Photogrammetry & Robotics Lab

# Short Introduction to SLAM
## (From a Photogrammetry Perspective)

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# 5 Minute Preparation for Today


https://www.ipb.uni-bonn.de/5min/

# What is SLAM?

- **Localize and map simultaneously**

- **Localization:** estimating the location and headings of the sensor/robot
- **Mapping:** building a map of the environment
- **SLAM:** building a map and localizing the robot simultaneously in that map

# Simultaneous Localization and Mapping for Mobile Robots

- A term from the **robotics** community
- Used to build maps that allow robots to **navigate** with
- **Sequences** and not sets of sensor measurements
- Use **whatever sensors** there are (cameras, RGBD, lidars, sonars, ...)
- Exploits locomotion constraints

# SLAM: Simultaneous Localization and Mapping

- **Simultaneously build a map** from a mobile platform and **localize** it in the map build so far
- **Arbitrary sensors**
- **Motion models**
- Different **environment representations**
- **Offline** vs. **online** operation

# Bundle Adjustment vs. SLAM

**BA**

- Observations are mainly images
- Sets of images
- Minimizes the reprojection error
- Map are 3D point locations (features)
- Least squares approach
- Mostly offline

**SLAM**

- All types of sensors
- Sequences, not sets
- Various error functions exists
- Maps: volumetric, landmarks, point clouds, ...
- Recursive Bayes f. or least squares
- Often online

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- clouds, ...
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**SLAM can be seen as a generalization of bundle adjustment**

# SLAM History

- 1985/86: Smith et al. and Durrant-Whyte describe geometric uncertainty and relationships between features or landmarks
- 1986: Discussions at ICRA on how to solve the SLAM problem followed by the key paper by Smith, Self and Cheeseman
- 1990-95: Kalman-filter based approaches
- 1995: SLAM acronym coined at ISRR’95
- 1995-1999: Convergence proofs & first demonstrations of real systems
- 2000: Wide interest in SLAM started

# SLAM History

- 1985/86: Smith et al. and Durrant-Whyte describe geometric uncertainty and relationships between features or landmarks

**Bundle adjustment developments started in the 1950ies in photogrammetry**

- 1995-1999: Convergence proofs & first demonstrations of real systems
- 2000: Wide interest in SLAM started

# In the 1950ies...

- Computers?
- Errors in computation?
- Digital cameras?
- Automatic image processing?
- ...

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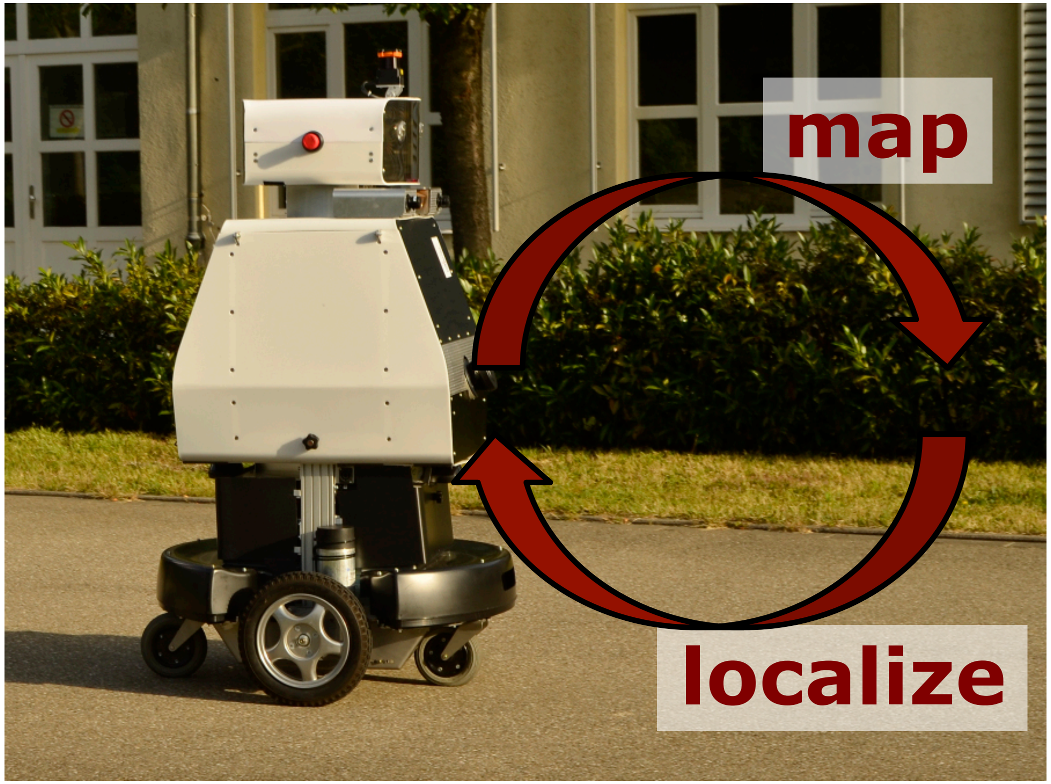
- …

