High-order Solution Transfer between Curved Meshes and Ill-conditioned Bézier Curve Intersection

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Outline

1. Introduction and motivation
2. Curved Elements
3. Solution Transfer
4. Ill-conditioned Bézier Curve Intersection
5. Compensated Evaluation
6. Modified Newton's for Intersection

Introduction and motivation

Method of Characteristics

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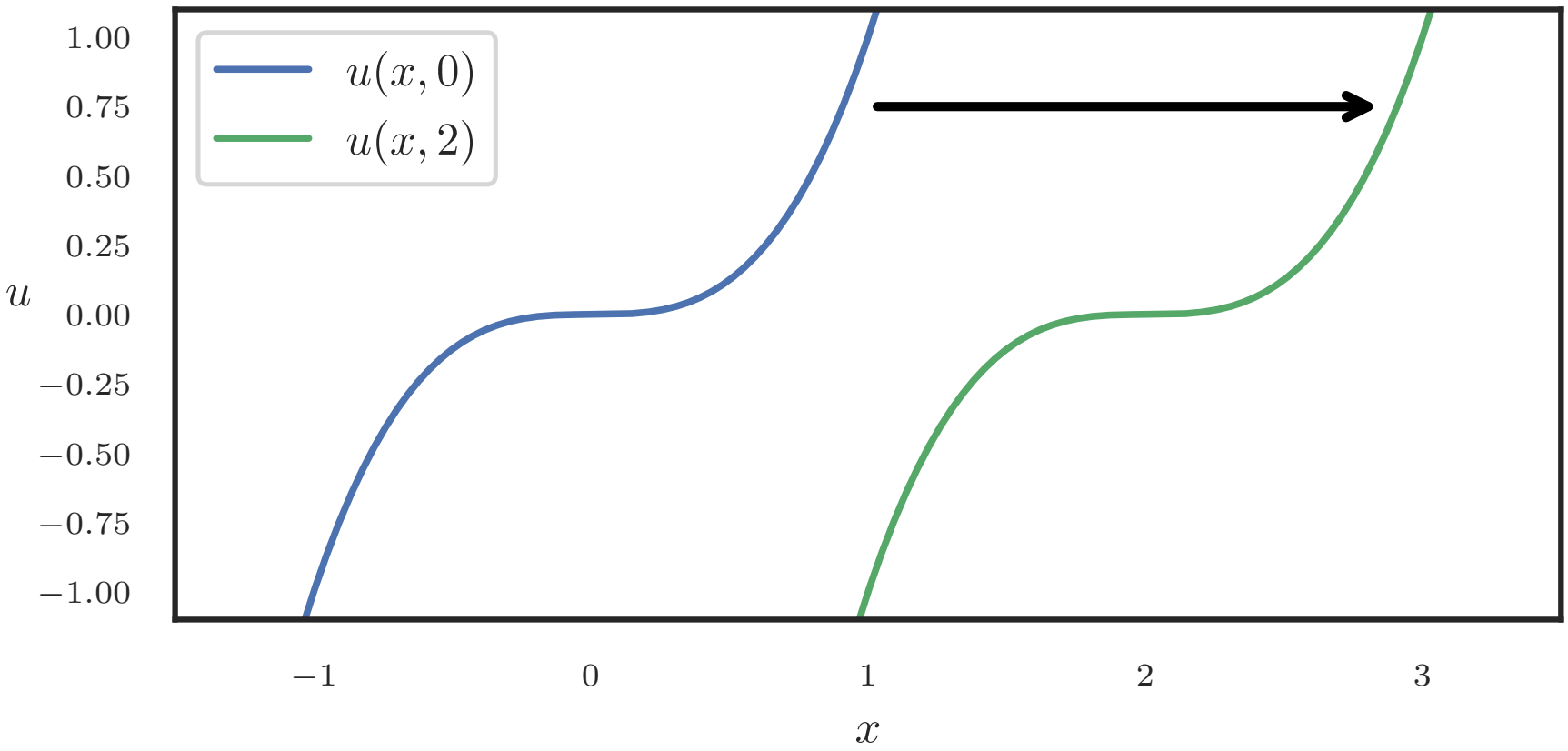
PDE becomes a (trivial) ODE

$$\frac{d}{dt} u(x(t), t) = 0.$$

Method of Characteristics



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- Transform PDE to family of ODEs

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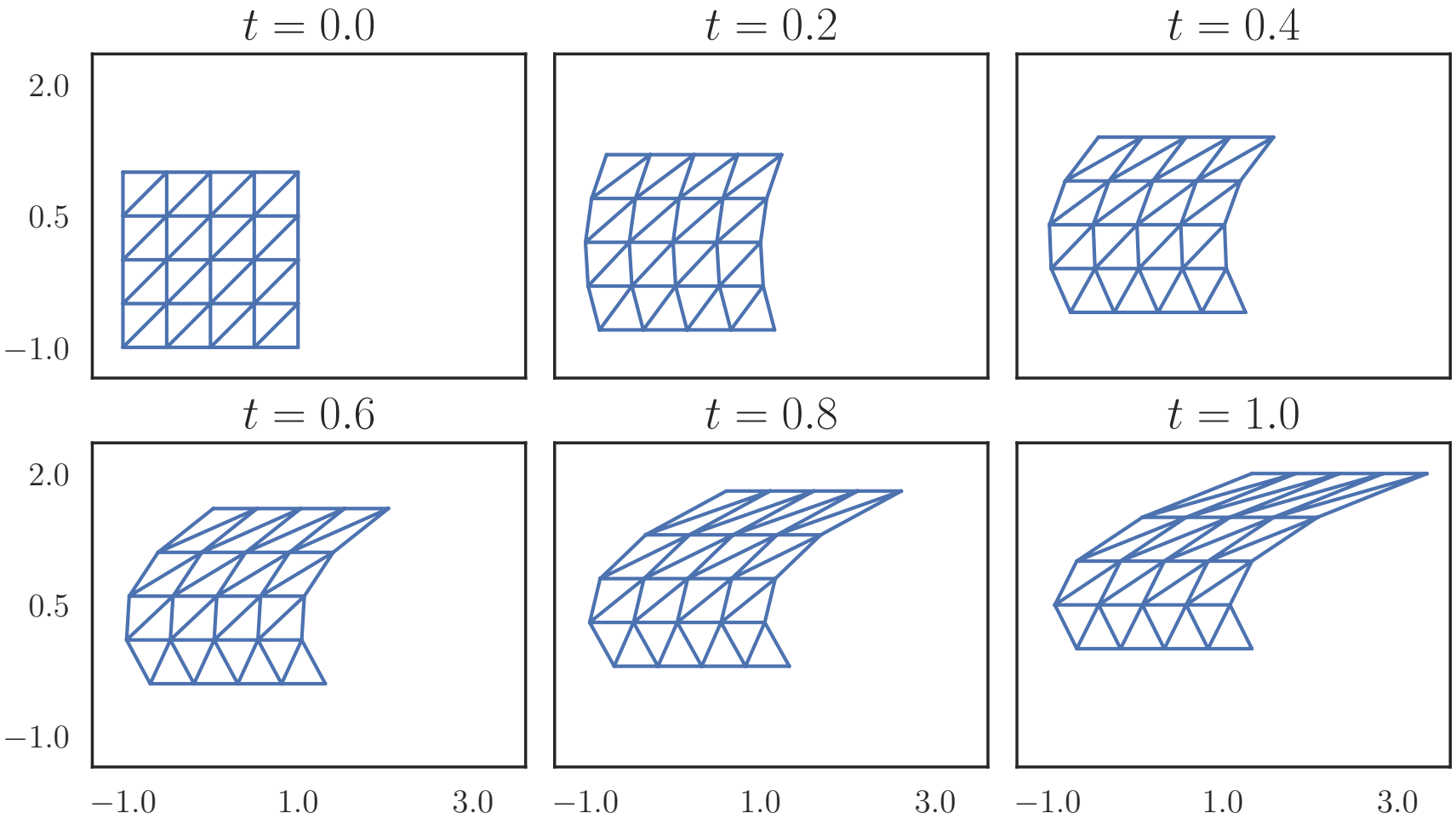
with cubic characteristics

