Lecture 22: Introduction to Optimization

Computer Graphics
CMU 15-462/15-662
Last time: physically-based animation

- Use dynamics to drive motion
- Complexity from simple models
- Technique: numerical integration
  - formulate equations of motion
  - take little steps forward in time
  - general, powerful tool
- Today: numerical optimization
  - another general, powerful tool
  - basic idea: “ski downhill” to get a better solution
  - used everywhere in graphics (not just animation)
  - image processing, geometry, rendering, ...
What is an optimization problem?

- Natural human desire: find the best solution among all possibilities (subject to certain constraints)
- E.g., cheapest flight, shortest route, tastiest restaurant ...
- Has been studied since antiquity, e.g., isoperimetric problem:

“The first optimization problem known in history was practically solved by Dido, a clever Phoenician princess, who left her Tyrian home and emigrated to North Africa, with all her property and a large retinue, because her brother Pygmalion murdered her rich uncle and husband Acerbas, and plotted to defraud her of the money which he left. On landing in a bay about the middle of the north coast of Africa she obtained a grant from Hiarbas, the native chief of the district, of as much land as she could enclose with an ox-hide. She cut the ox-hide into an exceedingly long strip, and succeeded in enclosing between it and the sea a very valuable territory on which she build Carthage.”

—Lord Kelvin, 1893

“Obvious” solution is a circle...

...but wait, what about the coastline?
Optimization in Graphics

Sumit Jain, Yuting Ye, and C. Karen Liu, “Optimization-based Interactive Motion Synthesis”
Optimization in Graphics

Niloy J. Mitra, Leonidas Guibas, Mark Pauly, “Symmetrization”
Moritz Bächer, Emily Whiting, Bernd Bickel, Olga Sorkine-Hornung,
“Spin-It: Optimizing Moment of Inertia for Spinnable Objects”
Optimization in Graphics

Nobuyuki Umetani, Yuki Koyama, Ryan Schmidt & Takeo Igarashi,
“Pteromys: Interactive Design and Optimization of Free-formed Free-flight Model Airplanes”
Continuous vs. Discrete Optimization

■ DISCRETE:
  - domain is a discrete set (e.g., finite or integers)
  - Example: best vegetable to put in a stew
    - Basic strategy? Try them all! (exponential)
    - sometimes clever strategy (e.g., MST)
    - more often, NP-hard (e.g., TSP)

■ CONTINUOUS:
  - domain is not discrete (e.g., real numbers)
  - Example: best temperature to cook an egg
  - still many (NP-)hard problems, but also large classes of “easy” problems (e.g., convex)
Optimization Problem in Standard Form

- Can formulate most continuous optimization problems this way:

  - "objective": how much does solution $x$ cost?
  - "constraints": what must be true about $x$? ("$x$ is feasible")

  $$\min_{x \in \mathbb{R}^n} f_0(x)$$
  subject to
  $$f_i(x) \leq b_i, \quad i = 1, \ldots, m$$

  ($f_i : \mathbb{R}^n \to \mathbb{R}, \ i = 0, \ldots, m$)

- Optimal solution $x^*$ has smallest value of $f_0$ among all feasible $x$

- Q: What if we want to maximize something instead?
  - A: Just flip the sign of the objective!

- Q: What if we want equality constraints, rather than inequalities?
  - A: Include two constraints: $g(x) \leq c$ and $g(x) \leq -c$
Local vs. Global Minima

- *Global* minimum is absolute best among all possibilities
- *Local* minimum is best “among immediate neighbors”

Philosophical question: does a local minimum “solve” the problem? Depends on the problem! (E.g., real protein folding is *local* minimum)

Other times, local minima can be really bad (e.g., path planning)
Q: Is this an optimization problem in standard form?  
A: Yes.

Q: Where is the optimal solution?  
A: There are two, (0,1), (0,-1).
Existence & Uniqueness of Minimizers

- Already saw that (global) minimizer is not unique.
- Does it always exist? Why?
- Just consider all possibilities and take the smallest one, right?

\[ f_0(x) \]

WRONG! Not all objectives are bounded from below.

It’s like that old adage: “no matter how good you are, there will always be someone better than you.”
Feasibility

- Ok, but suppose the objective is bounded from below.
- Then we can just take the best feasible solution, right?

value of objective doesn’t depend on $x$; all feasible solutions are equally good

$$\min_{x \in \mathbb{R}^n} \begin{cases} 0 \\ f_i(x) \leq b_i, \ i = 1, \ldots, m \end{cases}$$

- Not if there aren’t any!