**Keeping this in mind let's you appreciate the developments on bundle adjustment even more…**

# The SLAM Problem

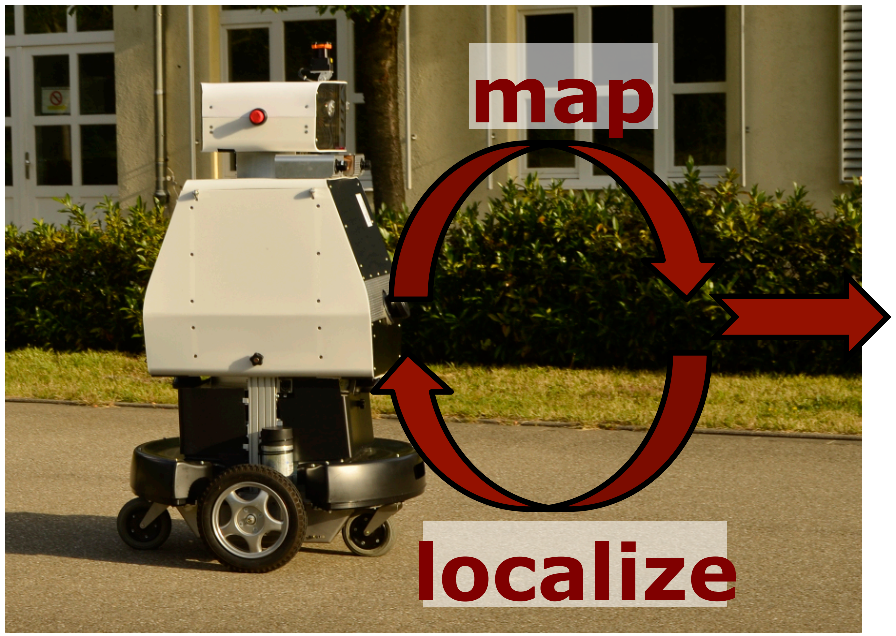
# SLAM Problem

- SLAM is a **chicken-or-egg** problem:
  - → a map is needed for localization and
  - → a pose estimate is needed for mapping



# SLAM is Relevant for Navigation

- It is considered a fundamental problem for truly autonomous robots
- Online SLAM is the basis for most autonomous navigation systems




**autonomous navigation**

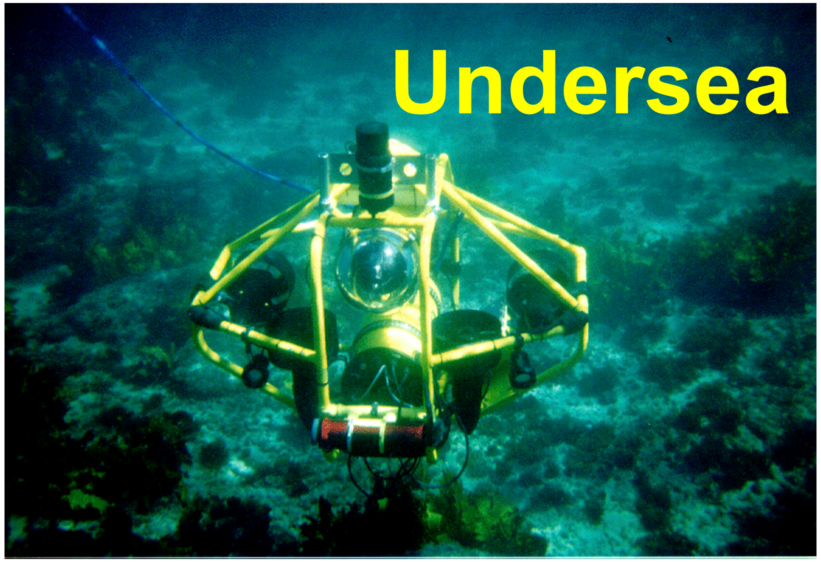
# SLAM Applications

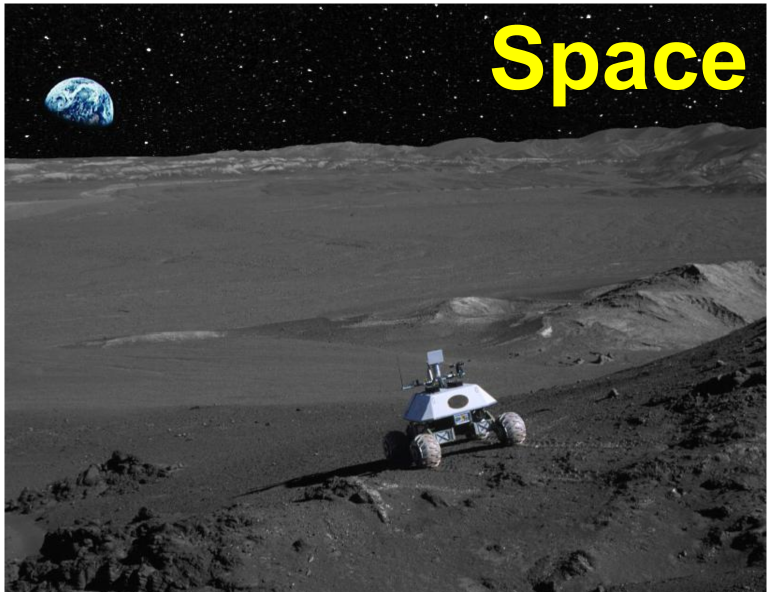
SLAM is central to a range of indoor, outdoor, air, and underwater applications – for both, manned and autonomous vehicles.