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \frac{1}{3} \begin{bmatrix} (y_0 + t)^3 - y_0^3 \\ 3t \end{bmatrix}.$$

Remeshing Example



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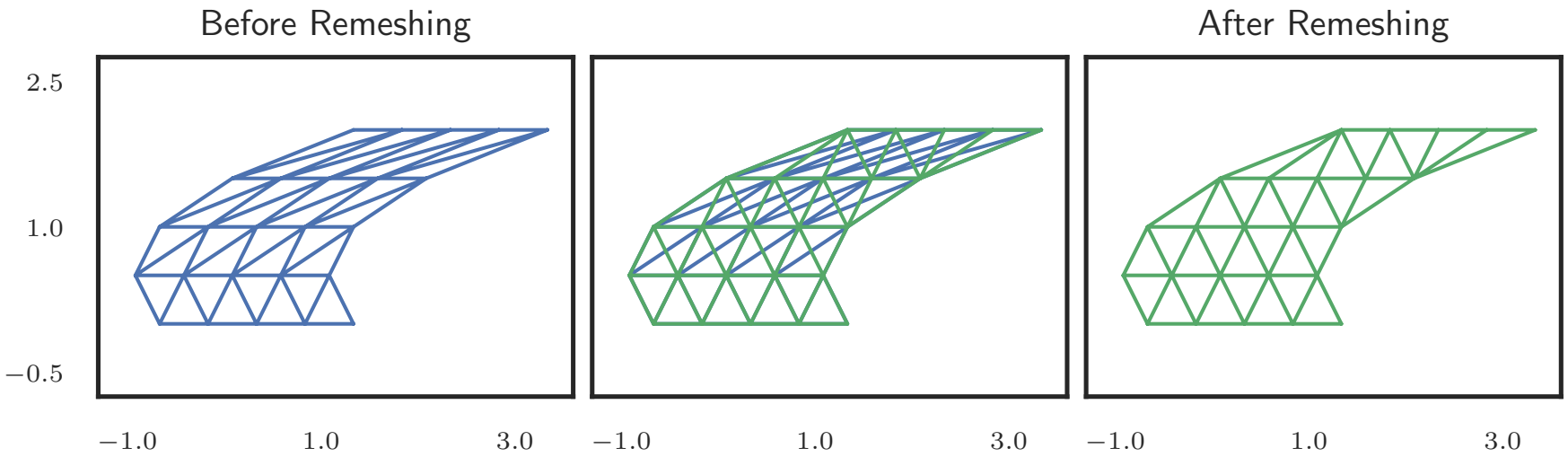

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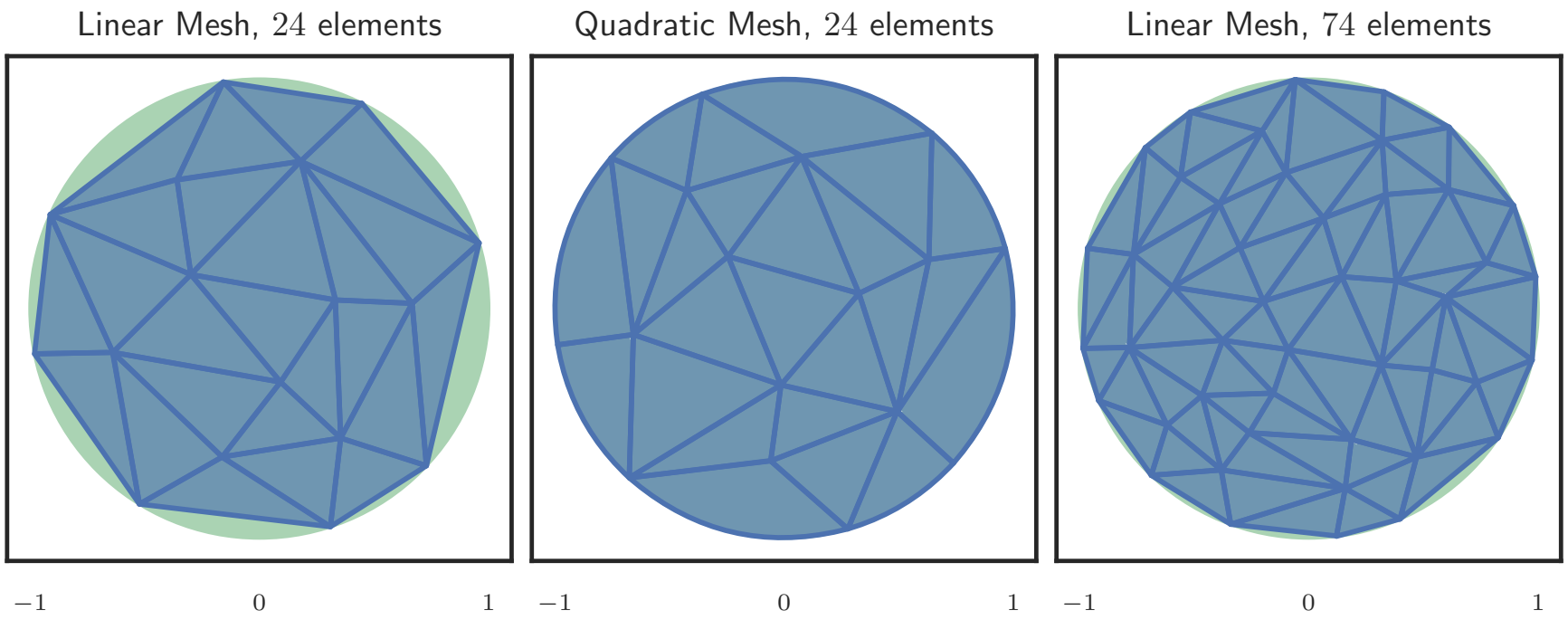

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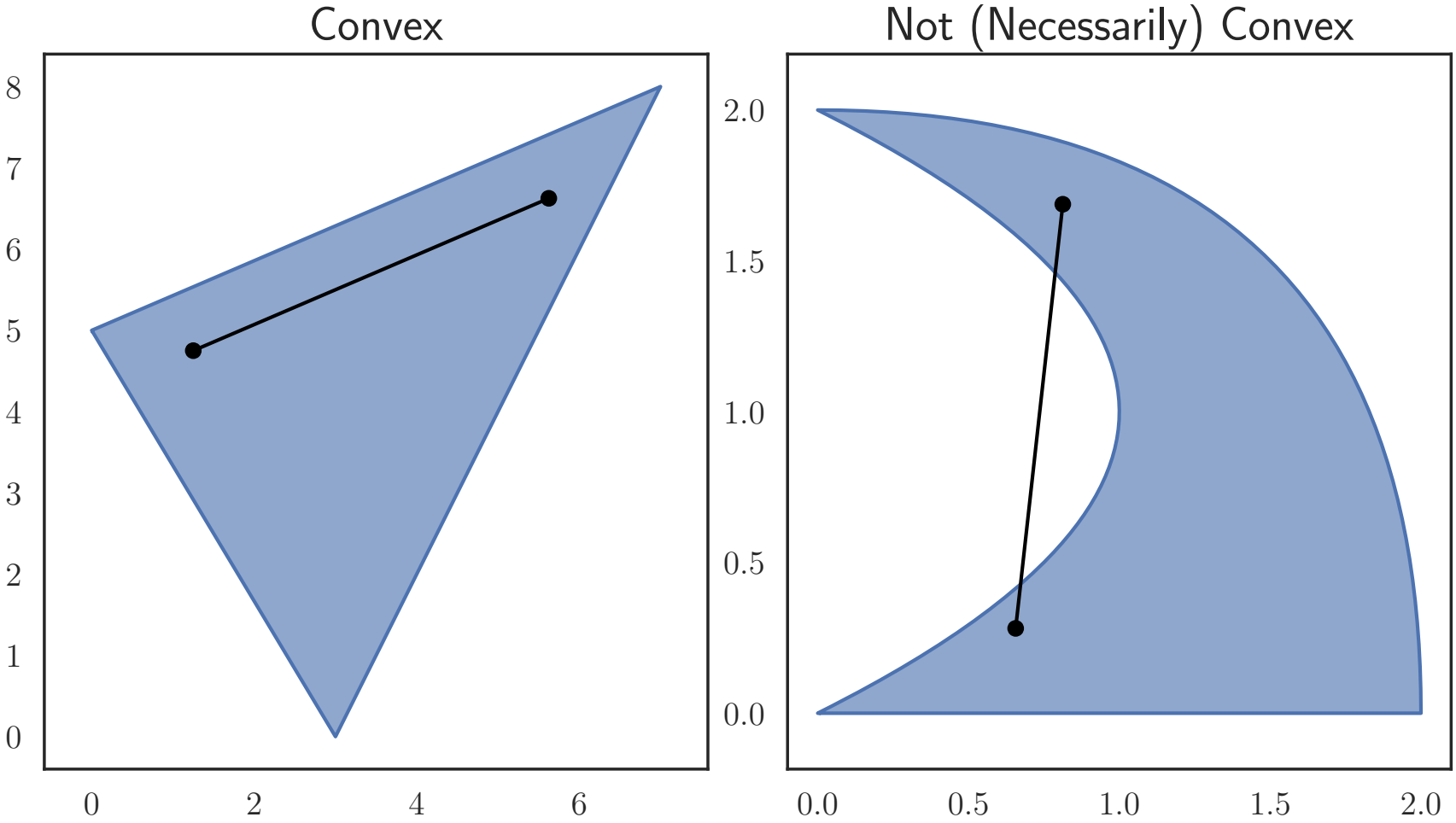
Curved Meshes



