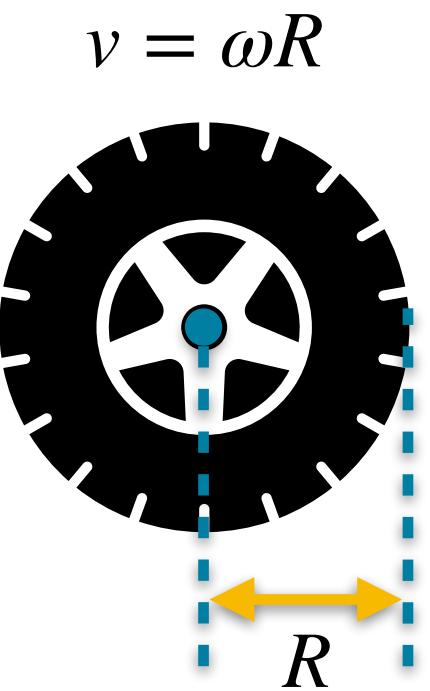


MODULE 5 LESSON 3

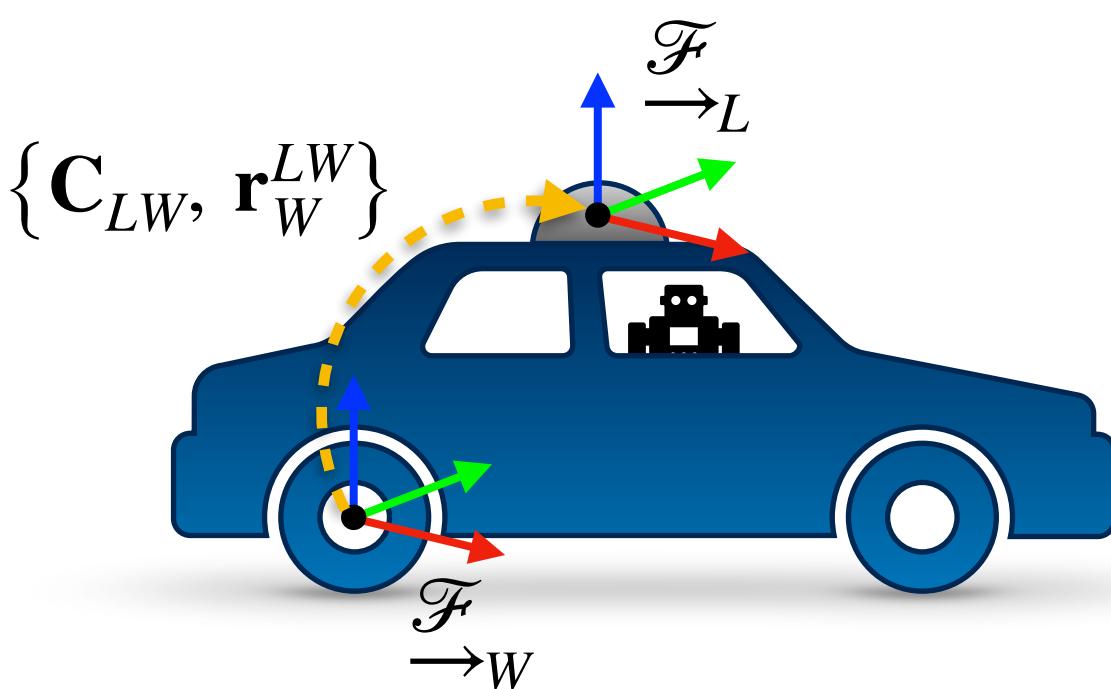
SENSOR CALIBRATION: A NECESSARY EVIL

# Calibration: A Necessary Evil

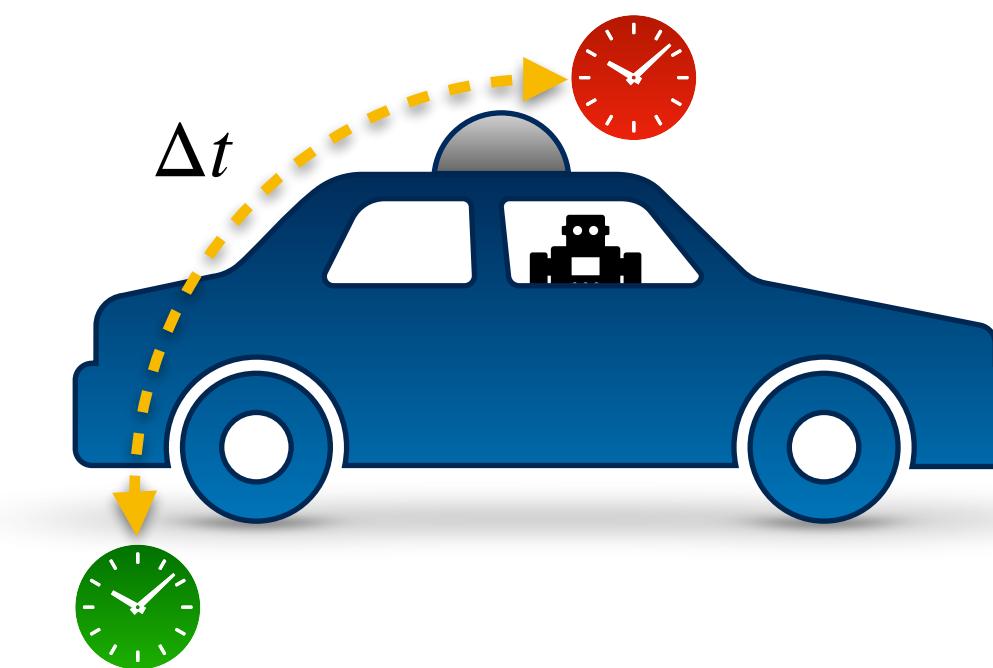
## Intrinsic Calibration



## Extrinsic Calibration



## Temporal Calibration



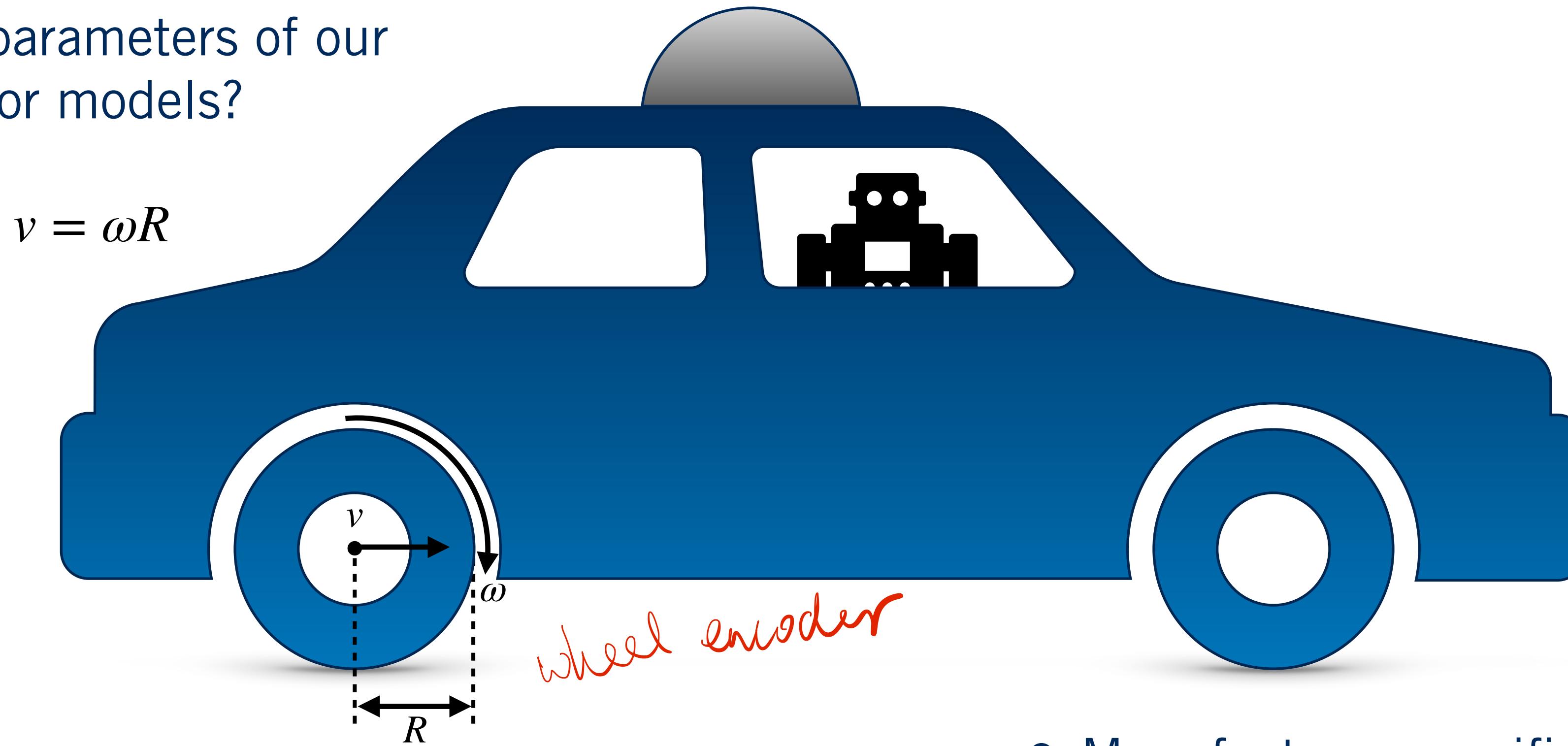