**Examples:**

- At home: vacuum cleaner, lawn mower
- Urban: autonomous cars
- Air: surveillance with unmanned air vehicles
- Underwater: reef monitoring
- Underground: exploration of mines
- Space: terrain mapping for localization

# SLAM Applications



Courtesy: Evolution Robotics, H. Durrant-Whyte, NASA, S. Thrun

# Definition of the SLAM Problem

## Given

- The executed controls

$$u_{1:T} = \{u_1, u_2, u_3, \ldots, u_T\}$$

- Observations

$$z_{1:T} = \{z_1, z_2, z_3, \ldots, z_T\}$$

## Wanted

- Map of the environment

$$m$$

- Path

$$x_{0:T} = \{x_0, x_1, x_2, \ldots, x_T\}$$

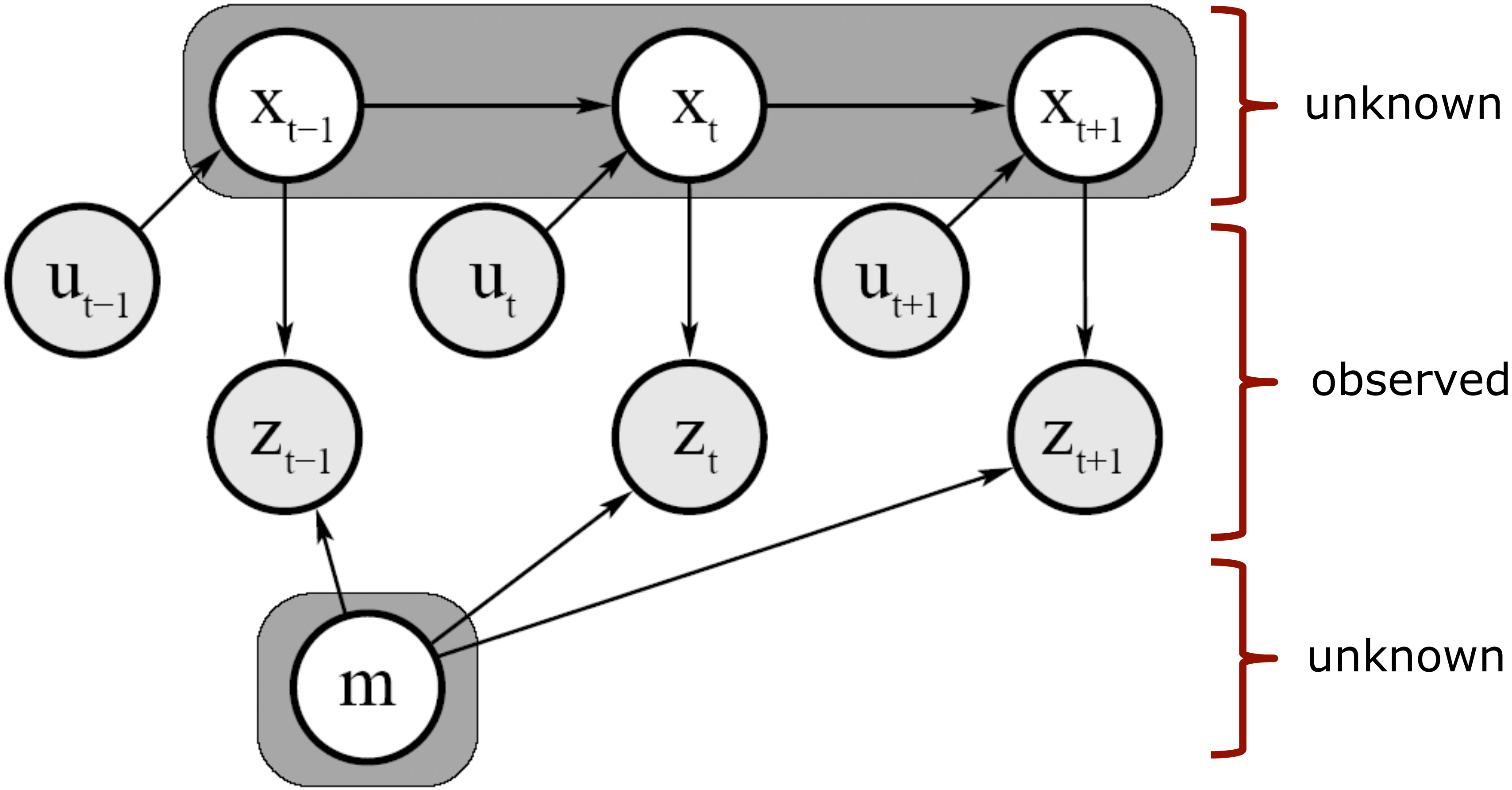
# Probabilistic Model

Estimate the path and the map

$$p(x_{0:T}, m \mid z_{1:T}, u_{1:T})$$

distribution path map given observations controls

# Graphical Model




$$p(x_{0:T}, m \mid z_{1:T}, u_{1:T})$$

Courtesy: Thrun, Burgard, Fox

# Full SLAM vs. Online SLAM

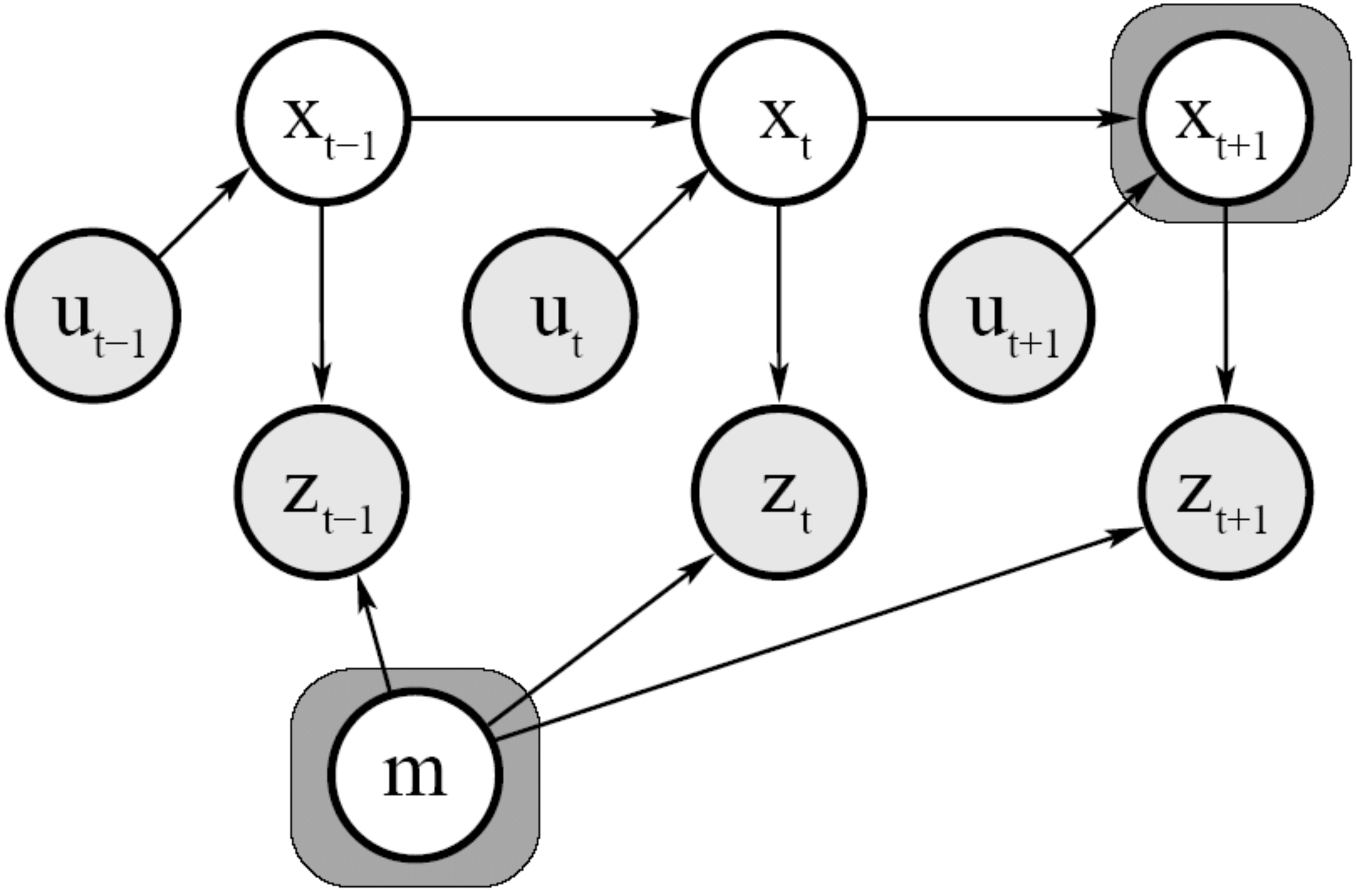
- Full SLAM estimates the entire path

$$p(x_{0:T}, m \mid z_{1:T}, u_{1:T})$$

- Online SLAM seeks to recover only the most recent pose

$$p(x_t, m \mid z_{1:t}, u_{1:t})$$

