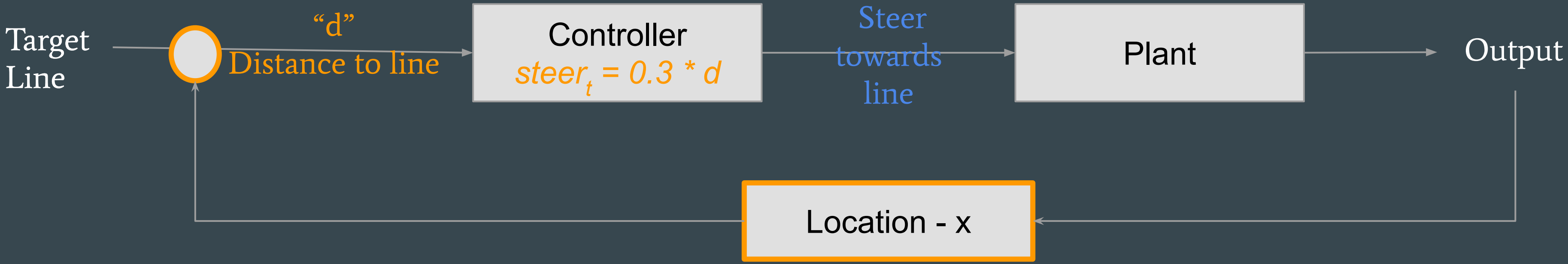

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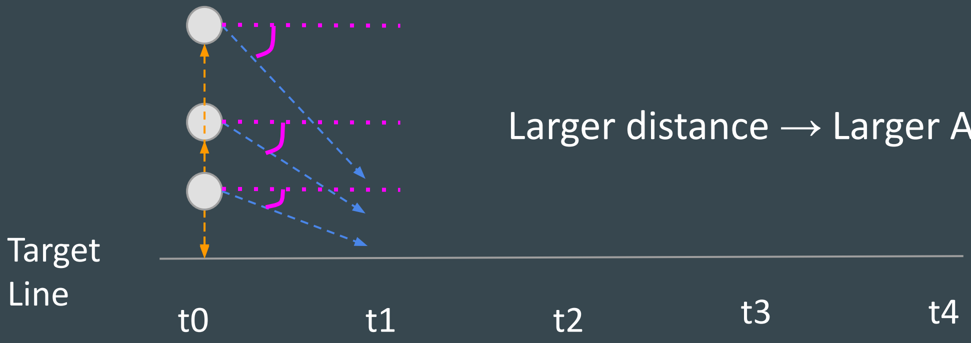
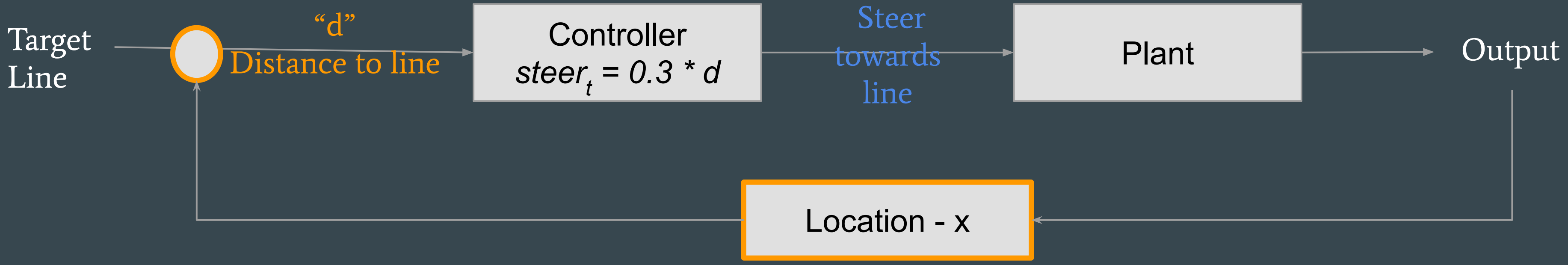


Larger distance → Larger Angle Correction



Target Line

"d"
Distance to line

Controller
$steer_t = 0.3 * d$

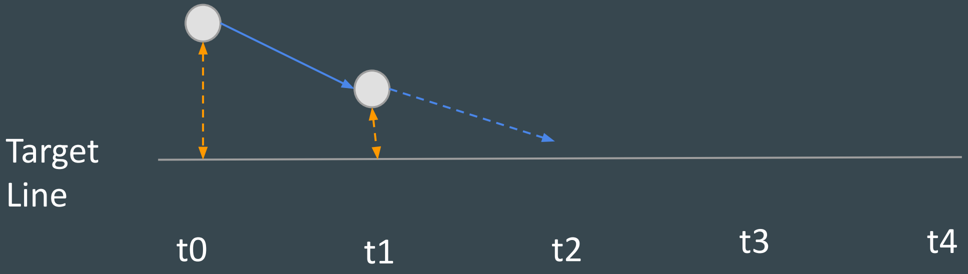
Steer towards line

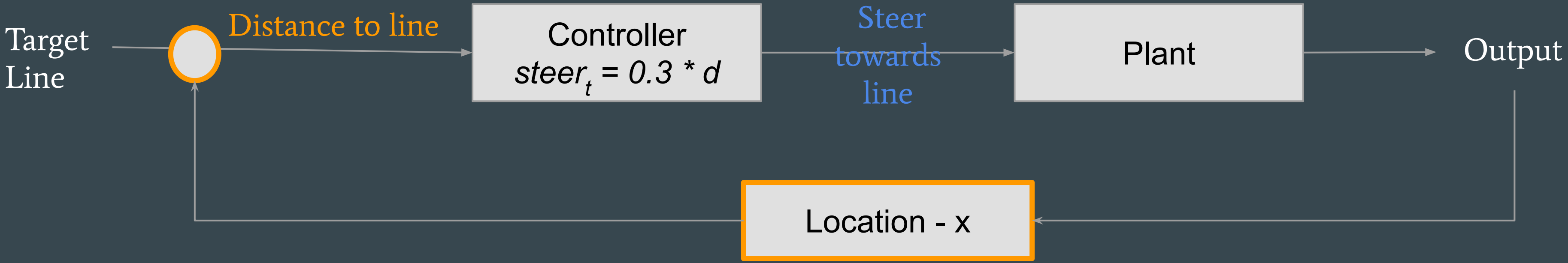
Plant

Output

Location - x

Close-Loop Controller: Proportional Example





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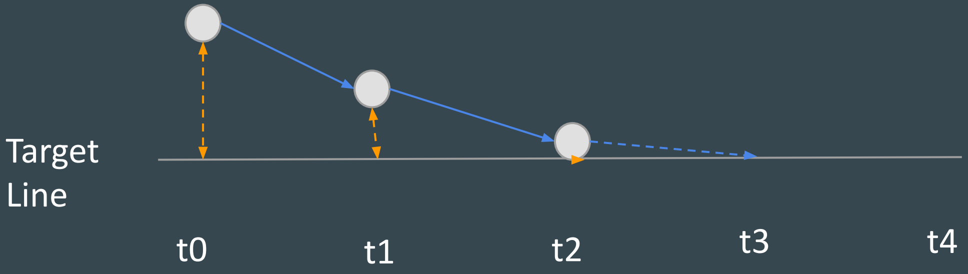