sensor parameters

how the sensor is  
positioned &  
oriented

time offset between  
sensor measurements

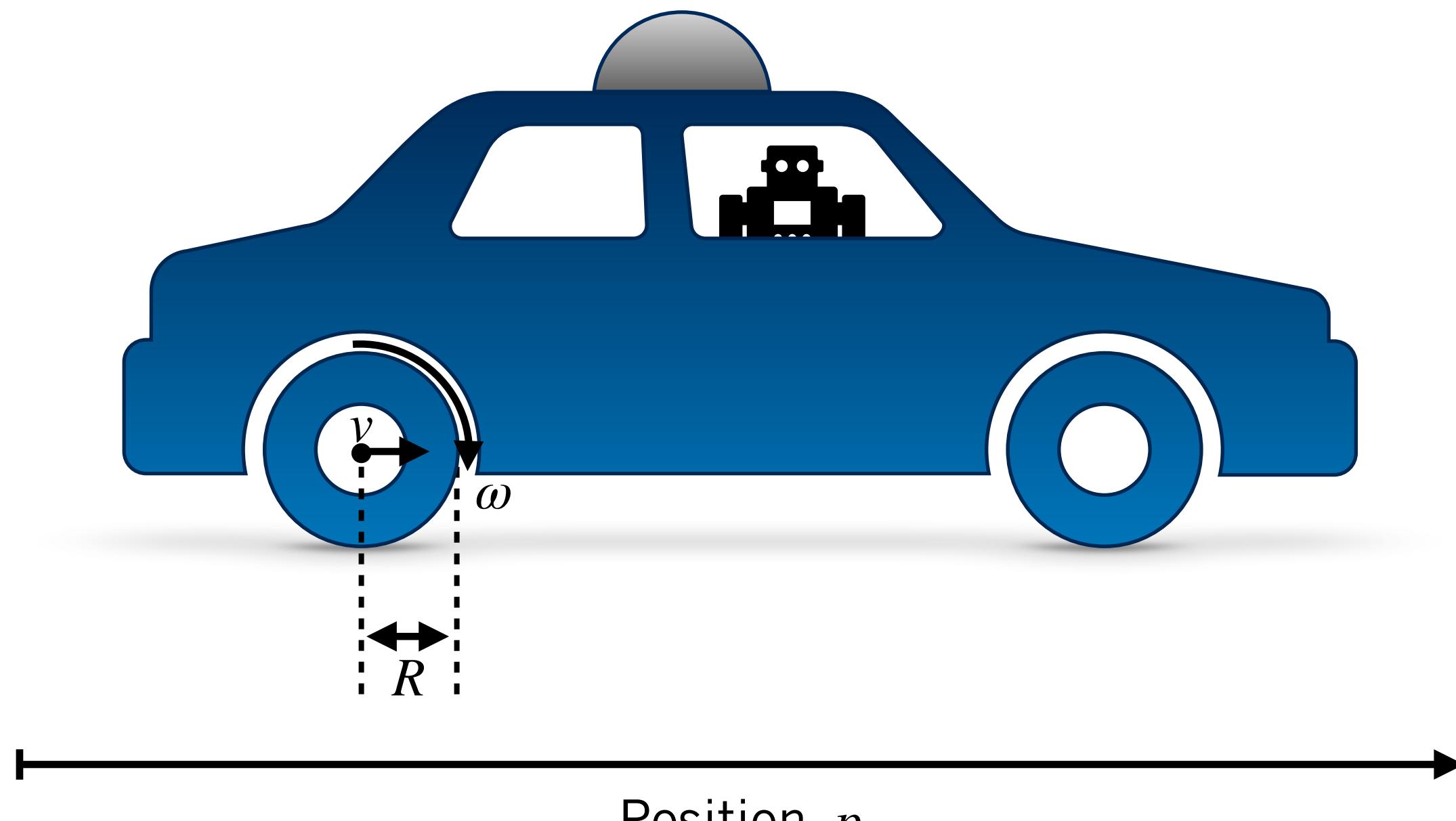
# Intrinsic Sensor Calibration

How can we determine the parameters of our sensor models?



- Manufacturer specifications
- Measure by hand