# Graphical Model of Online SLAM




$$p(x_{t+1}, m \mid z_{1:t+1}, u_{1:t+1})$$

Courtesy: Thrun, Burgard, Fox

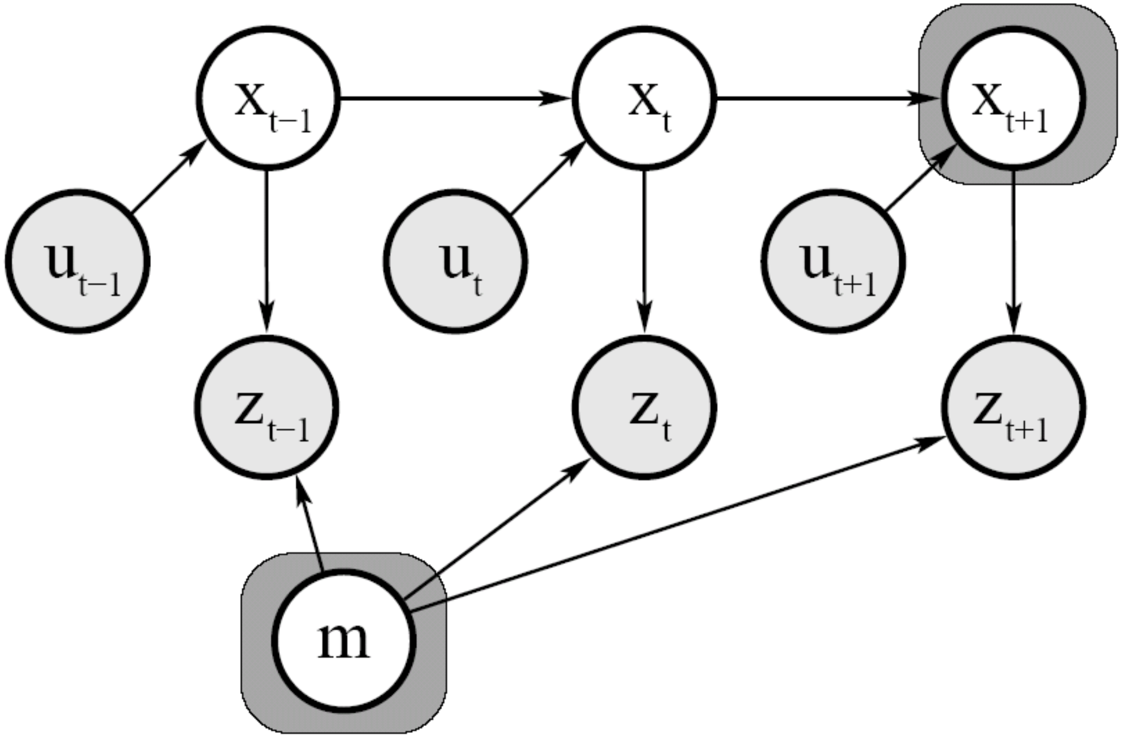
# Online SLAM

- Online SLAM means marginalizing out the previous poses

$$p(x_t, m \mid z_{1:t}, u_{1:t}) = \int \ldots \int p(x_{0:t}, m \mid z_{1:t}, u_{1:t}) \, dx_{t-1} \, \ldots \, dx_0$$

- Integrals are typically solved recursively, one at at time

# Graphical Model of Online SLAM

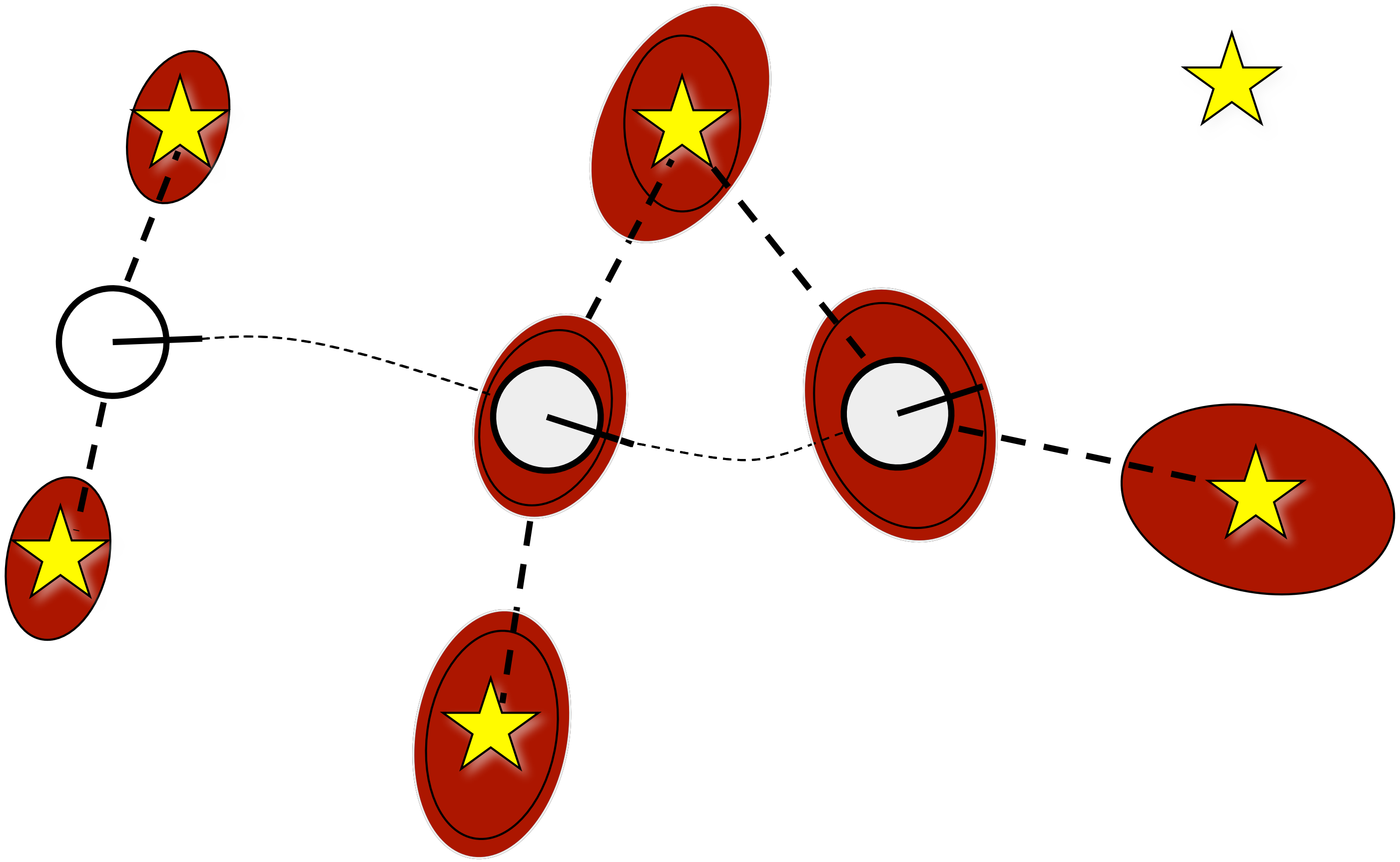



$$p(x_{t+1}, m \mid z_{1:t+1}, u_{1:t+1}) =$$
$$\int \ldots \int p(x_{0:t+1}, m \mid z_{1:t+1}, u_{1:t+1}) \, dx_t \ldots dx_0$$