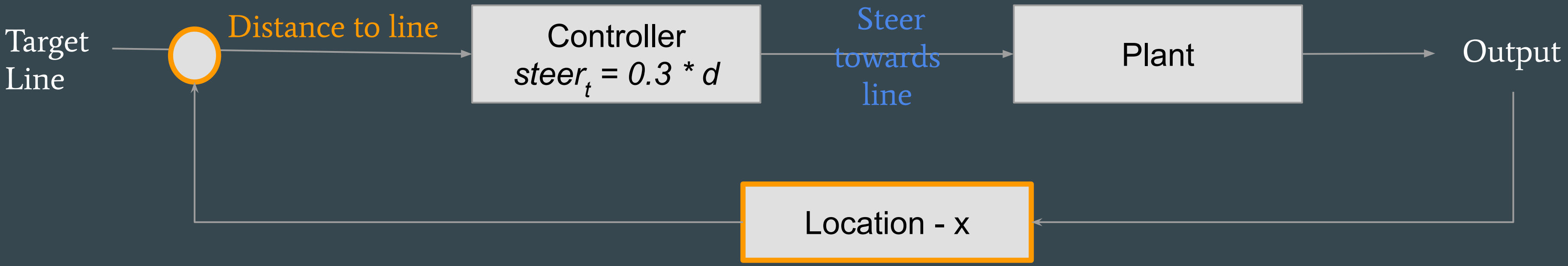

Target Line

Distance to line

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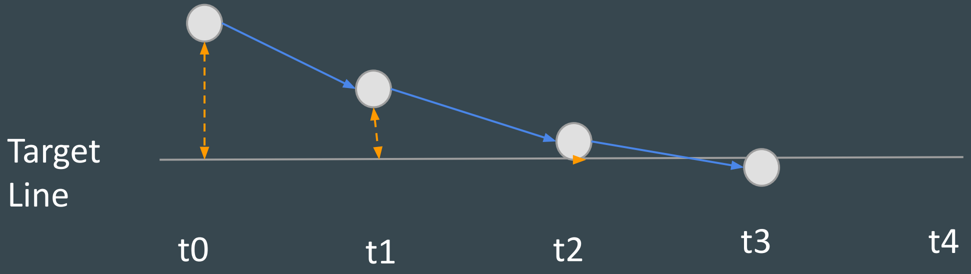
Steer towards line

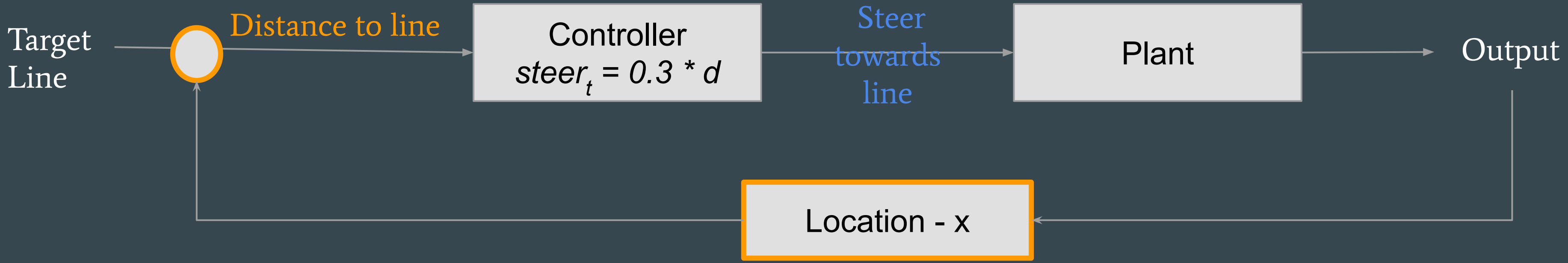
Plant

Output

Location - x

Close-Loop Controller: Proportional Example





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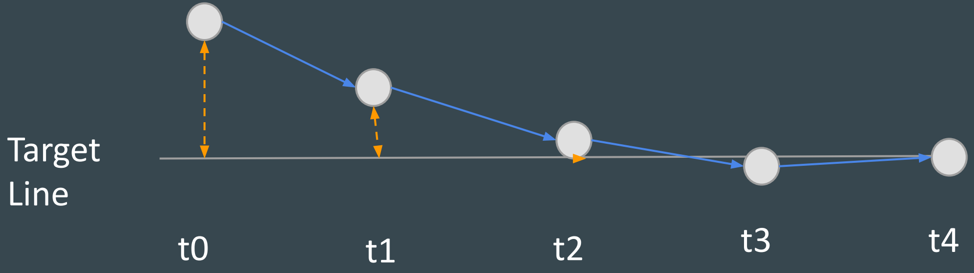
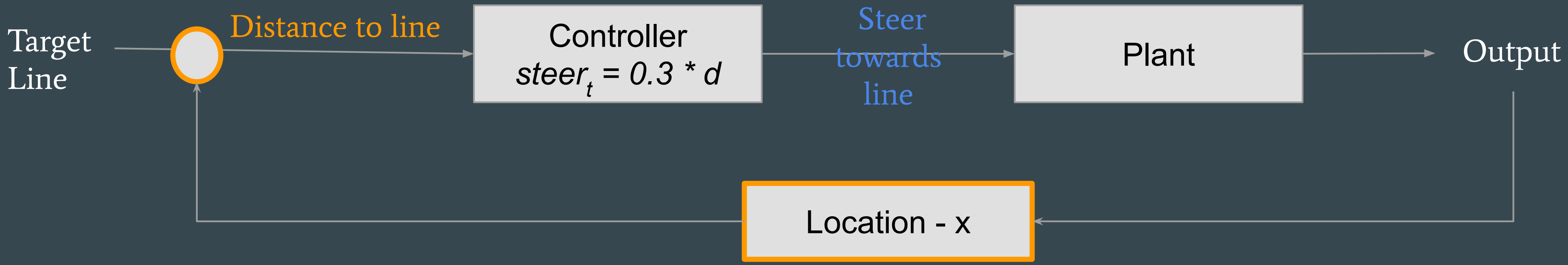
Plant

Output

Location - x

Close-Loop Controller: Proportional Example





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Output

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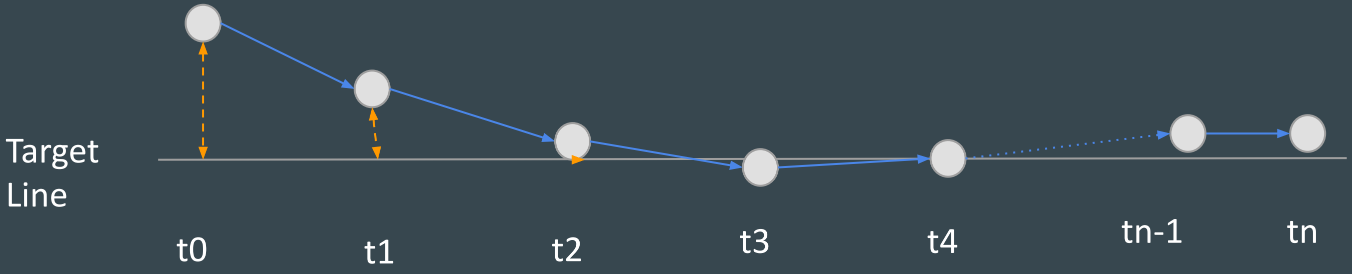
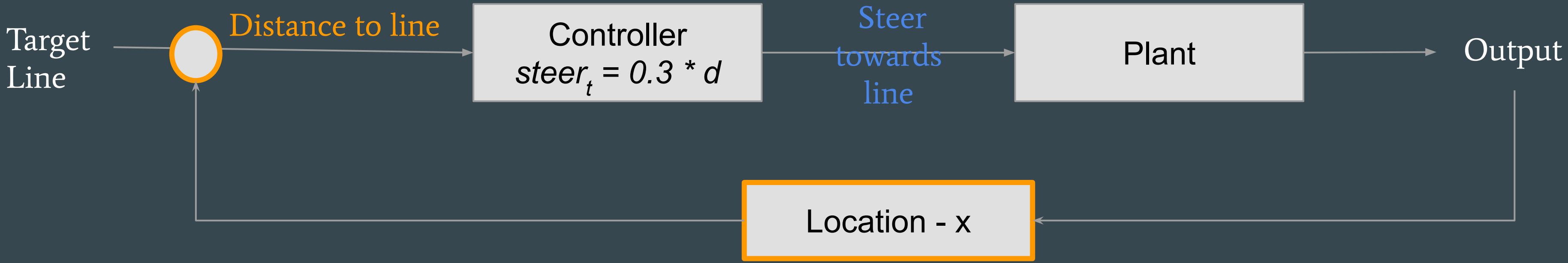