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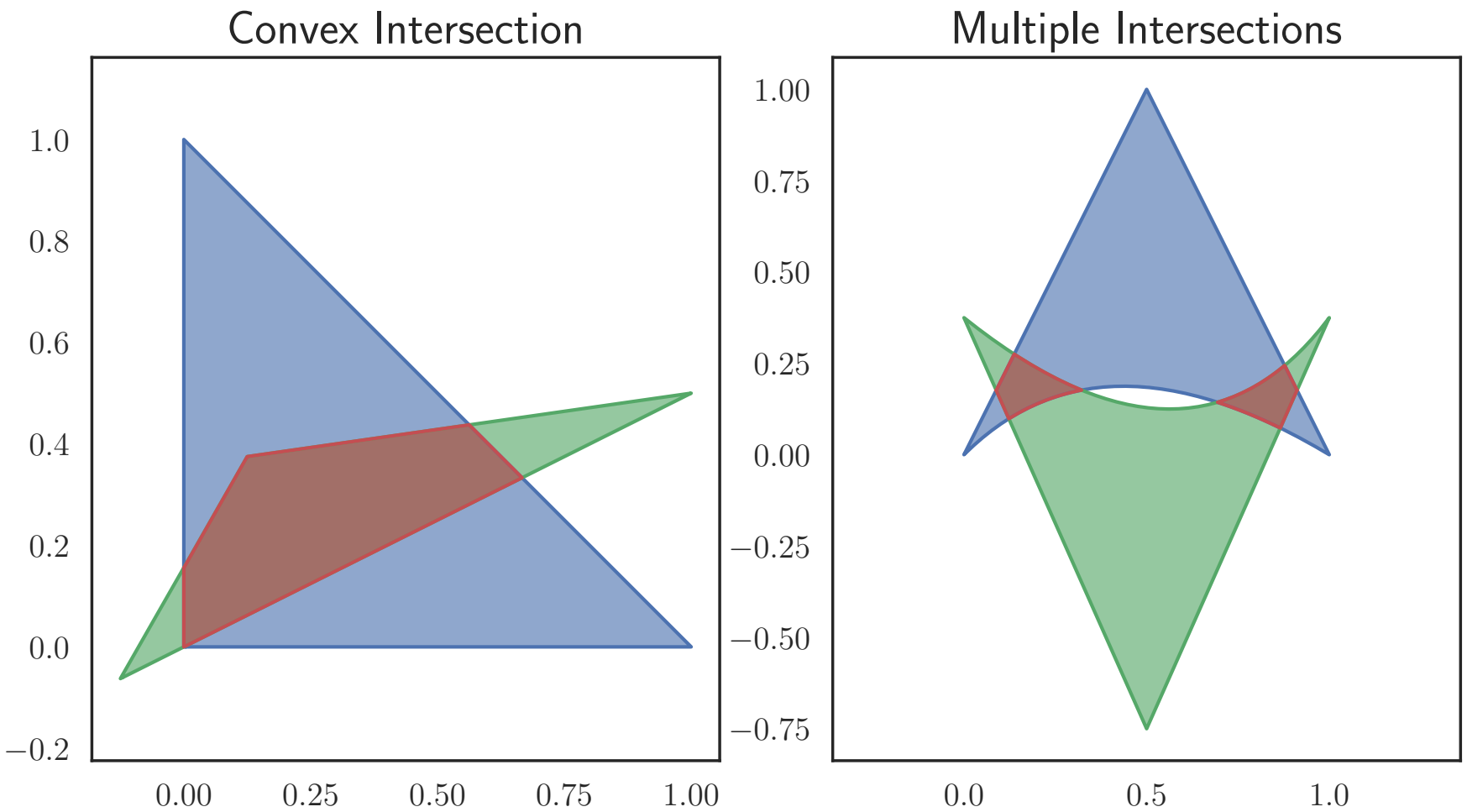

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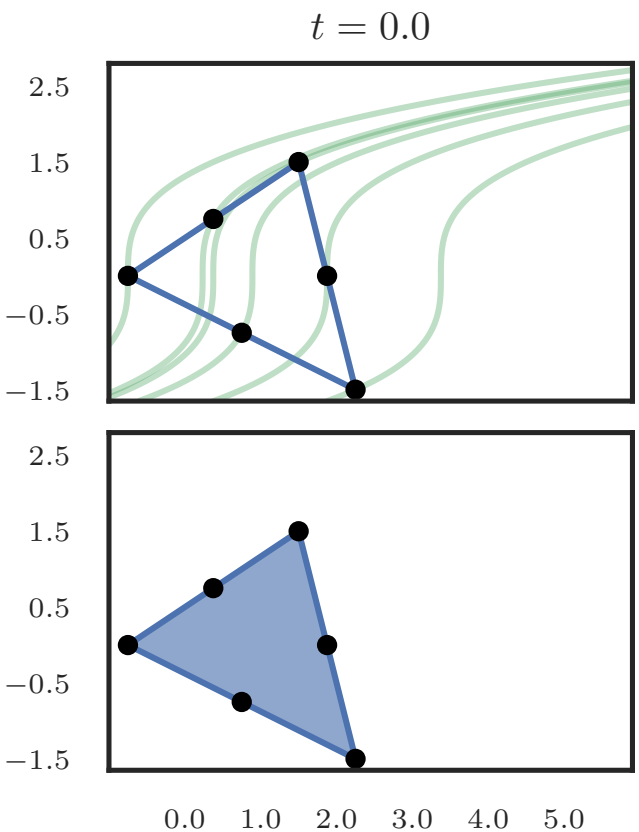
- Lagrangian method must either curve mesh or information about flow of geometry will be lost