Courtesy: Thrun, Burgard, Fox

# Why is SLAM a Hard Problem?

1. Robot path and map are both **unknown**

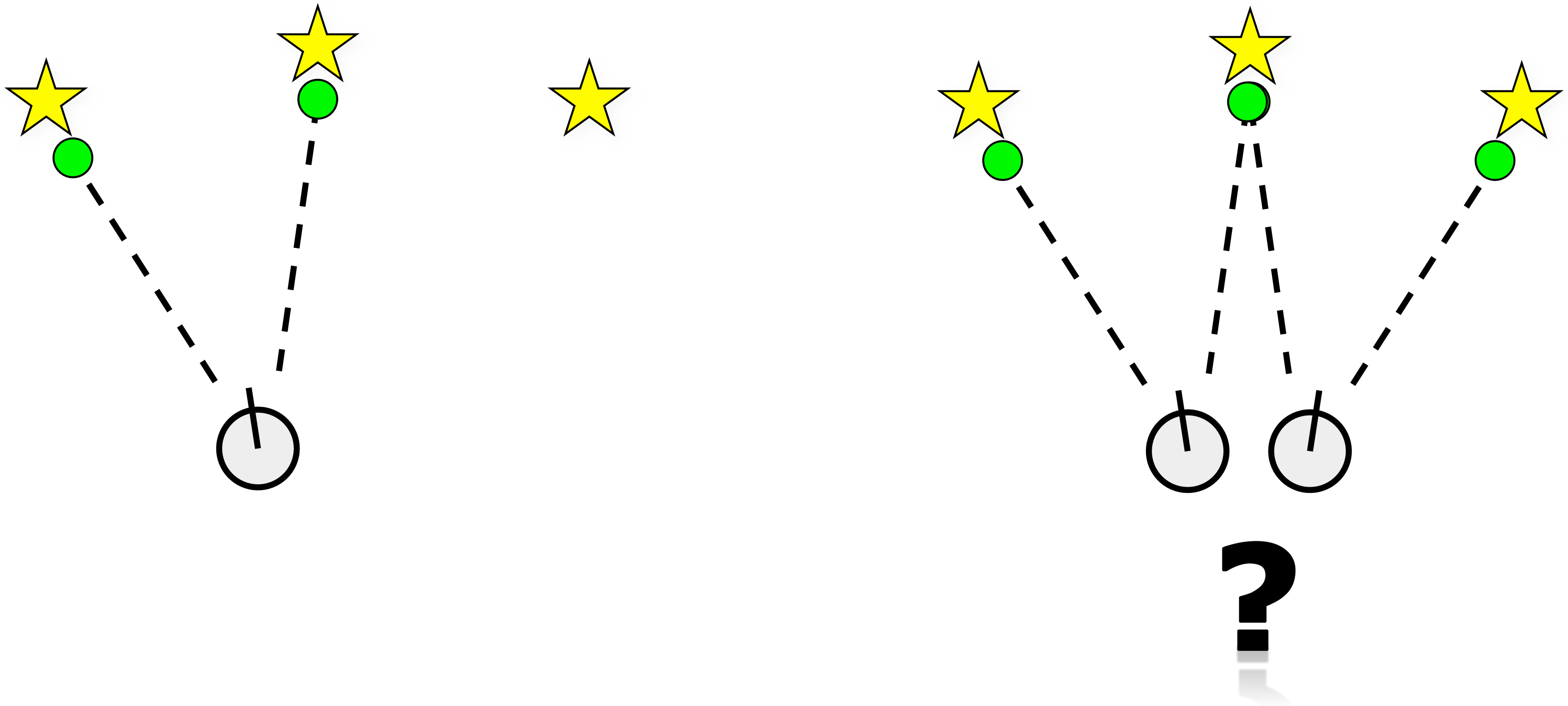


2. Map and pose estimates correlated

Courtesy: M. Montemerlo

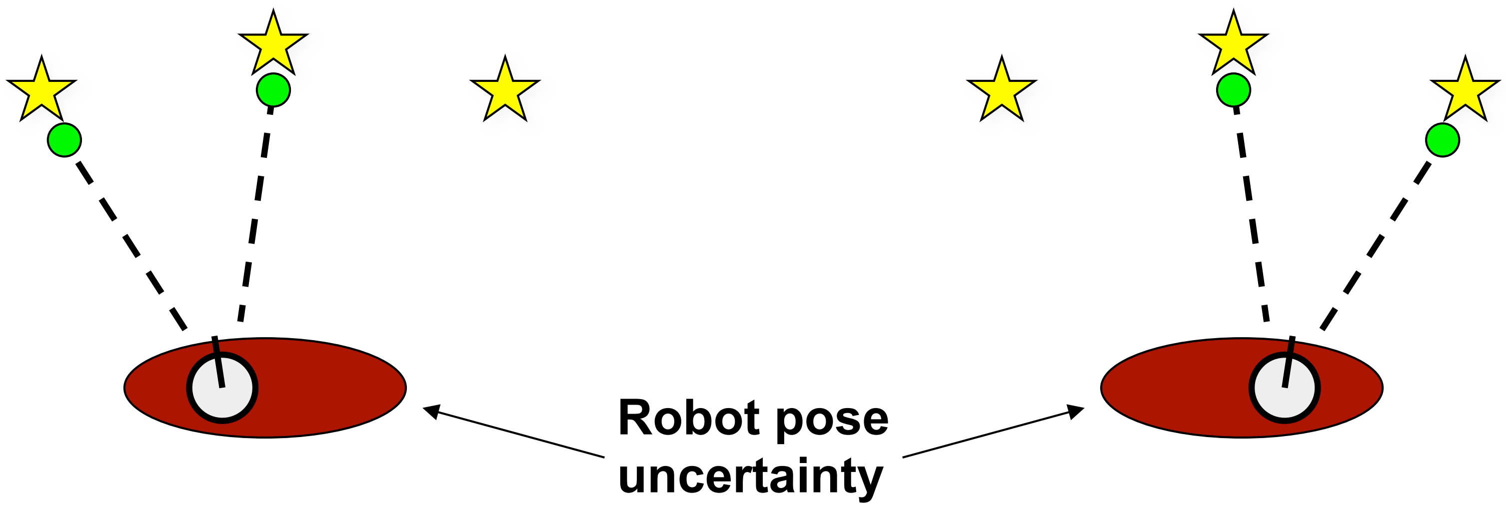
# Why is SLAM a Hard Problem?