Exercise: Develop Proportional Controller for Car Cruise Control

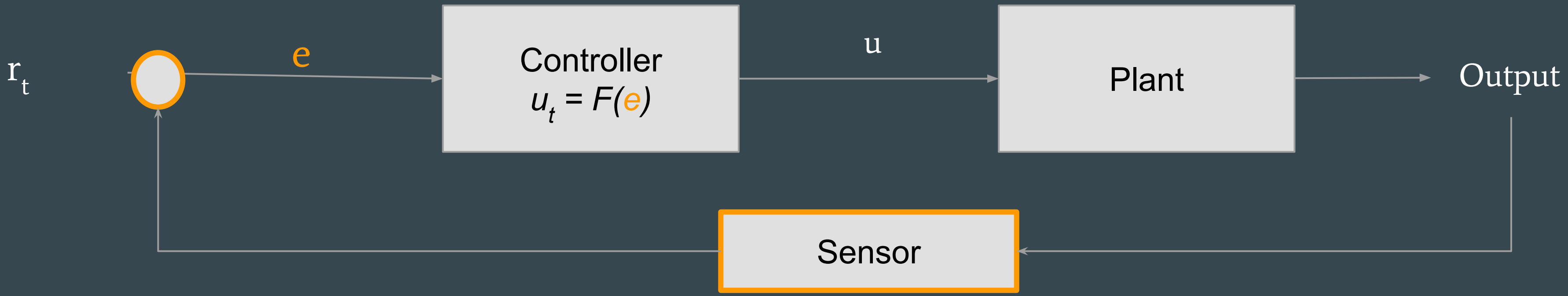
Plant:

Set point (rt):

Input to Plant (u):

Output of Plant (y):

Sensor:



Exercise: Develop Proportional Controller for Car Cruise Control

Plant: *Engine*

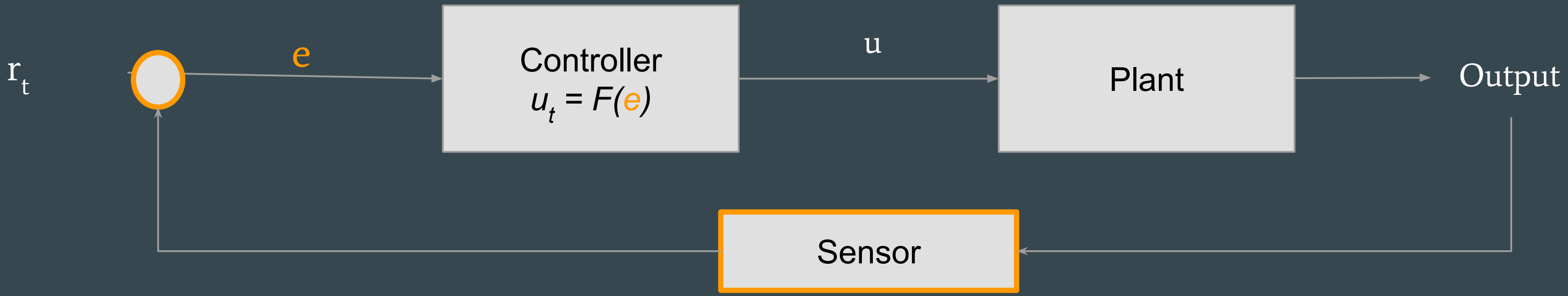
Set point (rt): *target speed*

Input to Plant (u): *torque*

Output of Plant (y): *vel/acc*

Sensor: *velocimeter*

Expected Disturbances:



Exercise: Develop Proportional Controller for Car Cruise Control

Plant: *Engine*

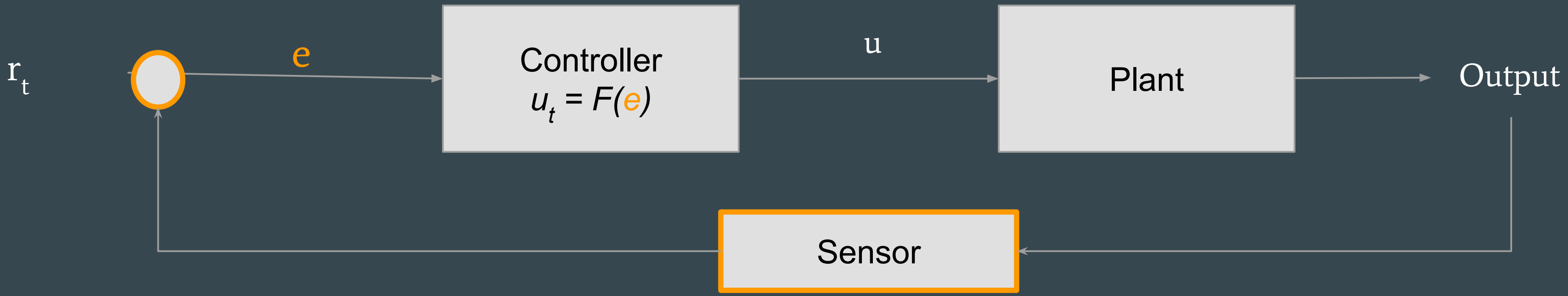
Set point (rt): *target speed*

Input to Plant (u): *torque*

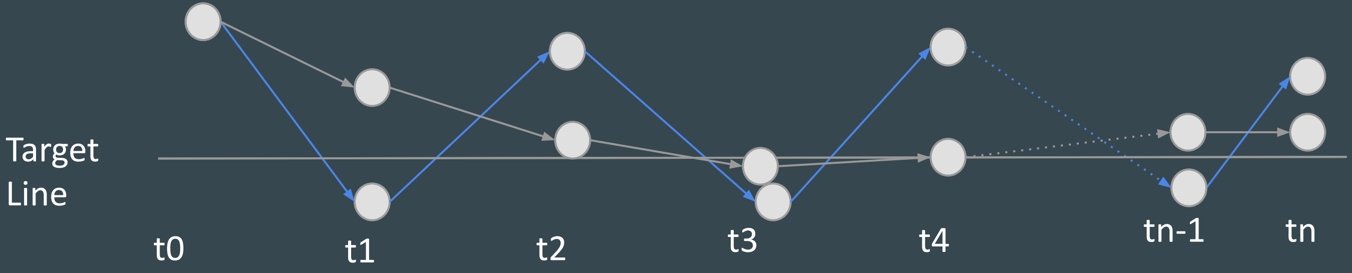
Output of Plant (y): *vel/acc*

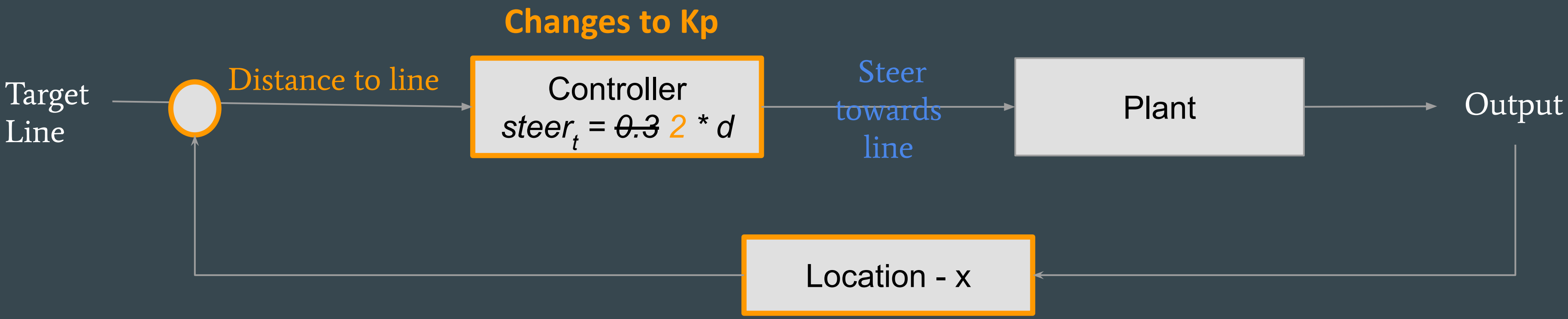
Sensor: *velocimeter*

Expected Disturbances: *hills, turns, traffic*



Close-Loop Controller: Proportional Example





Changes to Kp

Target Line

Distance to line

Controller

steer$_t$ = ~~*0.3*~~ 2 * *d*

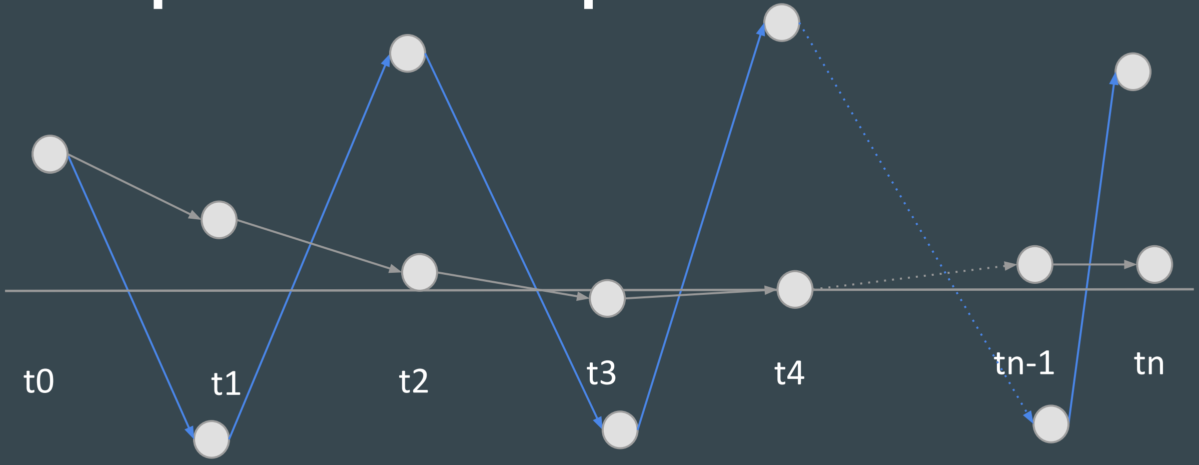
Steer towards line

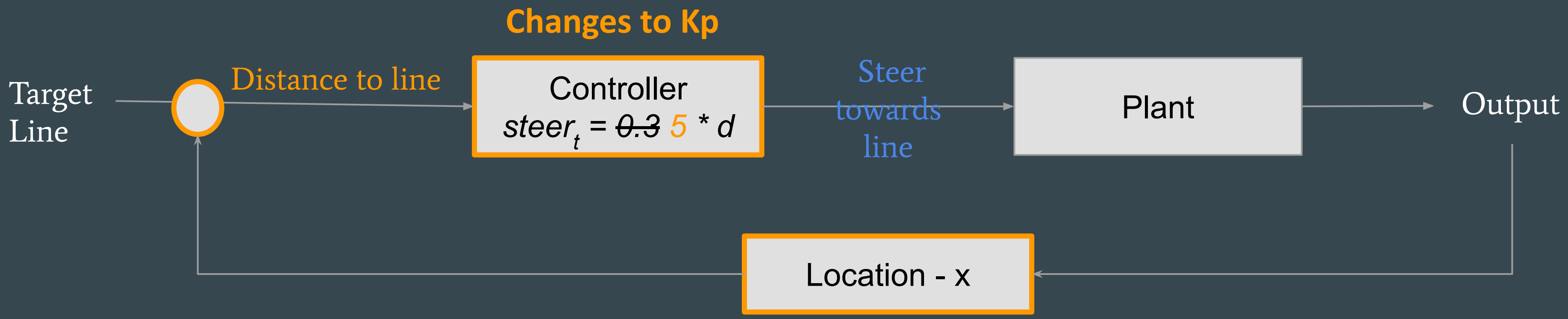
Plant

Output

Location - x

Close-Loop Controller: Proportional Example





Changes to Kp

Target Line

Distance to line

Controller

steer$_t$ = ~~*0.3*~~ 5 * *d*

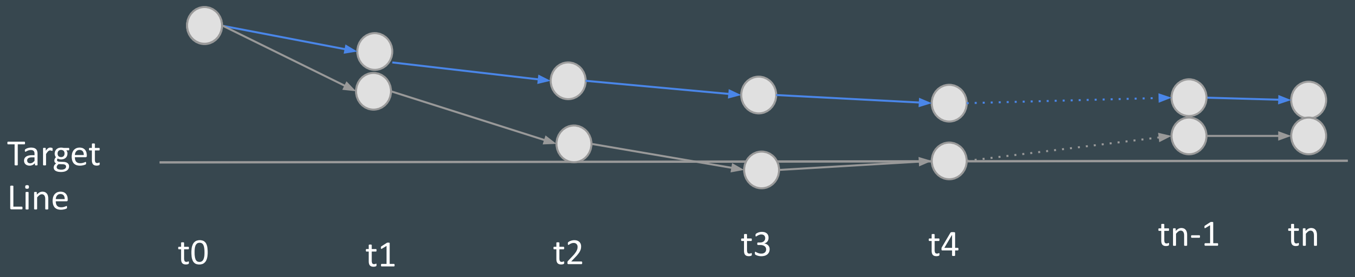
Steer towards line

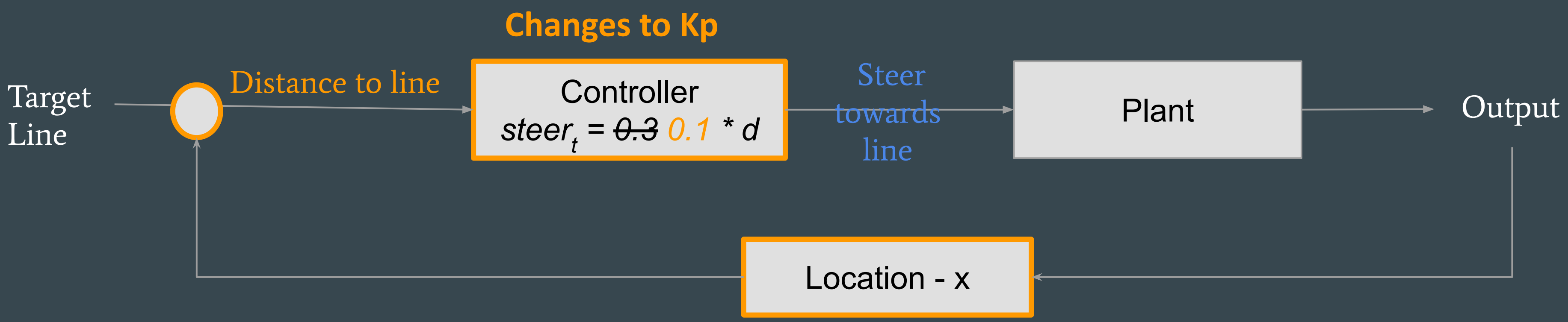
Plant

Output

Location - x

Close-Loop Controller: Proportional Example





Changes to Kp

Target Line

Distance to line

Controller

steer$_t$ = ~~*0.3*~~ 0.1 * *d*

Steer towards line

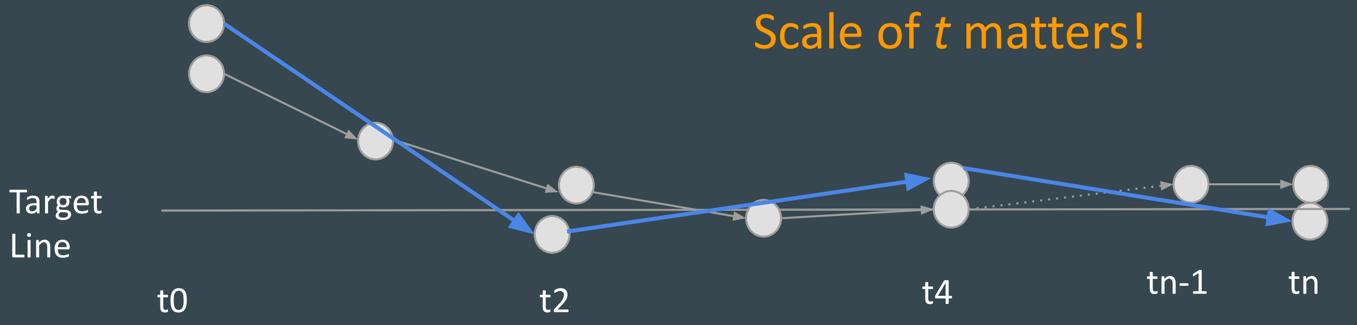
Plant

Output

Location - x

Close-Loop Controller: Proportional Example

Scale of *t* matters!