- Estimate as part of the state

# Calibration by Estimation



## Motion Model

$$\mathbf{x}_k = \begin{bmatrix} 1 & \Delta t & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{x}_{k-1} + \begin{bmatrix} 0 \\ \Delta t \end{bmatrix} \mathbf{u}_{k-1} + \mathbf{w}_{k-1}$$

$$\mathbf{w}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{Q}_k)$$

## Position / Wheel Rate Observations

$$\mathbf{x} = \begin{bmatrix} p \\ \dot{p} \\ R \end{bmatrix}$$

$$\mathbf{u} = \ddot{p}$$

$$\dot{p} = v = \omega R$$

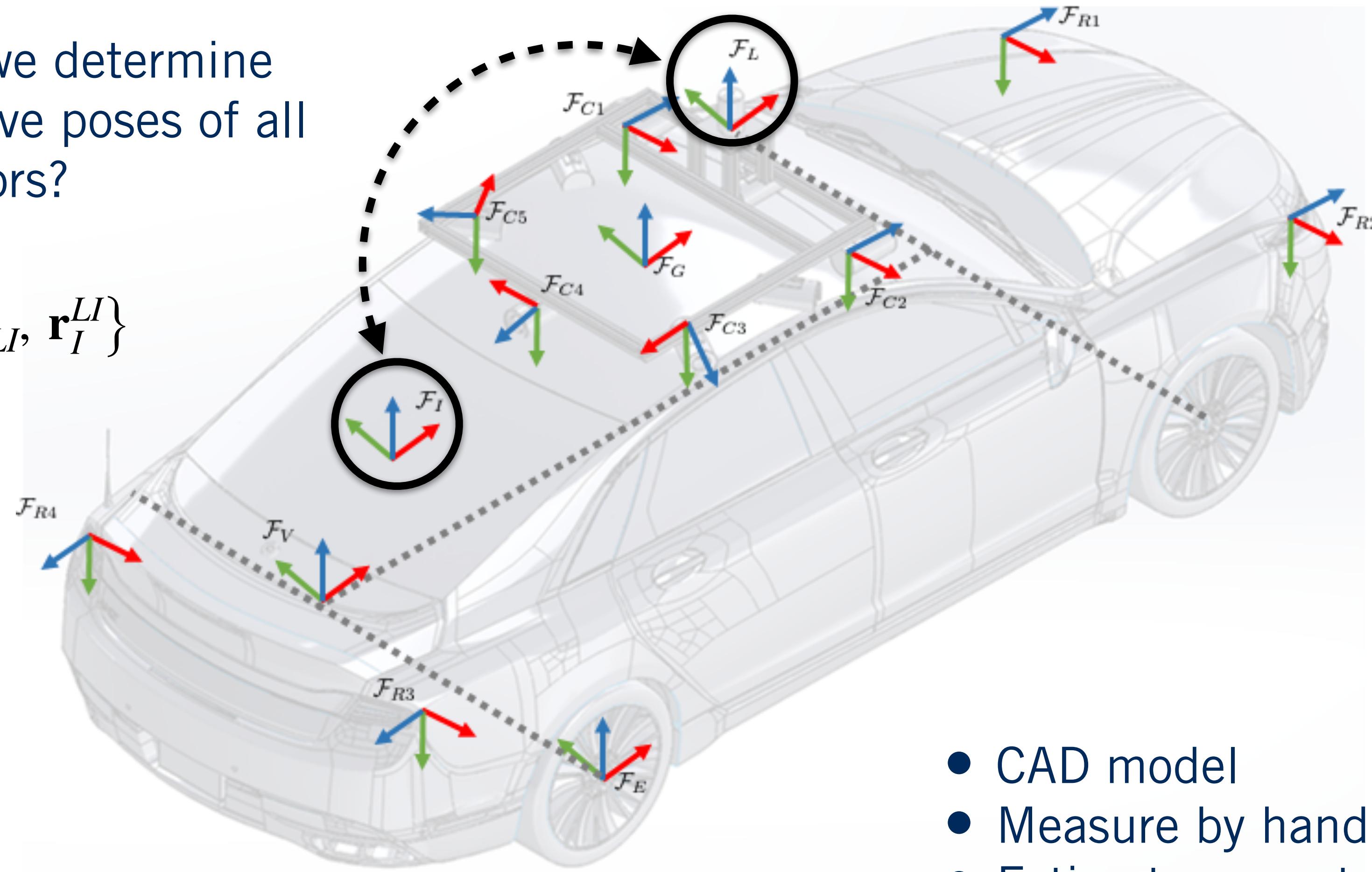
$$\mathbf{y}_k = \begin{bmatrix} p_k \\ \dot{p}_k / R_k \end{bmatrix} + \mathbf{v}_k$$