Curved Elements: Necessary for High-order



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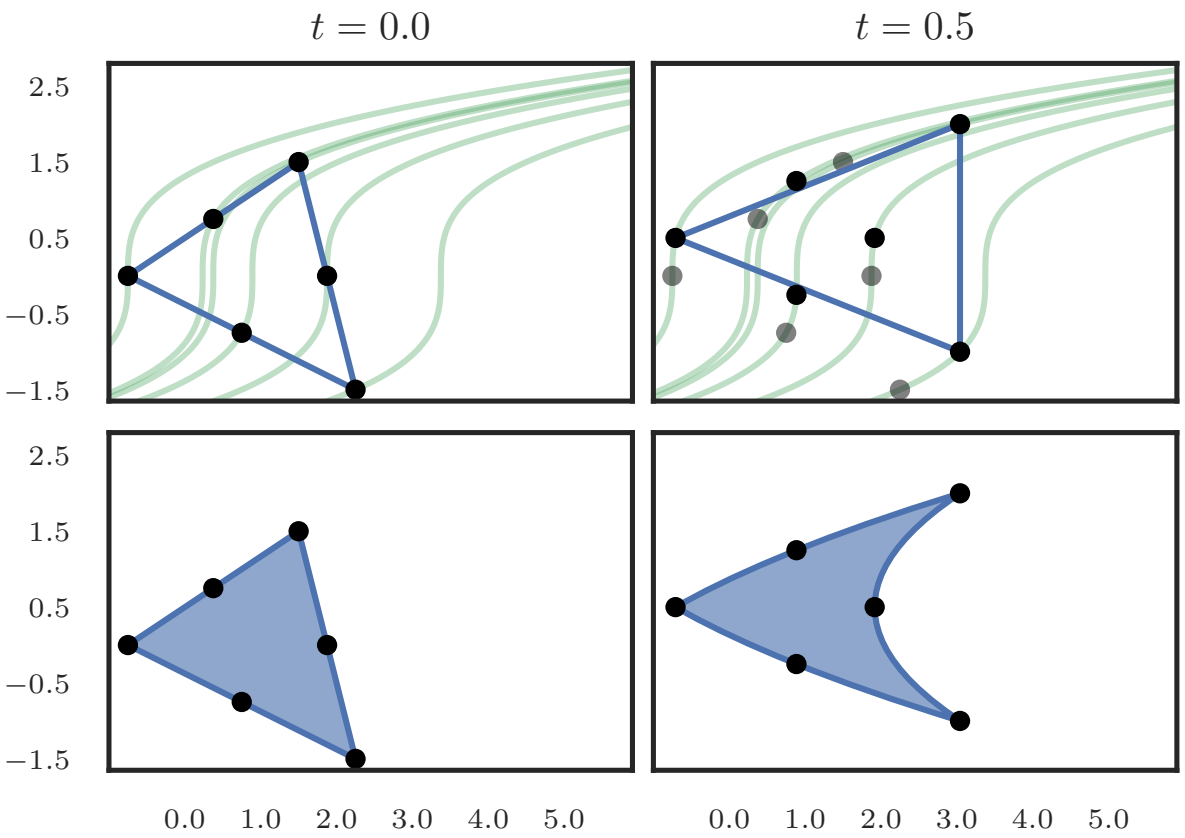

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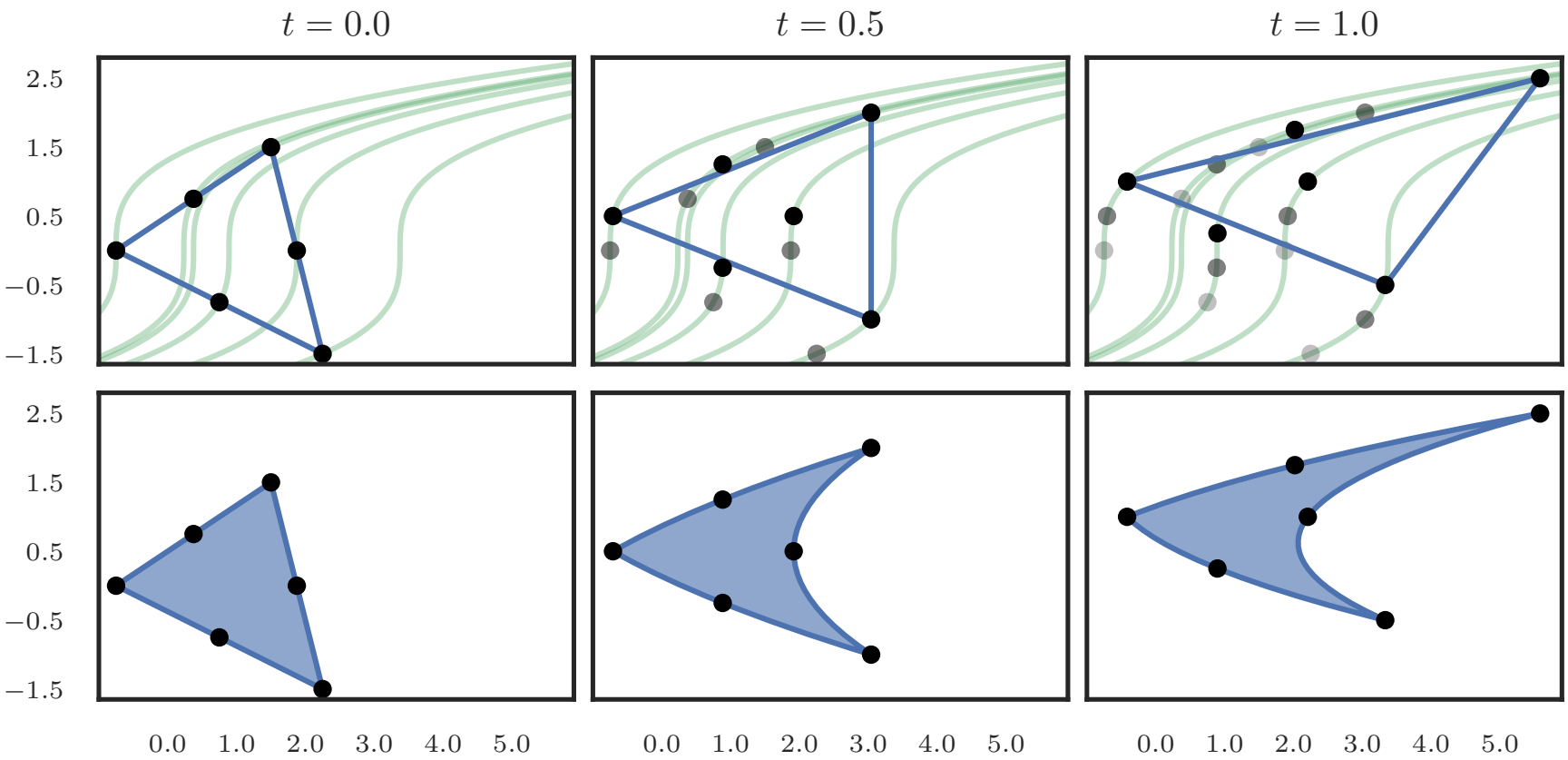

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- Convex combination of control points

$$b(s, t) = \sum_{\substack{i+j+k=n \\ i,j,k \geq 0}} \binom{n}{i, j, k} \lambda_1^i \lambda_2^j \lambda_3^k \, \boldsymbol{p}_{i,j,k}$$