- Every system of equations is an optimization problem.
- But not all problems have solutions!
- (You’ll appreciate this more as you get older.)
Q: Is this problem feasible?

A: No—the two sublevel sets (points where $f_i(x) \leq 0$) have no common points, i.e., they do not overlap.

\[
\begin{align*}
\min_{x \in \mathbb{R}^2} & \quad \sin(x_1) + x_2^2 \\
\text{s.t.} & \quad (x_1 - 2)^2 + x_2^2 \leq 1, \\
& \quad x_1 \leq -1
\end{align*}
\]
Existence & Uniqueness of Minimizers, cont.

- Even being bounded from below is not enough:

\[ f(x) \]

\[
\min_{x \in \mathbb{R}} e^{-x}
\]

- No matter how big \( x \) is, we never achieve the lower bound (0)

- So when does a solution exist? Two sufficient conditions:
  - Extreme value theorem: continuous objective & compact domain
  - Coercivity: objective goes to \( +\infty \) as we travel (far) in any direction
Characterization of Minimizers

- Ok, so we have some sense of when a minimizer might exist
- But how do we know a given point $x$ is a minimizer?

- Checking if a point is a global minimizer is (generally) hard
- But we can certainly test if a point is a local minimum (ideas?)
- (Note: a global minimum is also a local minimum!)
Characterization of Local Minima

- Consider an objective $f_0: \mathbb{R} \rightarrow \mathbb{R}$. How do you find a minimum?
- (Hint: you may have memorized this formula in high school!)

Find points where

$$f'_0(x^*) = 0$$

...but what about this point?

- Also need to check second derivative (how?)
- Make sure it’s positive
- Ok, but what does this all mean for more general functions $f_0$?

- must also satisfy

$$f''_0(x^*) \geq 0$$
In general, our objective is $f_0 : \mathbb{R}^n \to \mathbb{R}$.

How do we test for a local minimum?

1st derivative becomes gradient; 2nd derivative becomes Hessian.

\[ \nabla f := \begin{bmatrix} \frac{\partial f}{\partial x_1} \\ \vdots \\ \frac{\partial f}{\partial x_n} \end{bmatrix} \]

\[ \nabla^2 f := \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial f}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \frac{\partial^2 f}{\partial x_n \partial x_2} & \cdots & \frac{\partial f}{\partial x_n^2} \end{bmatrix} \]

GRADIENT (measures “slope”)

HESSIAN (measures “curvature”)

Optimality conditions?

\[ \nabla f_0(x^*) = 0 \]

1st order

\[ \nabla^2 f_0(x^*) \succeq 0 \]

2nd order

positive semidefinite (PSD) \((u^T A u \geq 0 \text{ for all } u)\)
Optimality Conditions (Constrained)

- What if we have constraints?
- Is gradient at minimizer still zero?
- Is Hessian at minimizer still PSD?
- Not necessarily! (See example above)

- In general, any (local or global) minimizer must at least satisfy the *Karush–Kuhn–Tucker (KKT)* conditions:

\[
\exists \lambda_i \text{ s.t. } \nabla f_0(x^*) = -\sum_{i=1}^{n} \lambda_i \nabla f_i(x^*) \quad \text{stationarity}
\]

\[
f_i(x^*) \leq 0, \; i = 1, \ldots, n \quad \text{primal feasibility}
\]

\[
\lambda_i \geq 0, \; i = 1, \ldots, n \quad \text{dual feasibility}
\]

\[
\lambda_i f_i(x^*) = 0, \; i = 1, \ldots, n \quad \text{complementary slackness}
\]

- ...we won’t work with these in this class! (But good to know where to look.)
Convex Optimization

- Special class of problems that are almost always “easy” to solve (polynomial-time!)
- Problem convex if it has a convex domain and convex objective

Why care about convex problems in graphics?
- can make guarantees about solution (always the best)
- doesn’t depend on initialization (strong convexity)
- often quite efficient, but not always
Convex Quadratic Objectives & Linear Systems

- Very important example: convex quadratic objective
- Already saw this with, e.g., quadric error simplification
- Valuable “variational” way of looking at many common equations
- Can be expressed via positive-semidefinite (PSD) matrix:
  \[ f_0(x) = \frac{1}{2} x^T A x - x^T b, \quad A \succeq 0 \]

- Q: 1st-order optimality condition? \[ A x = b \]
  just solve a linear system!