$$\mathbf{v}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{R}_k)$$

# Extrinsic Sensor Calibration

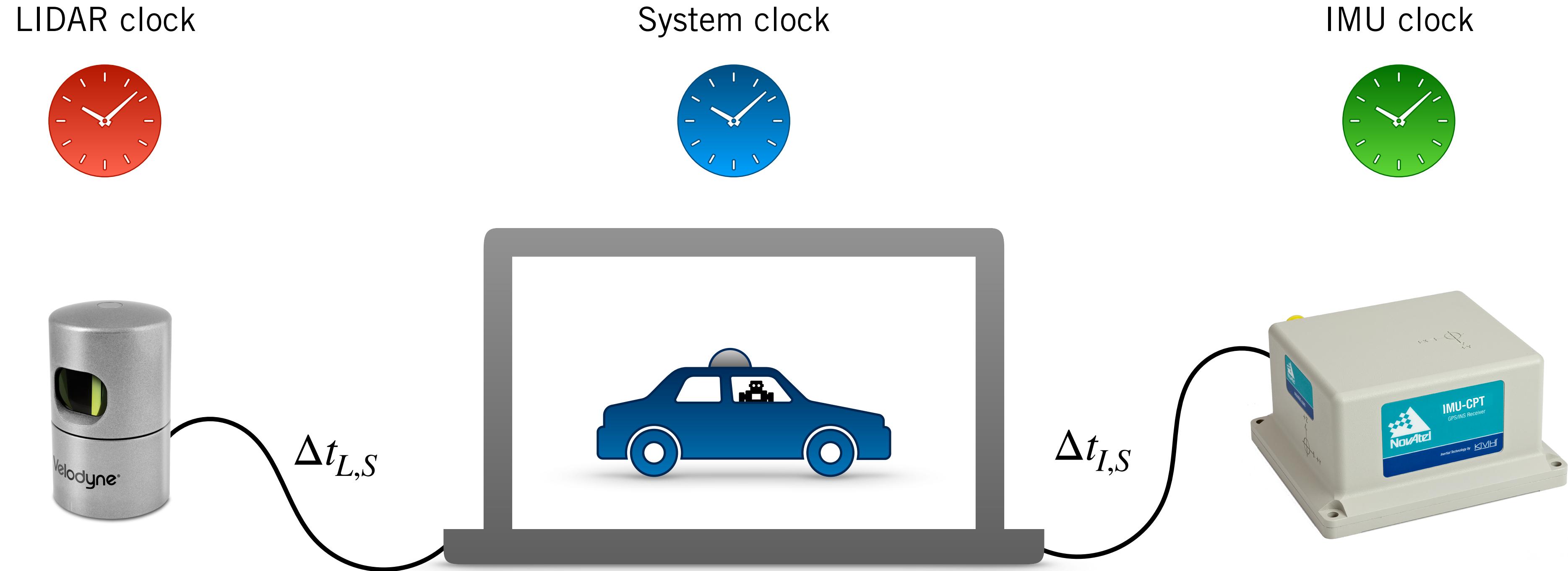
How do we determine  
the relative poses of all  
the sensors?