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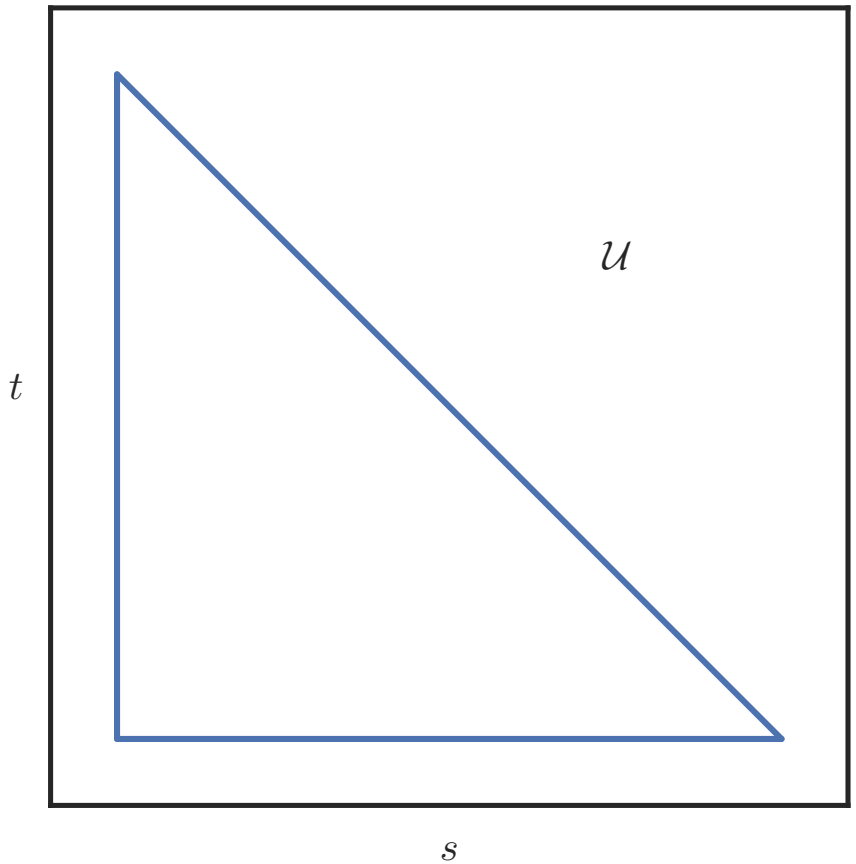

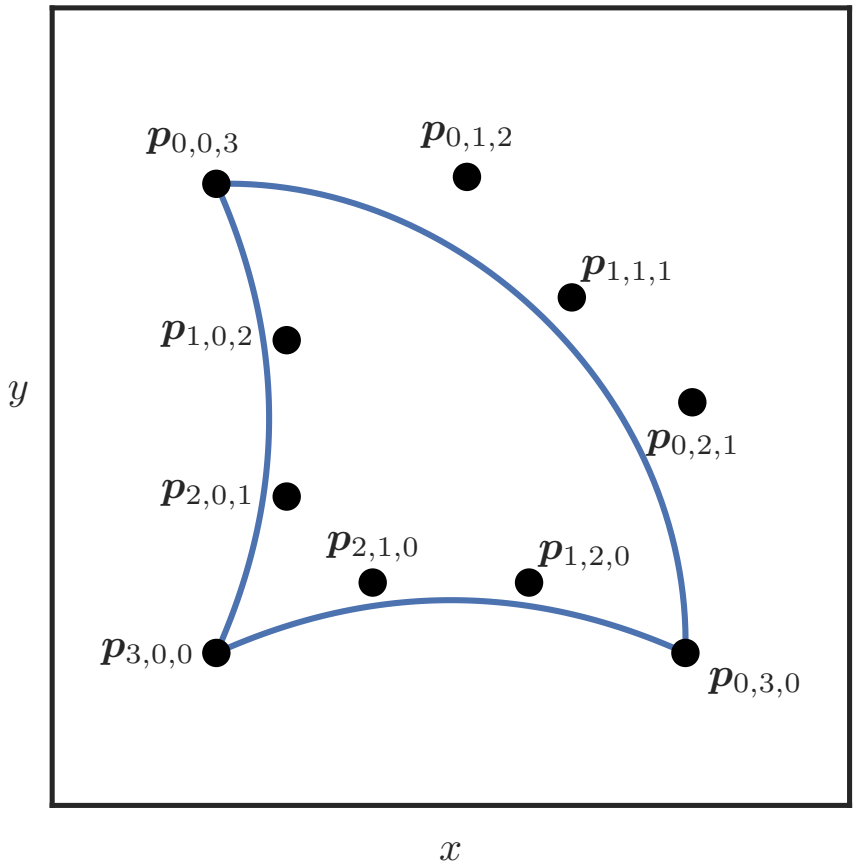

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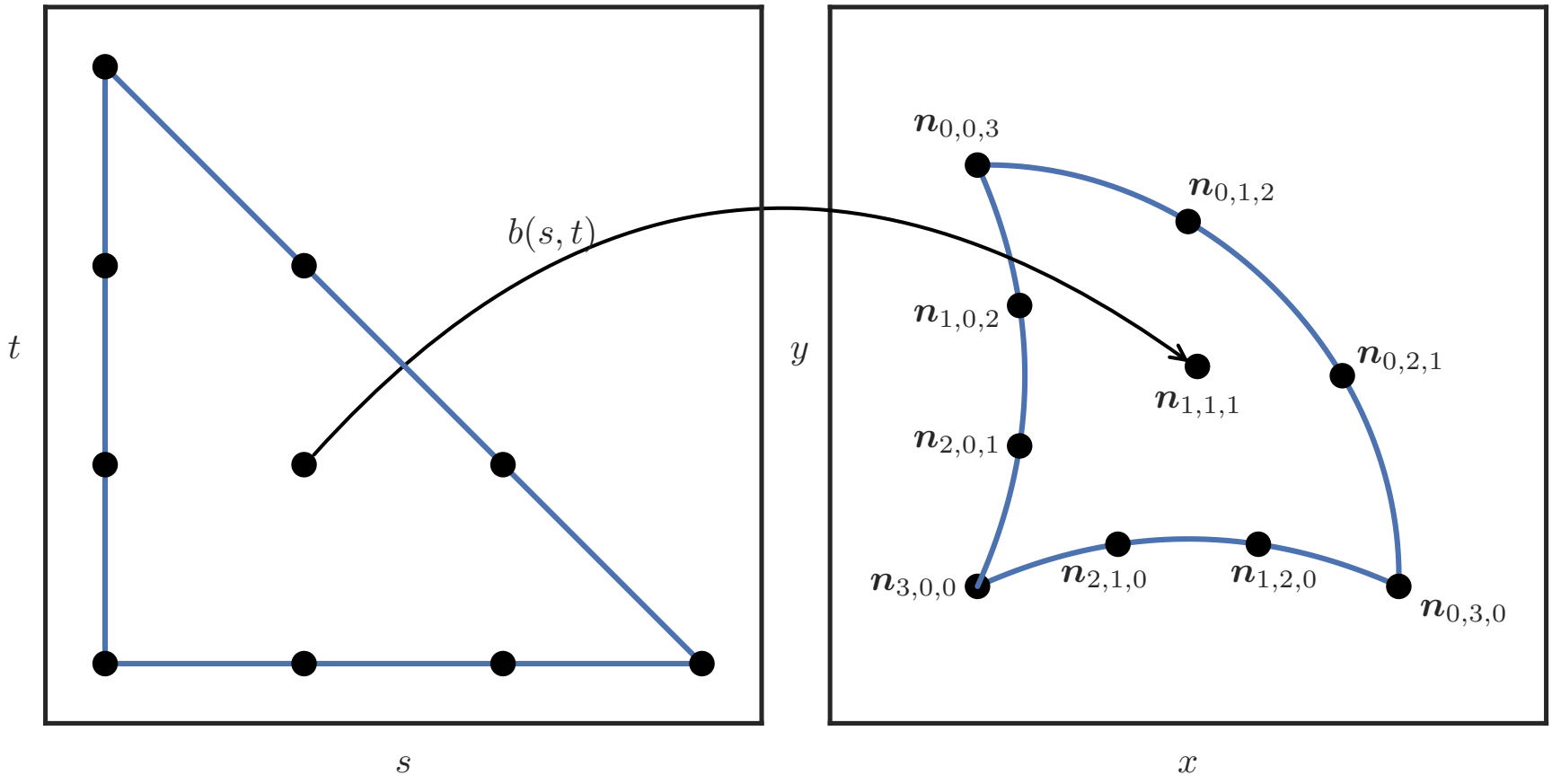

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- Conversion between $\boldsymbol{n}_{i,j,k}$ and $\boldsymbol{p}_{i,j,k}$ has condition number exponential in n

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- $\det(Db)$ positive, preserves orientation

Inverted Element

Consider element given by map

$$b(s,t) = \lambda_1^2 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \lambda_2^2 \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \lambda_3^2 \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