Target Line

t0

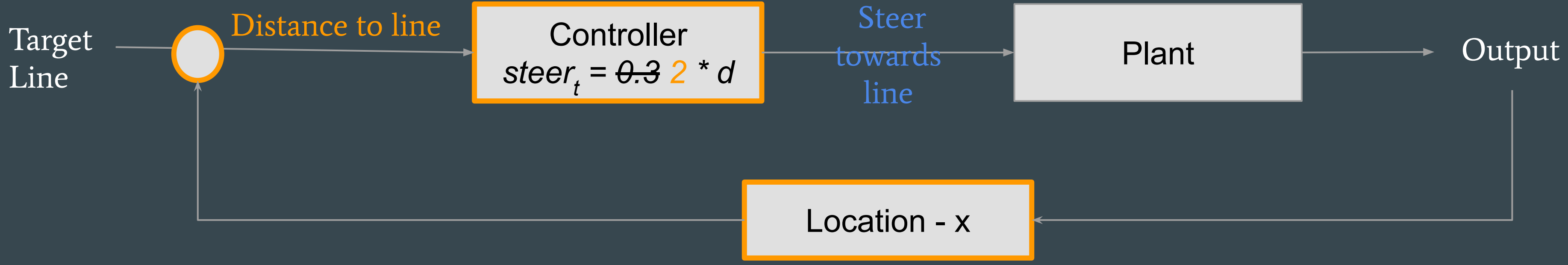
t2

t4

tn-1

tn

Changes to Kp



Target Line

Distance to line

Controller

$steer_t$ = ~~*0.3*~~ 2 ** d*

Steer towards line

Plant

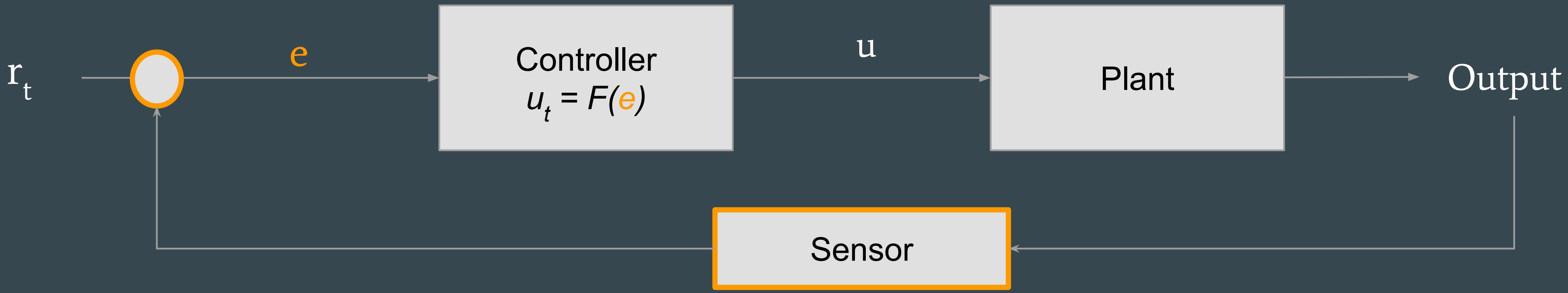
Output

Location - x

Close-Loop Controller: Proportional Derivative

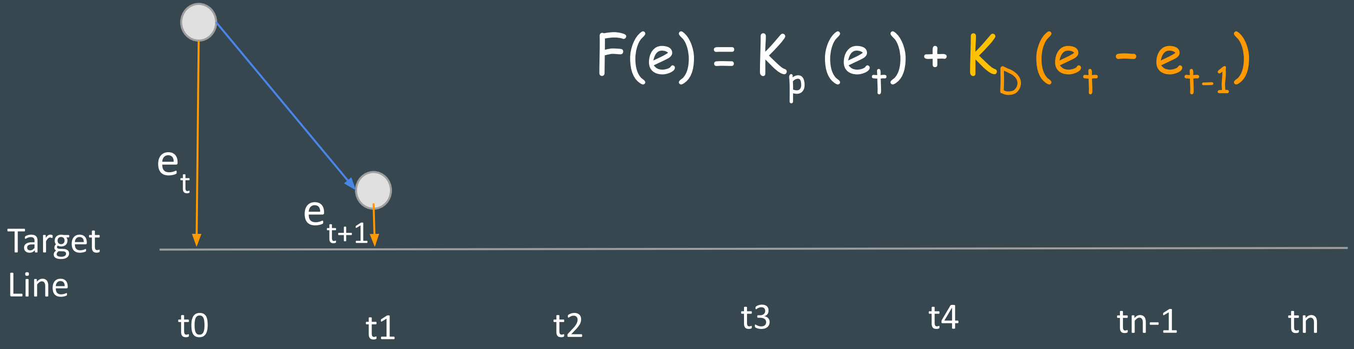
- Objective: reduce oscillation
- Adjust input based on rate of output change
  - If too slow, increase input
  - If too fast, decrease input

$$F(e) = K_p\,(e_t) + K_D\,(e_t - e_{t-1})$$

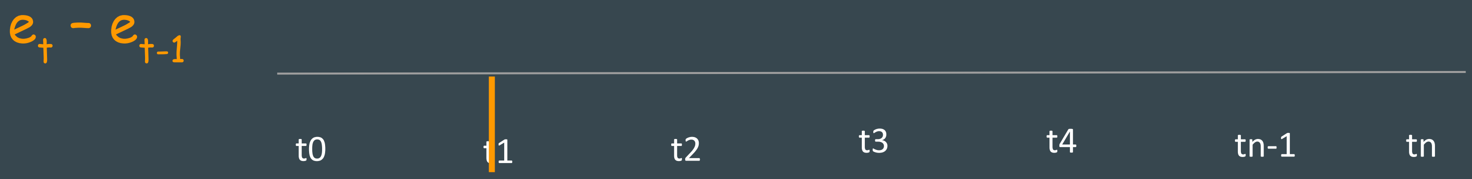


Close-Loop Controller: Proportional Derivative Example

$$F(e) = K_p\,(e_t) + K_D\,(e_t - e_{t-1})$$

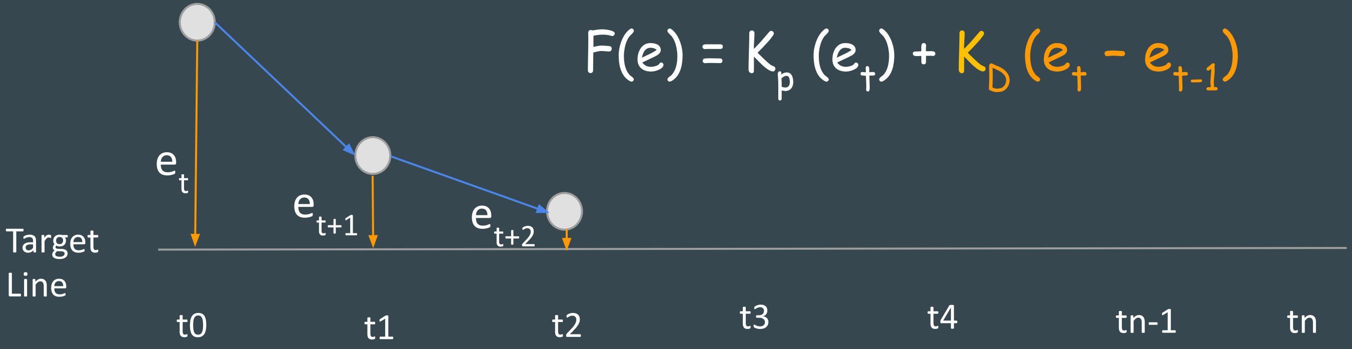


- Error is reducing from t0 to t1
- Derivative term is negative
- Derivative counters Proportional term