Known vs. **unknown** correspondence



# Data Association Problem

- **Mapping between observations** and the **map is unknown**
- Picking **wrong** data associations can have **catastrophic** consequences

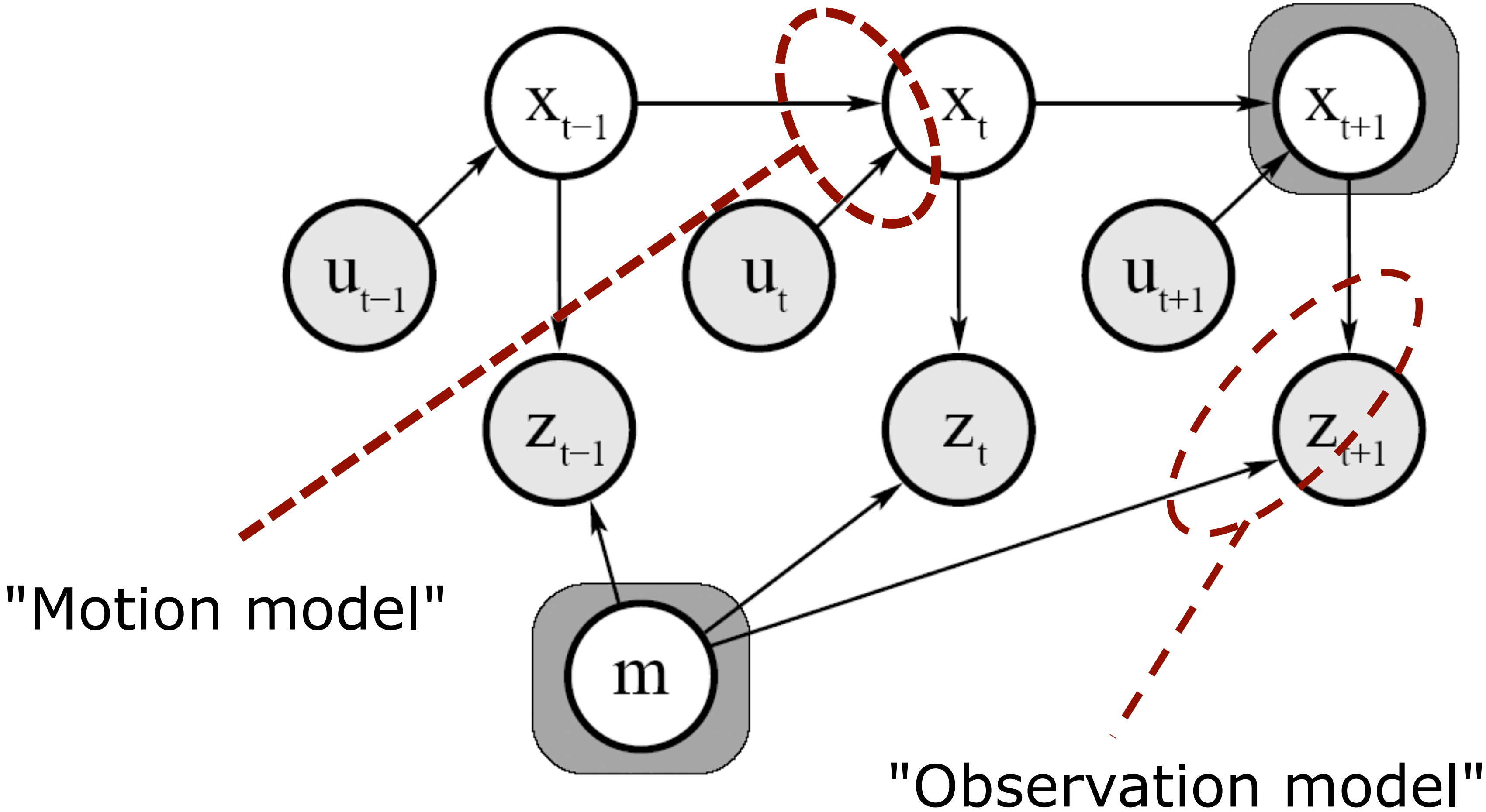



Courtesy: M. Montemerlo

# Three Traditional Paradigms

| Kalman filter | Particle filter | Least squares |
|---|---|---|
| EKF SLAM | | Graph-SLAM, BA, ... |