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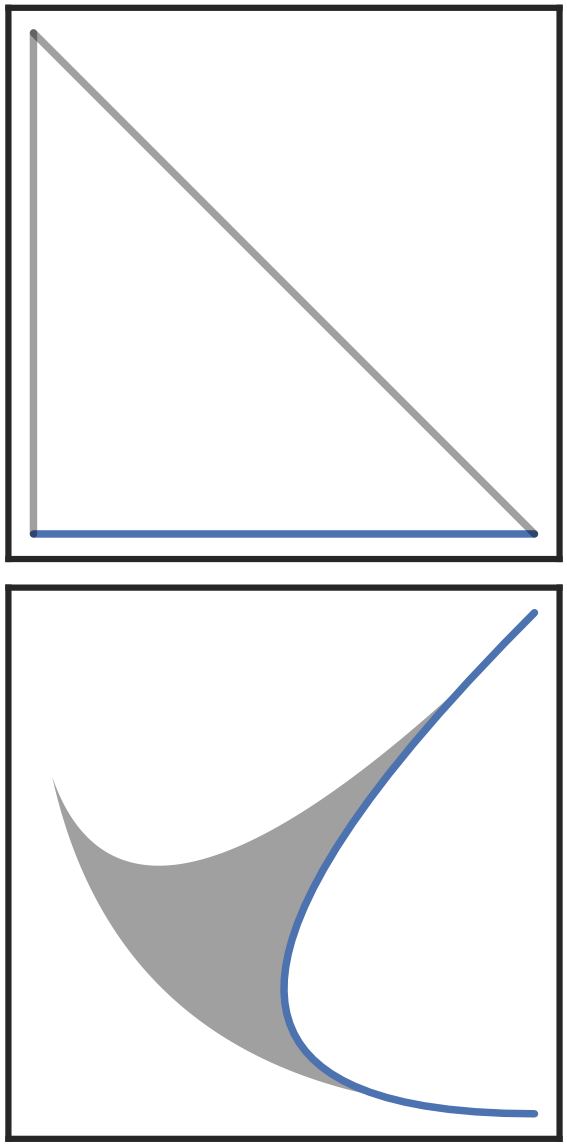

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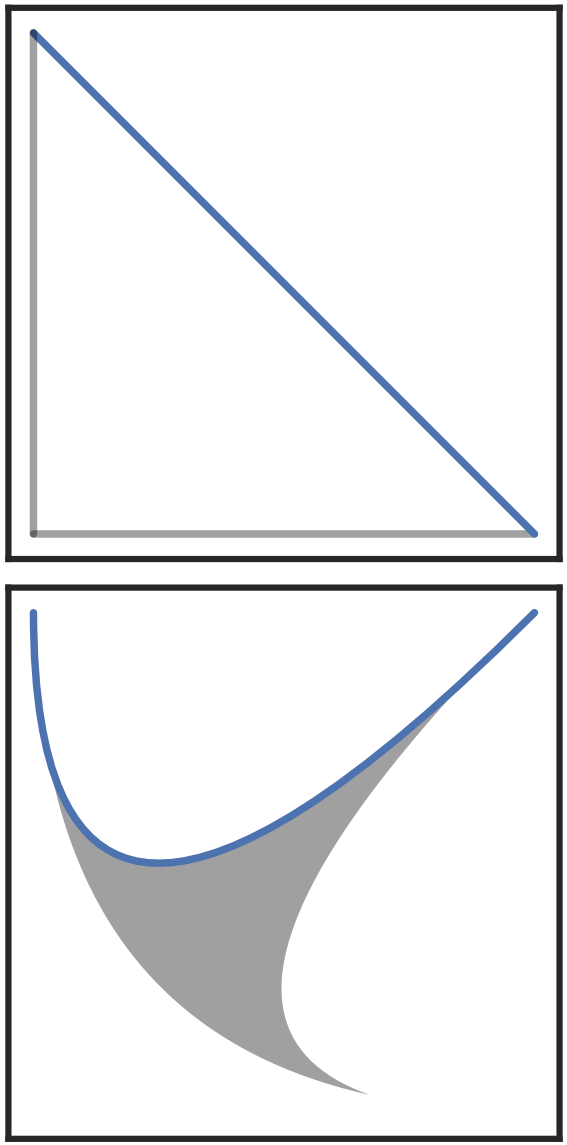

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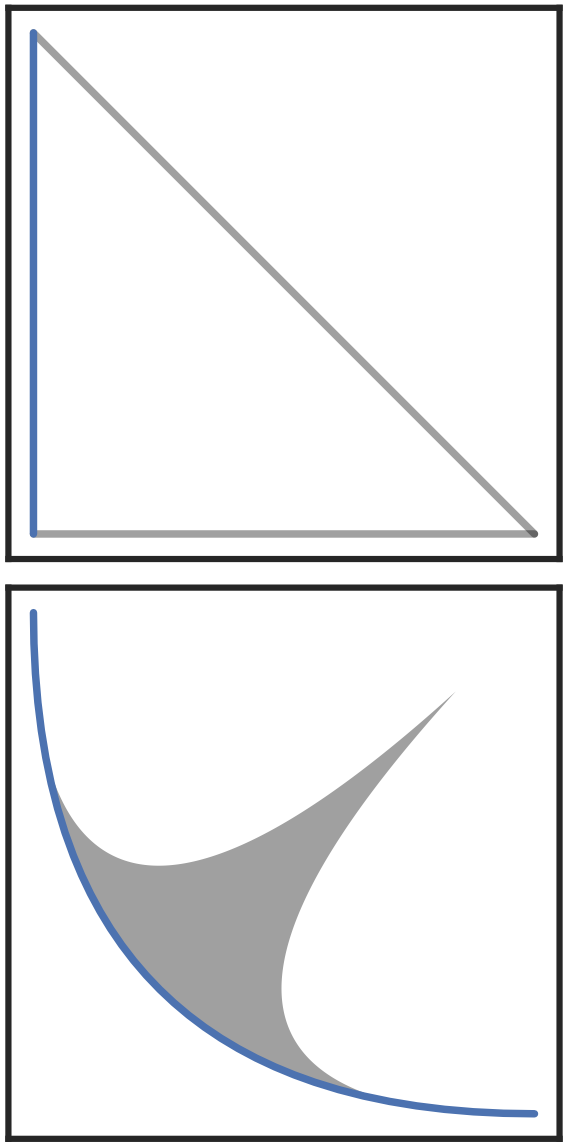