- Q: 2nd-order optimality condition? \[ A \succeq 0 \]
  satisfied by definition

- positive definite
- positive semidefinite
- indefinite
Sadly, life is not usually that easy. How do we solve optimization problems in general?
Descent Methods

An idea as old as the hills:
Gradient Descent (1D)

- Basic idea: follow the gradient “downhill” until it’s zero
- (Zero gradient was our 1st-order optimality condition)

\[ \frac{d}{dt} x(t) = -f'_0(x(t)) \]

- Do we always end up at a (global) minimum?
- How do we compute gradient descent in practice?
Gradient Descent Algorithm (1D)

- Did you notice that gradient descent equation is an ODE?

- Q: How do we solve it numerically?
  \[ \frac{d}{dt} x(t) = -f'_0(x(t)) \]

- One way: forward Euler:
  \[ x_{k+1} = x_k + \tau f'_0(x_k) \]

- Q: How do we pick the time step?

- If we’re not careful, we’ll go zipping all over the place; won’t make any progress.

- Basic idea: use “step control” to determine step size based on value of objective & derivatives.

- A careful strategy (e.g., Armijo-Wolfe) can guarantee convergence at least to a local minimum.

- For now we will do something simpler: make \( \tau \) really small!
Gradient Descent Algorithm (nD)

- Q: How do we write gradient descent equation in general?
  \[
  \frac{d}{dt}x(t) = -\nabla f_0(x(t))
  \]

- Q: What’s the corresponding discrete update?
  \[
  x_{k+1} = x_k - \tau \nabla f_0(x_k)
  \]

- Basic challenge in nD:
  - solution can “oscillate”
  - takes many, many small steps
  - very slow to converge
Higher Order Descent

- General idea: apply a coordinate transformation so that the local energy landscape looks more like a “round bowl”
- Gradient now points directly toward nearby minimizer
- Most basic strategy: Newton’s method:

\[ x_{k+1} = x_k - \tau (\nabla^2 f_0(x_k))^{-1} \nabla f_0(x_k) \]

- Great for convex problems (even proofs about # of steps!)
- For nonconvex problems, need to be more careful
- In general, nonconvex optimization is a **BLACK ART**
- Meta-strategy: try lots of solvers, see what works!
  - quasi-Newton, trust region, L-BFGS, ...
Example: Inverse Kinematics

Example 12: IK-driven robot claw
Forward Kinematics

- Many systems well-described by a *kinematic chain*
  - collection of rigid bodies, connected by joints
  - joints have various behaviors (ball, piston, ...)
  - also have constraints (e.g., range of angles)
  - hierarchical structure (body $\rightarrow$ leg $\rightarrow$ foot)
- In animation, often called a *rig*
- How do we specify the configuration of a “rig”? 
  - One way: artist sets each joint individually
  - Another way: ...optimization!
Simple Kinematic Chain

- Consider a simple path-like chain in 2D
- Q: How do we write \( p_1 \) in terms of the root position \( p_0 \), angles, \& vectors \( u := c_{i+1} - c_i \)?

\[
p_1 = p_0 + \begin{bmatrix} \cos \theta_0 & \sin \theta_0 \\ -\sin \theta_0 & \cos \theta_0 \end{bmatrix} u_0
\]

- (For brevity, can use complex numbers:)

\[
p_1 = p_0 + e^{i\theta_0} u_0
\]

- Q: How about \( p_2 \)?

\[
p_2 = p_0 + e^{i\theta_0} u_0 + e^{i\theta_0} e^{i\theta_1} u_1
\]
Simple IK Algorithm

- Basic idea behind our IK algorithm:
  - write down distance between final point and “target”
  - compute gradient with respect to angles
  - apply gradient descent

- Objective?

\[ f_0(\theta) = \frac{1}{2} |\tilde{p}_n - p_n|^2 \]

- Constraints?
  - None! The joint angle can take any value.
  - Though we could limit joint angles (for instance)
Coming up next: PDEs in Computer Graphics

Frank Losasso, Jerry O. Talton, Nipun Kwatra, and Ron Fedkiw, “Two-Way Coupled SPH and Particle Level Set Fluid Simulation”