# Motion and Observation Model



# Motion Model

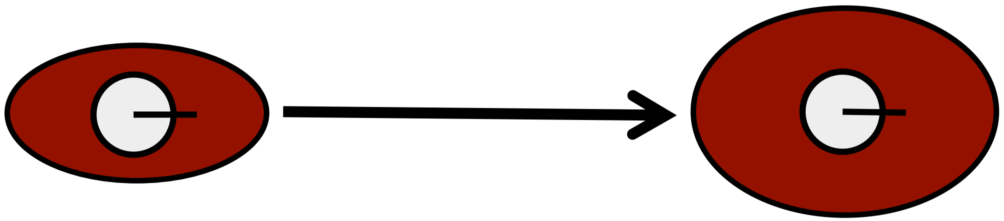
- The motion model describes the relative motion of the robot

$$p(x_t \mid x_{t-1}, u_t)$$

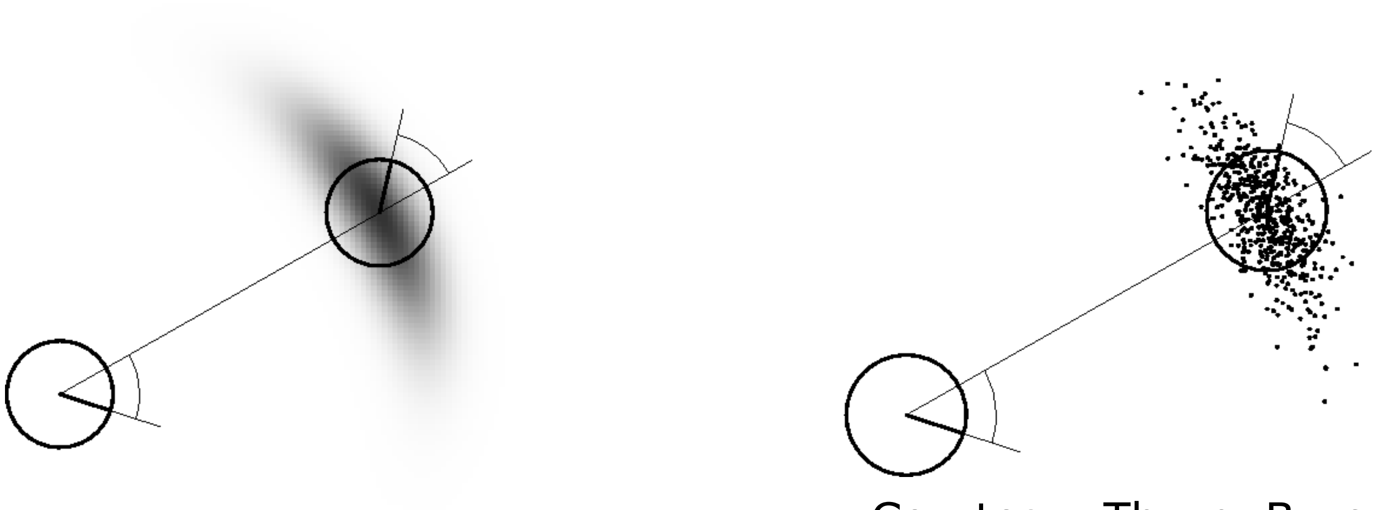
distribution new pose given old pose control

# Motion Model Examples

- Gaussian model



- Non-Gaussian model



Courtesy: Thrun, Burgard, Fox

# Observation Model

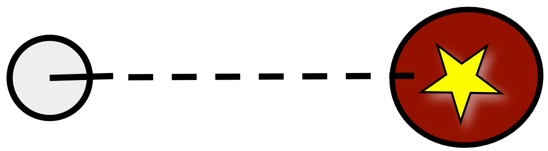
- The observation or sensor model relates measurements with the robot's pose

$$p(z_t \mid x_t)$$

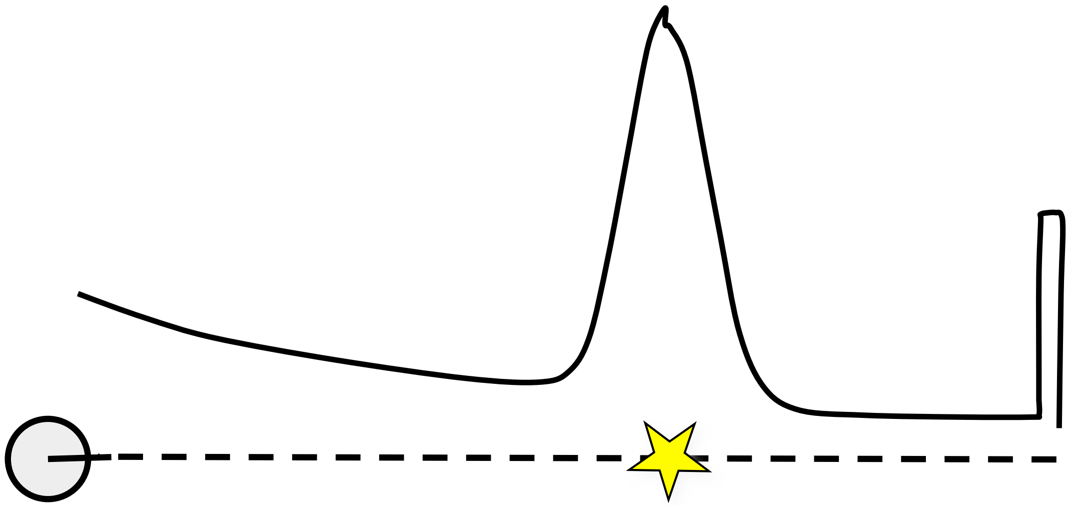
distribution observation given pose

# Observation Model Examples

- Gaussian model



- Non-Gaussian model



# Summary

- Mapping is the task of modeling the environment
- Localization means estimating the robot’s pose
- SLAM = simultaneous localization and mapping
- Full SLAM vs. Online SLAM
- Bundle adjustment = Full SLAM using a camera minimizing the reprojection error of features and no motion model

# Reading Material

## General SLAM Overview

Springer "Handbook on Robotics", Chapter on Simultaneous Localization and Mapping, subsection 1 & 2 (see E-Campus)