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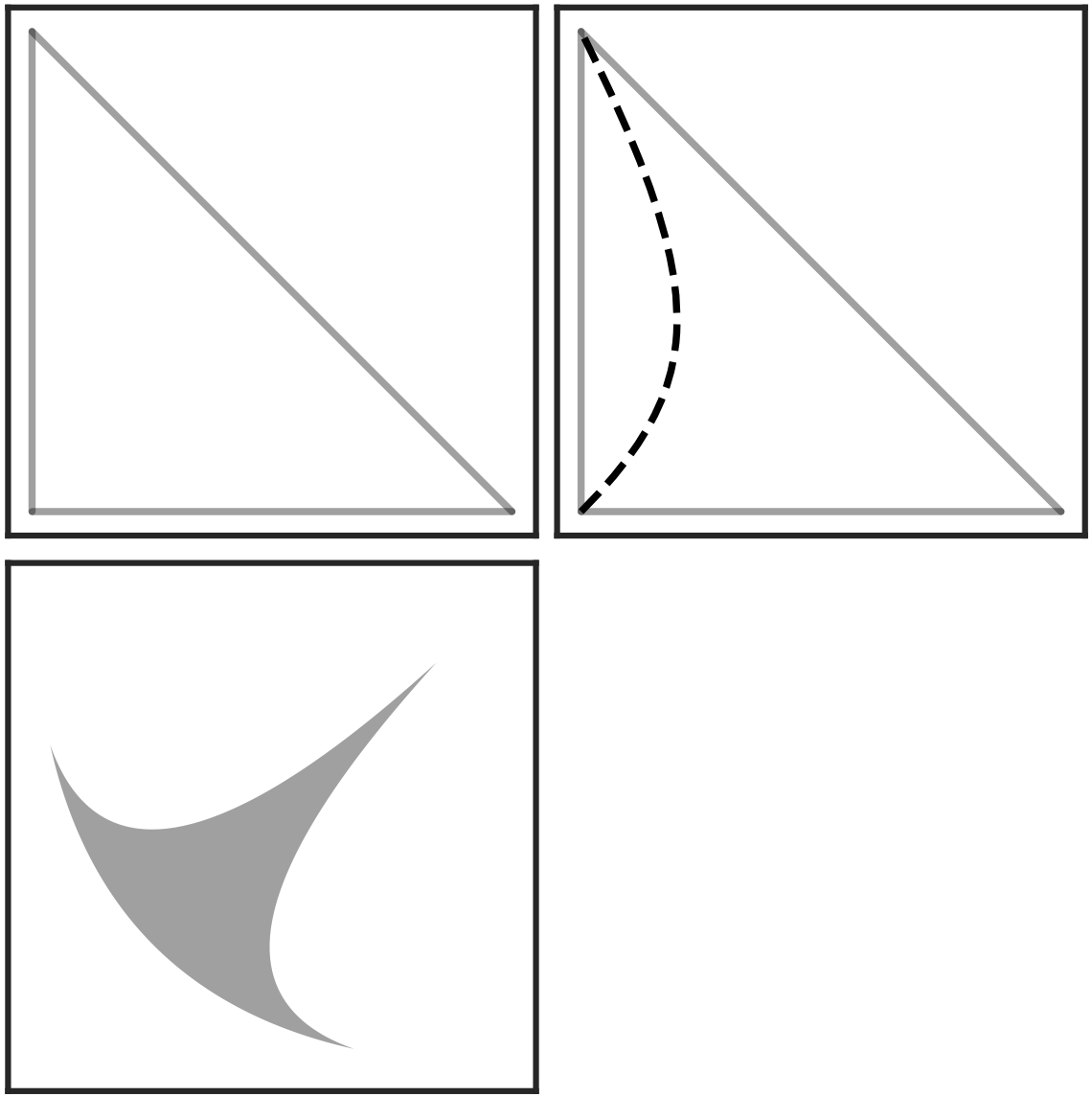

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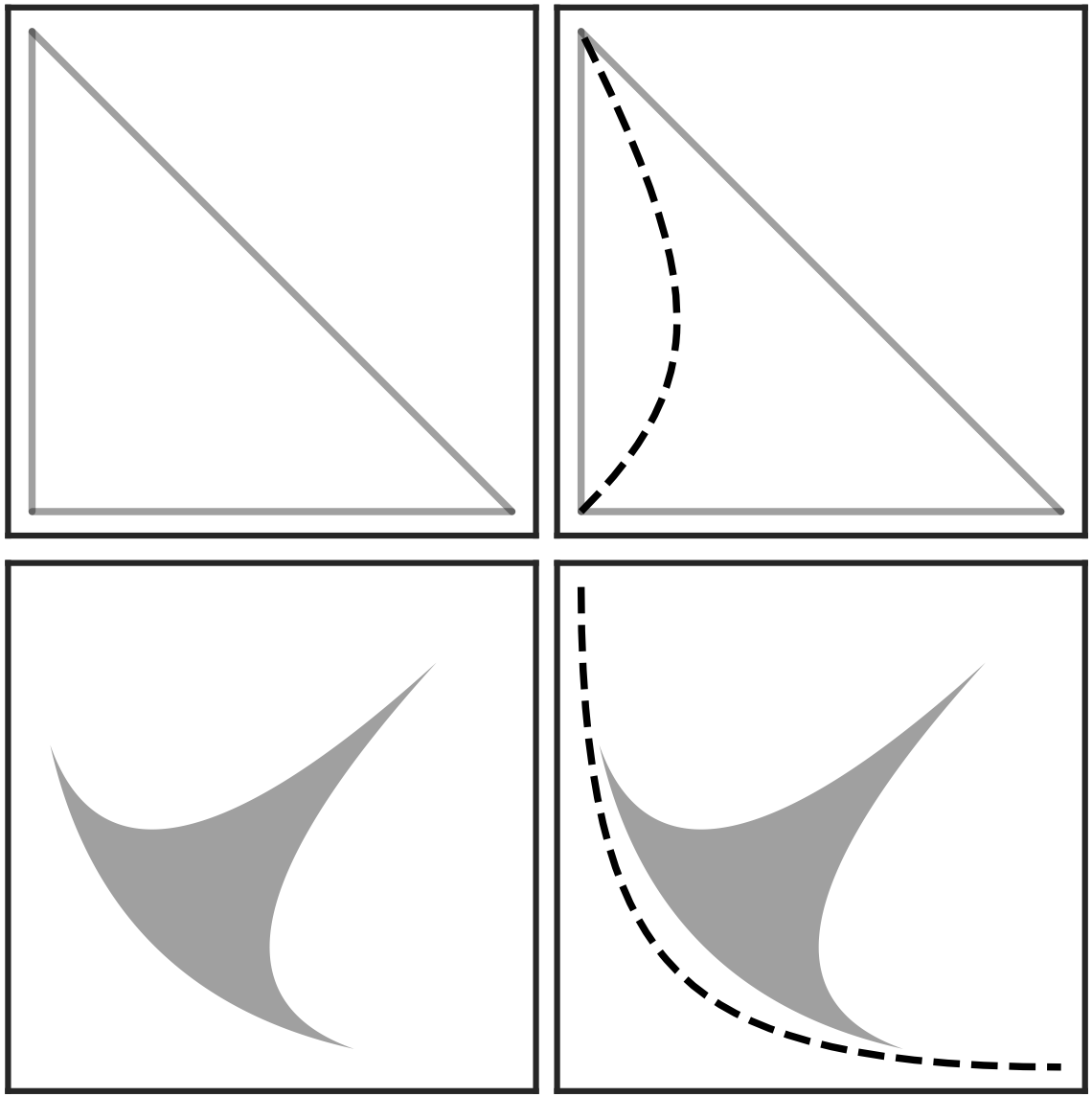

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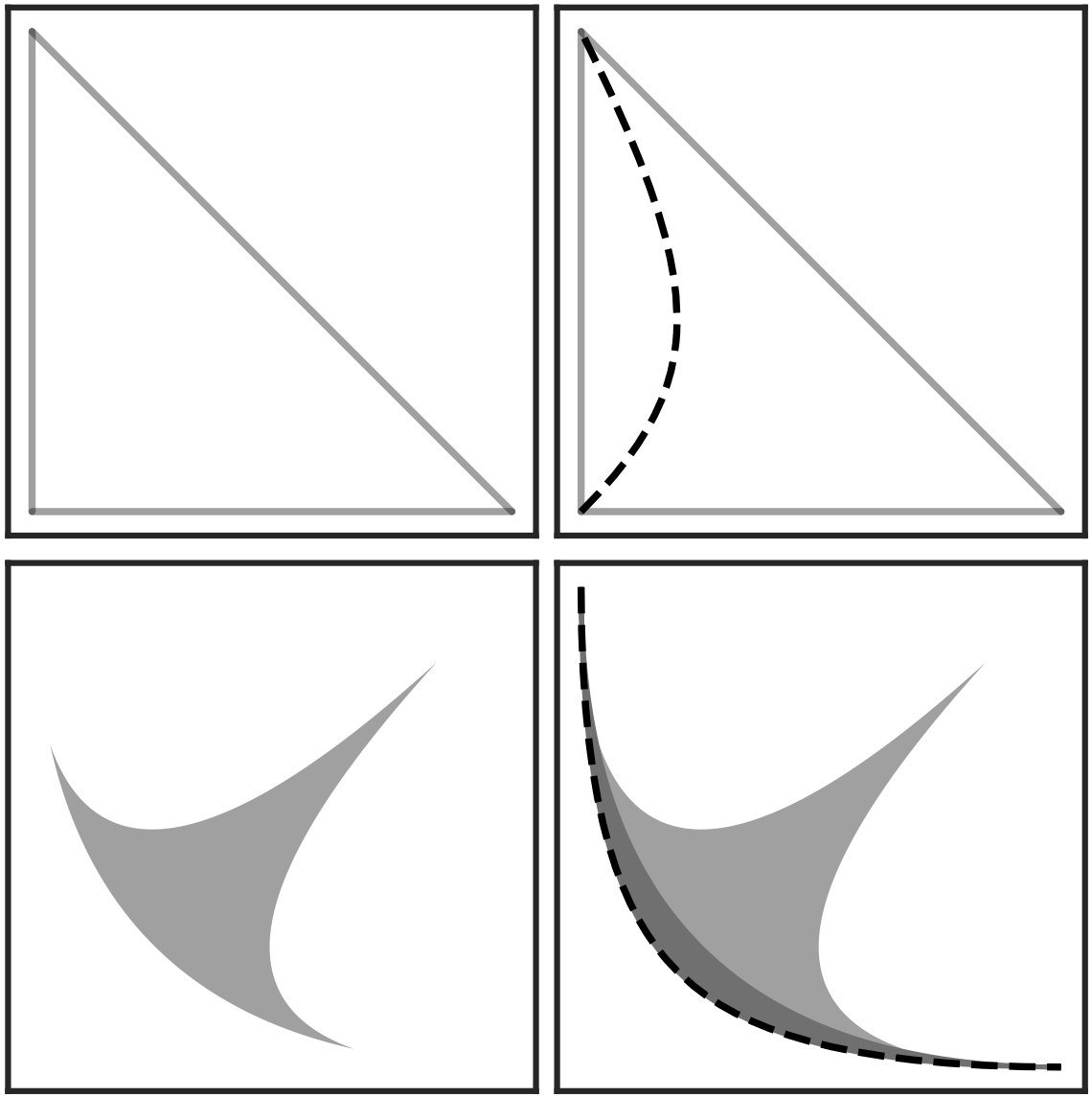