$$\{\mathbf{C}_{LI}, \mathbf{r}_I^{LI}\}$$



- CAD model
- Measure by hand (*not easy*)
- Estimate as part of the state

# Temporal Calibration



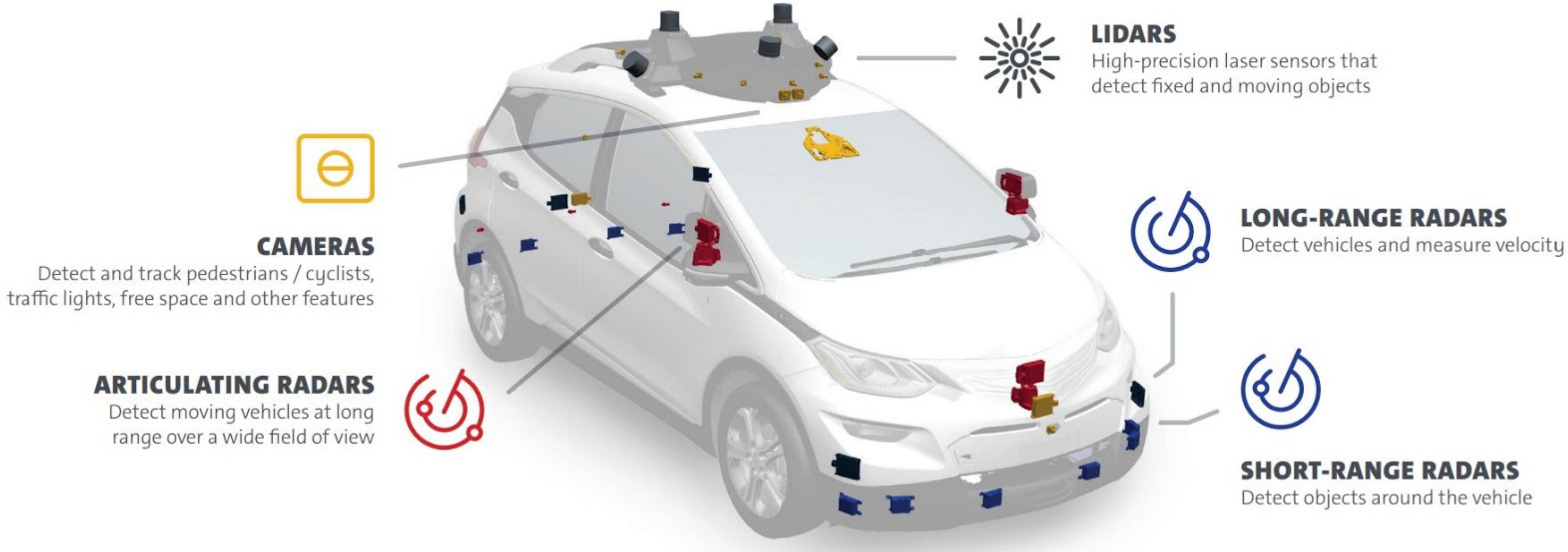
How do we determine the relative time delays of all the sensors?