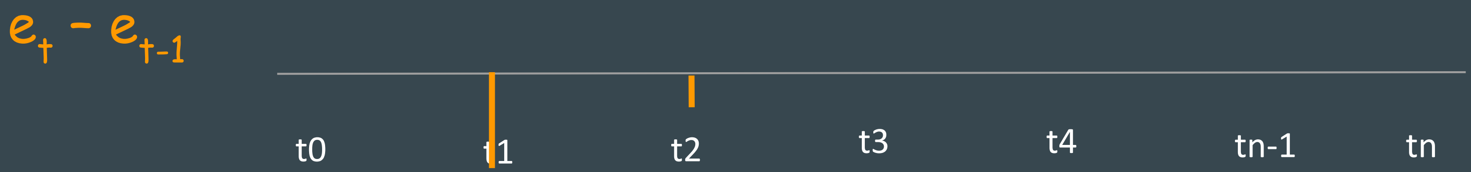


Close-Loop Controller: Proportional Derivative Example

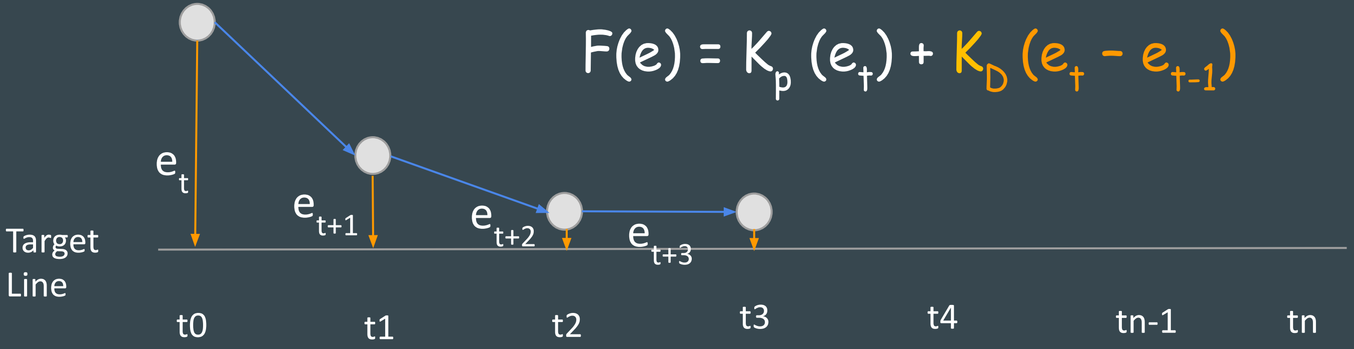
$$F(e) = K_p\,(e_t) + K_D\,(e_t - e_{t-1})$$



- Error is reducing from t0 to t1 to t2
- Derivative term is still negative
- Derivative term becomes smaller as amount of error decreases

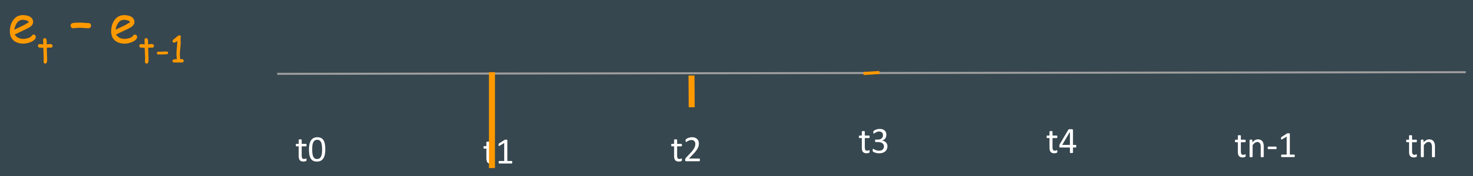


Close-Loop Controller: Proportional Derivative Example

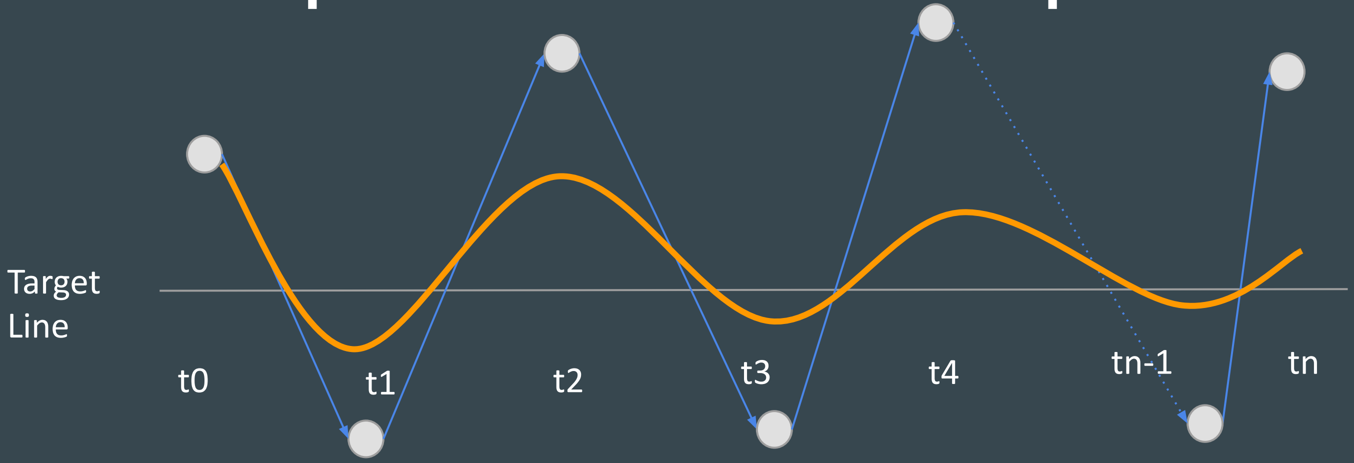


$$F(e) = K_p\,(e_t) + K_D\,(e_t - e_{t-1})$$

- Error is constant
- Derivative term is zero
- Only proportional term correction



Close-Loop Controller: Proportional Derivative Example



D term damps the aggressiveness of P

Proportional to error growth

Exercise: Develop PD Controller for Altitude Controller

Plant:

Set point (rt):

Input to Plant (u):

Output of Plant (y):

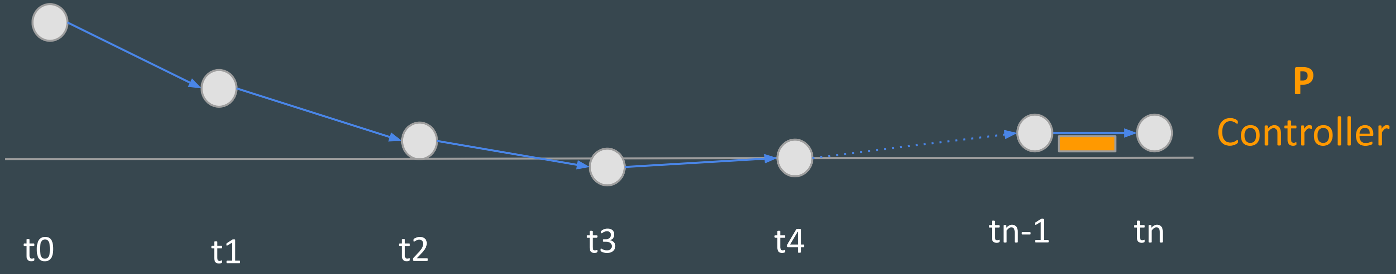
Sensor:

Close-Loop Controller: Proportional + Derivative + Integral

- Objective: reduce steady state error
- Sum total error over time (potential for overcompensation)

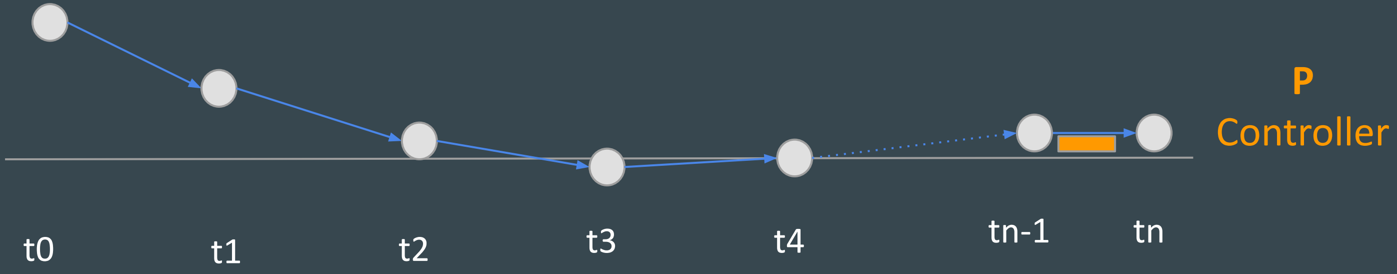
$$F(e) = K_p\,(e_t) + K_D\,(e_t - e_{t-1}) + K_I\,(e_0 + e_1 + e_2 + \ldots + e_{t-1})$$

Close-Loop Controller: Proportional + Integral Example



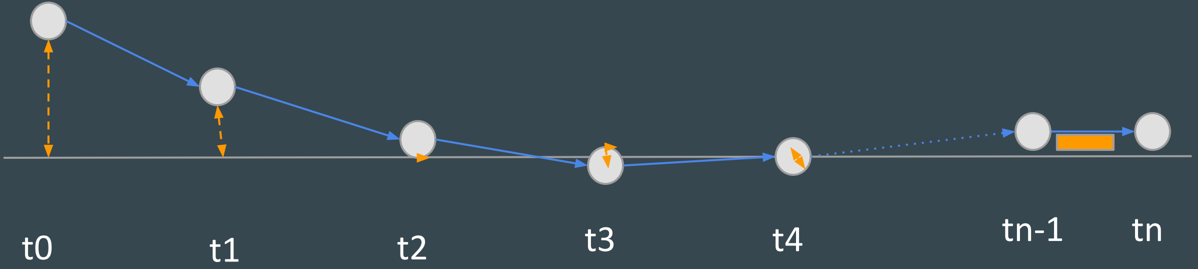
- Steady-State error is the final difference with setpoint
  - P gets to stable point that is deemed too far from setpoint
- Caused by disturbances
  - Gravity
  - More friction turning right than left
  - Leaning certain way

Close-Loop Controller: Proportional + Integral Example



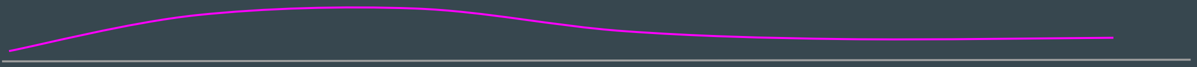
$$F(e) = K_p\,(e_t) + K_I\,(e_0 + e_1 + e_2 + \ldots + e_{t-1})$$

Close-Loop Controller: Proportional + Integral Example

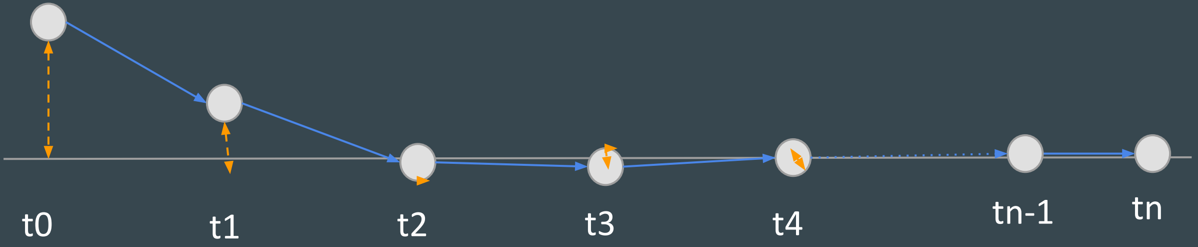


P Controller

$$F(e) = K_p (e_t) + K_I (e_0 + e_1 + e_2 + \ldots + e_{t-1})$$

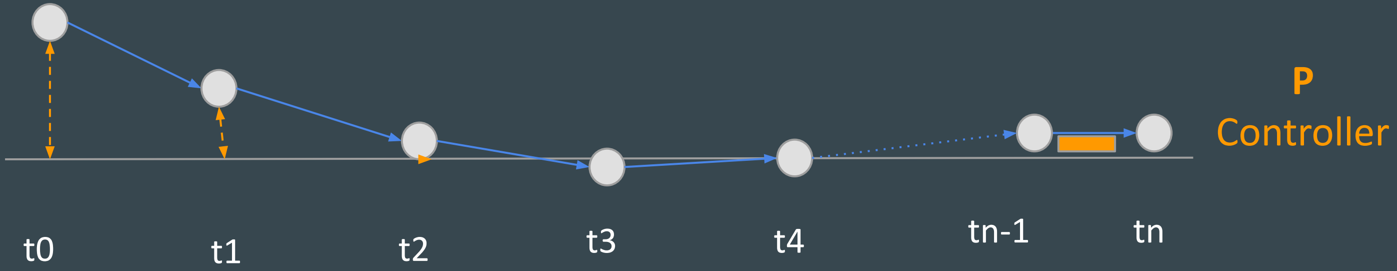


Integral Term



PI Controller

Close-Loop Controller: Proportional + Integral Example

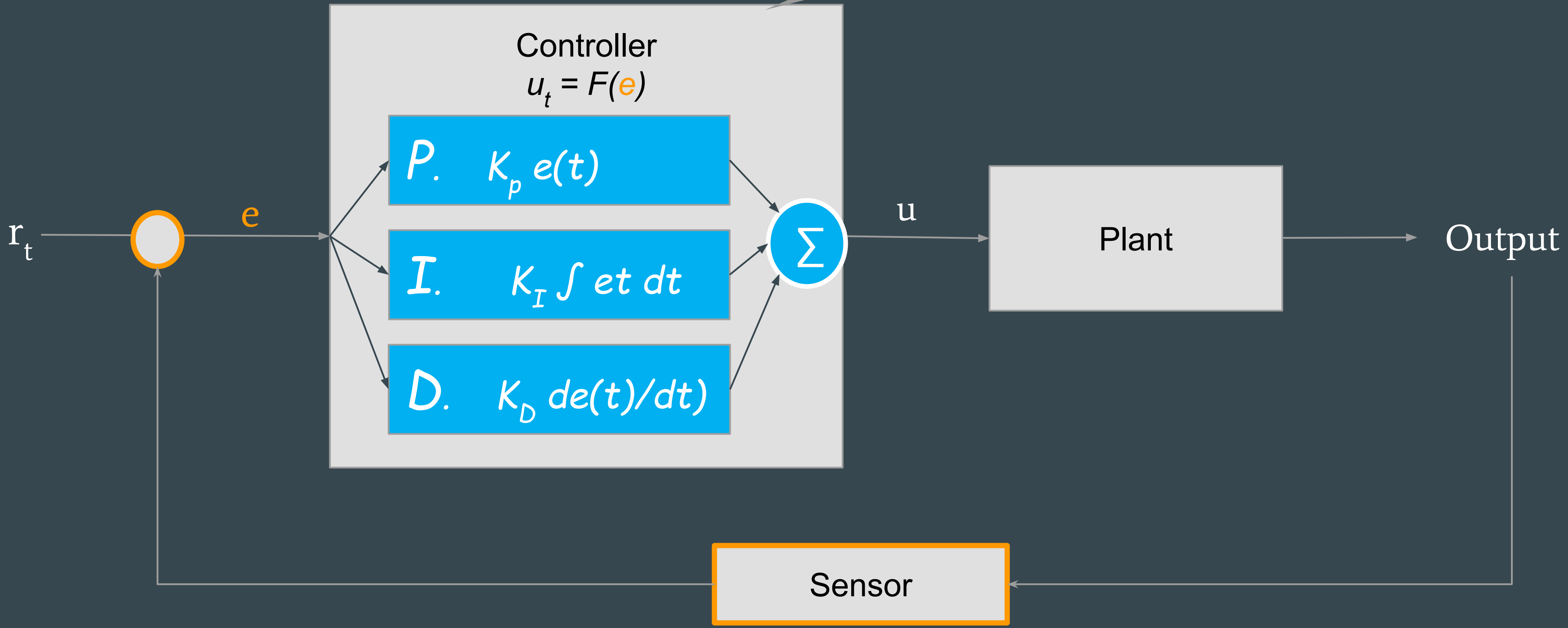


$$F(e) = K_p\,(e_t) + K_I\,(e_0 + e_1 + e_2 + \ldots + e_{t-1})$$

Integral Windup curse

- Integral term increases while output is ramping up
- This can cause overshoot and oscillation
- Solution is to limit integral term

PID Controller



Note impact of *t* choice!!!