- Assume zero
- Hardware synchronization
- Estimate as part of the state

**MODULE 5 LESSON 4**

**LOSS OF ONE OR MORE SENSORS**

# Multiple Sensors are Essential



Source: GM/Cruise Safety Report

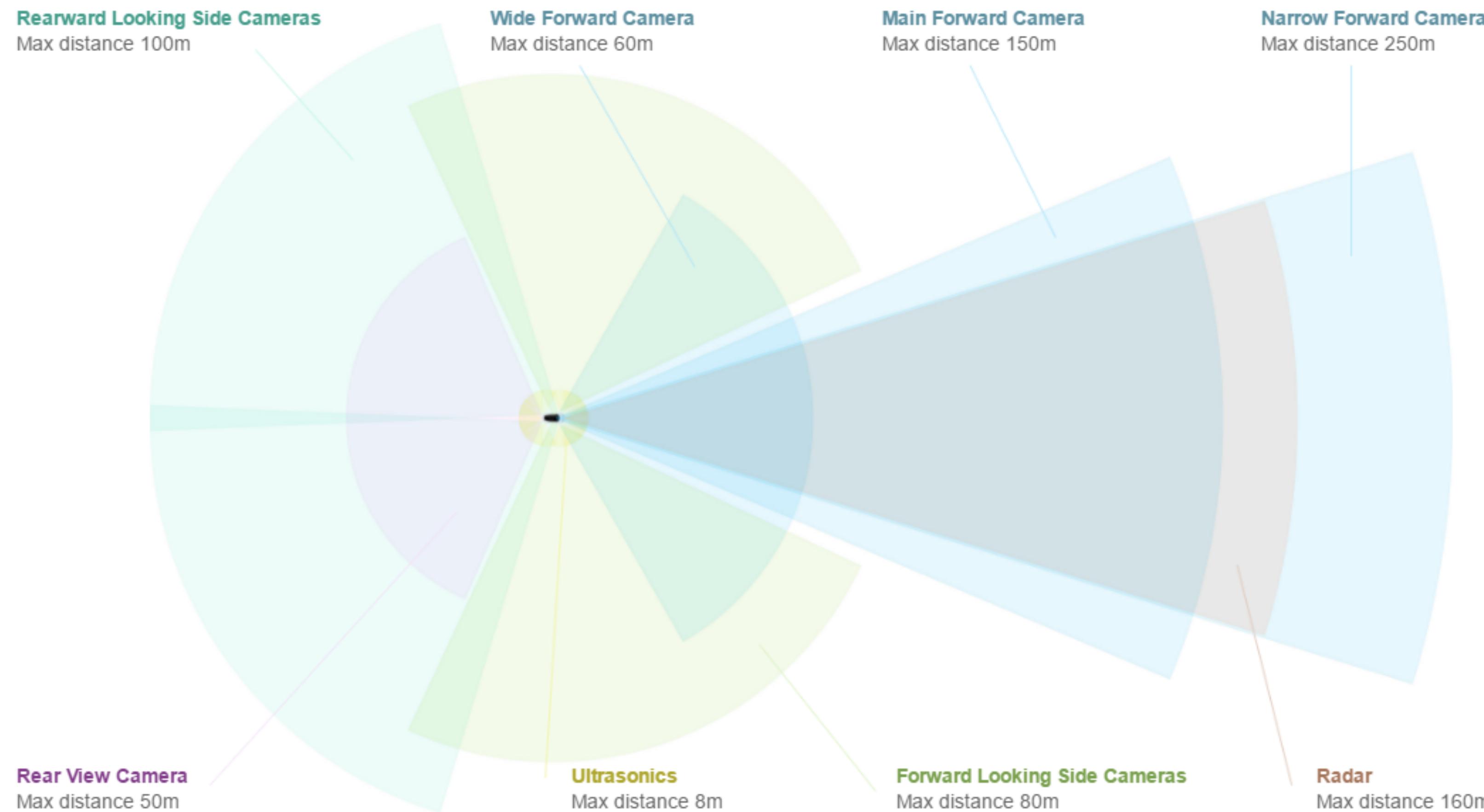
# Sensing Failures



GNSS and other external sensors can fail as a result of the environment, or weather.

# Sensors Measurement Ranges

2016 Tesla Model S Autopilot Sensors



Source: [electrek.co](http://electrek.co)

# Redundancy is Crucial | Obstacle avoidance (I)



2007 DARPA  
Urban Challenge

Team MIT and  
Cornell collide

[https://www.youtube.com/watch?v=HacG\\_FWWPOw](https://www.youtube.com/watch?v=HacG_FWWPOw)

# Redundancy is Crucial | Obstacle avoidance (II)



<https://www.youtube.com/watch?v=G6gz344tt6U>

# Redundancy is Crucial | Lane keeping



<https://www.youtube.com/watch?v=6QCF8tVqM3I>

# Summary | Loss of One or More Sensors

- Multiple sensors are crucial to robust localization in varied environments