In Code

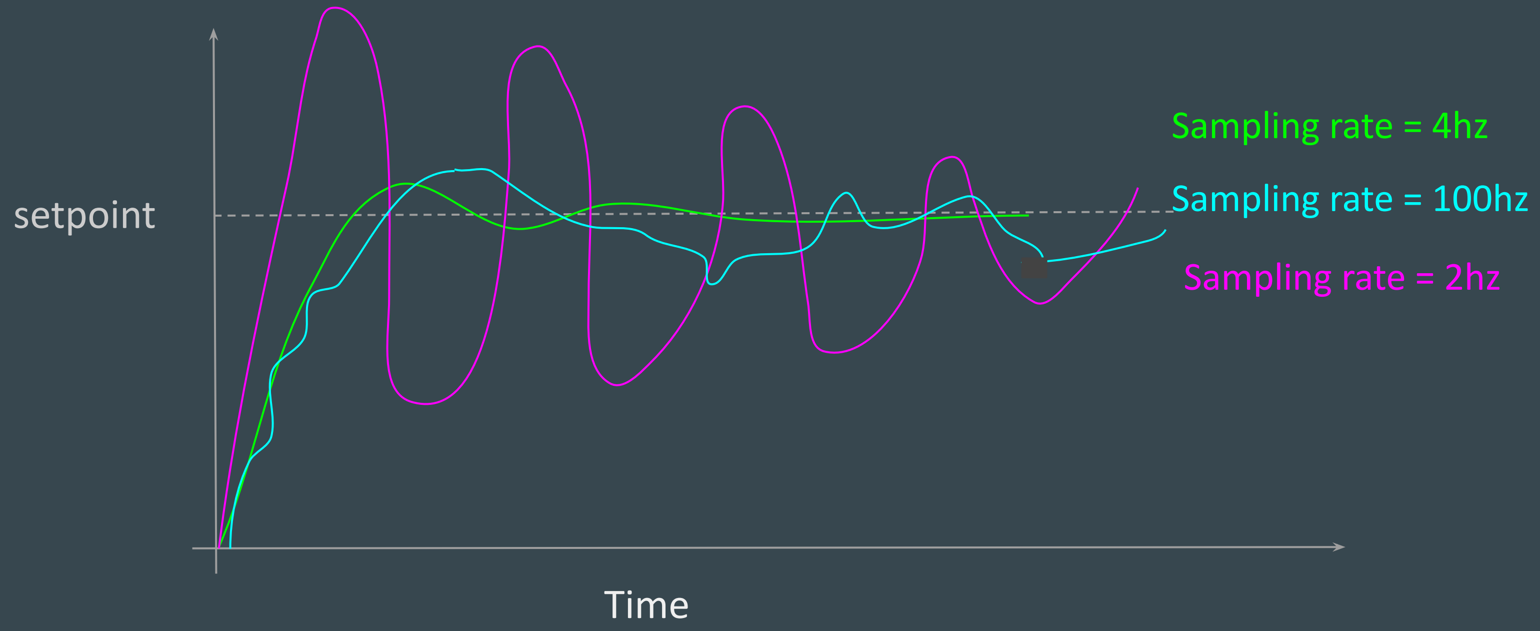
```
float setpoint = read()
float lasterr = 0;
float integral = 0;

float  PIDcontroller (float measure) {
      err = setpoint - measure;
      dt = currentTime - lastTime;
       integral += err * dt;
      float deriv = (err – lasterr ) / dt;
      float output = Kp*err + Ki*integral + Kd*deriv;
      lasterr = err;
      lastTime = currentTime
      return output;
}
```

Missing

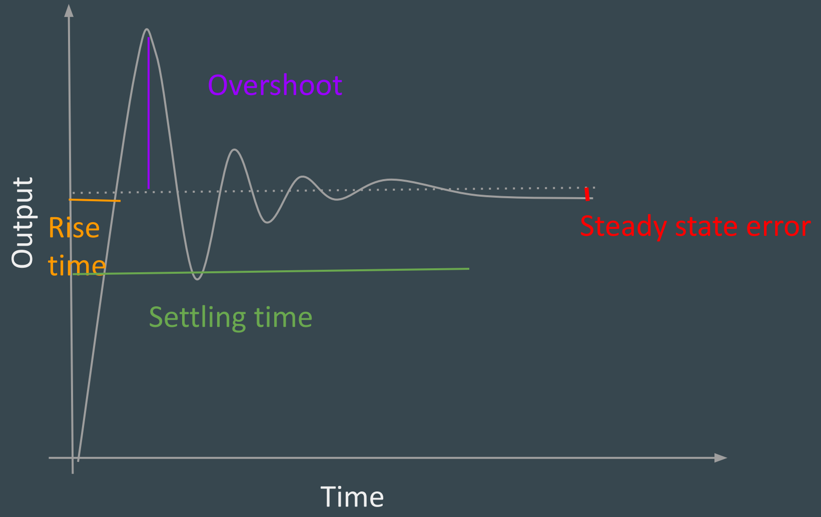
- Definition of K coefficients
- Bounds on output
- Bounds/reset integral term

Caveat: Tuning depends on Sampling Rate



Controller Performance

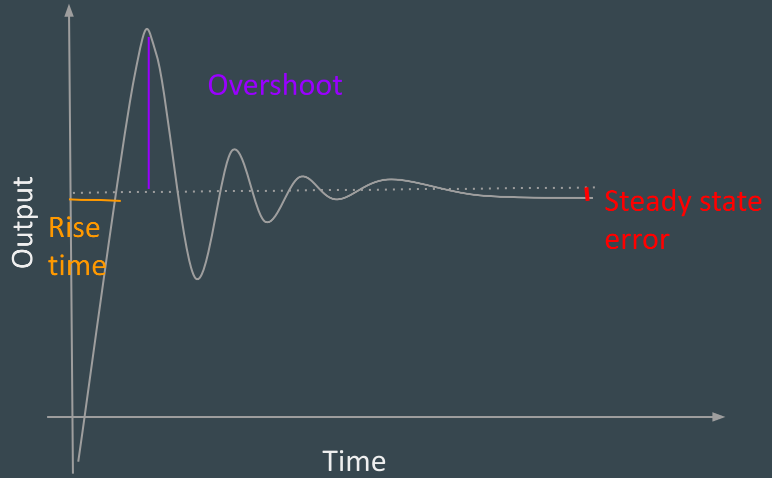
- Stability
  - Error should converge to within threshold
  - No oscillation
- Performance
  - Rise time - within threshold of steady state
  - Overshoot - over final value
  - Settling time - time before output within threshold
- Robustness
  - Stability and performance variations in the presence of plant changes



Tuning PID

- Many heuristics, my favorite
    - Initialize Kd = Ki = 0
    - Iterate
        - Increase Kp until oscillation
        - Decrease Kp by 2
        - Increase Ki until just before loss of stability
        - Increase Kd to reduce oscillation

Tuning PID



Debugging / Trade-offs present through subtle interactions

Effect Increasing Term	Rise Time	Overshoot	SS error
Proportional	decrease	increase	decrease
Integral	decrease	increase	eliminate
Derivative		decrease	

Takeaways

- Controllers can
  - Make your robot respond faster
  - Abstracts physics away from desired response
- Close-loop
  - Feedback helps to adjust/tolerate unexpected world
- PID Controllers
  - Most controllers in the world, simple, effective
  - Setting K constants and sampling time are the keys!