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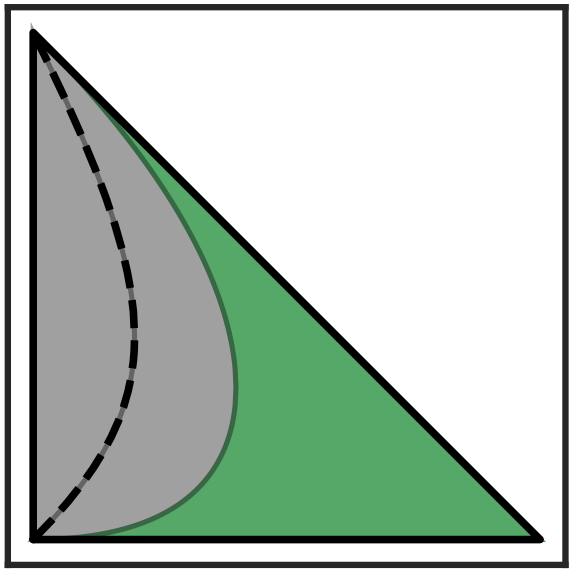

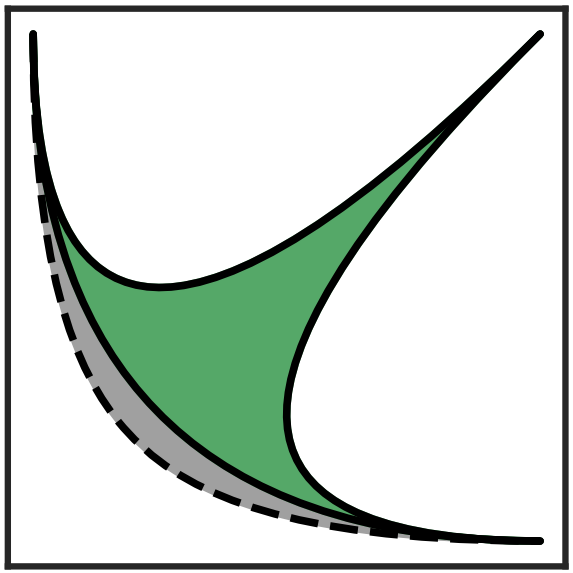

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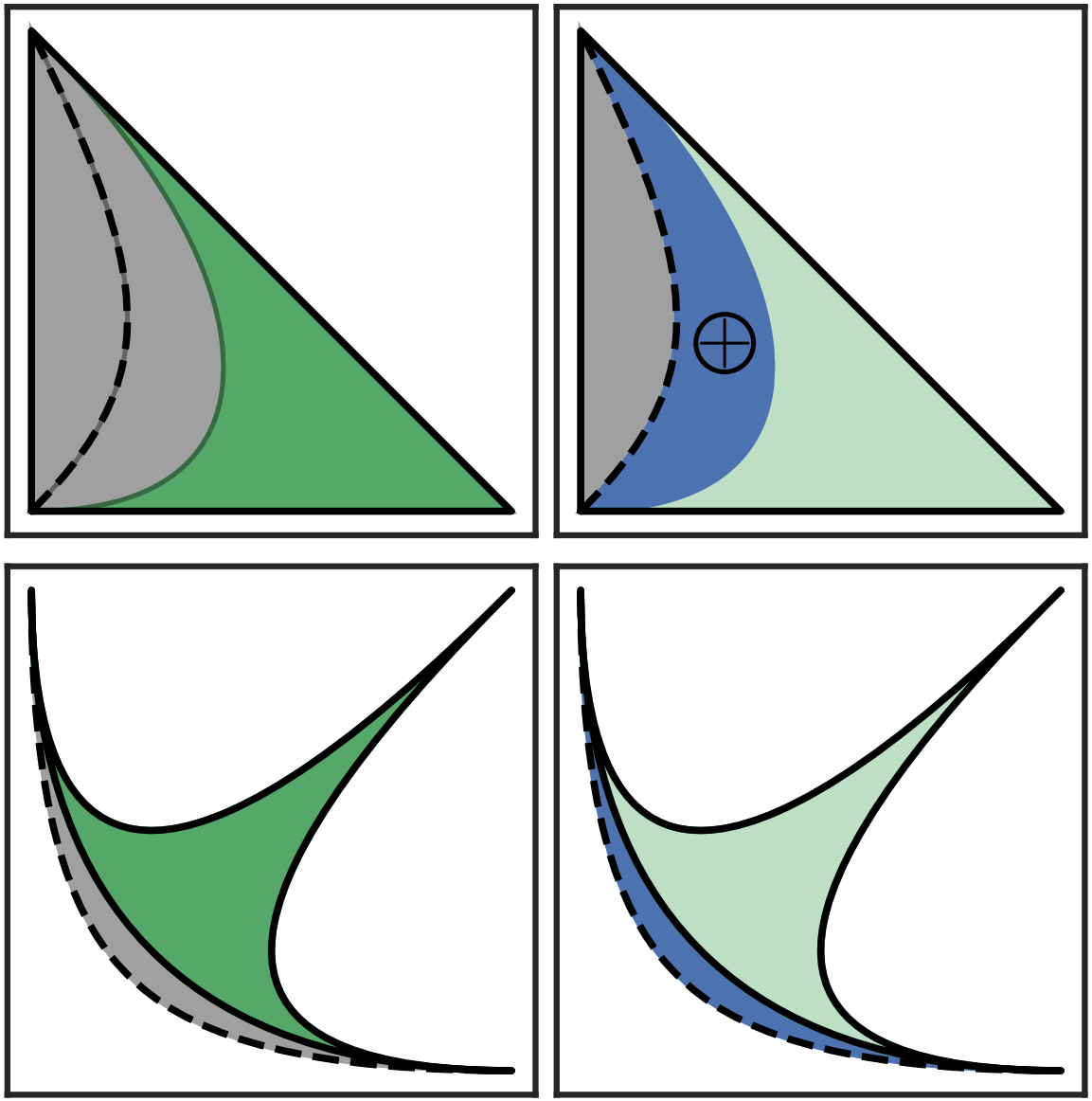

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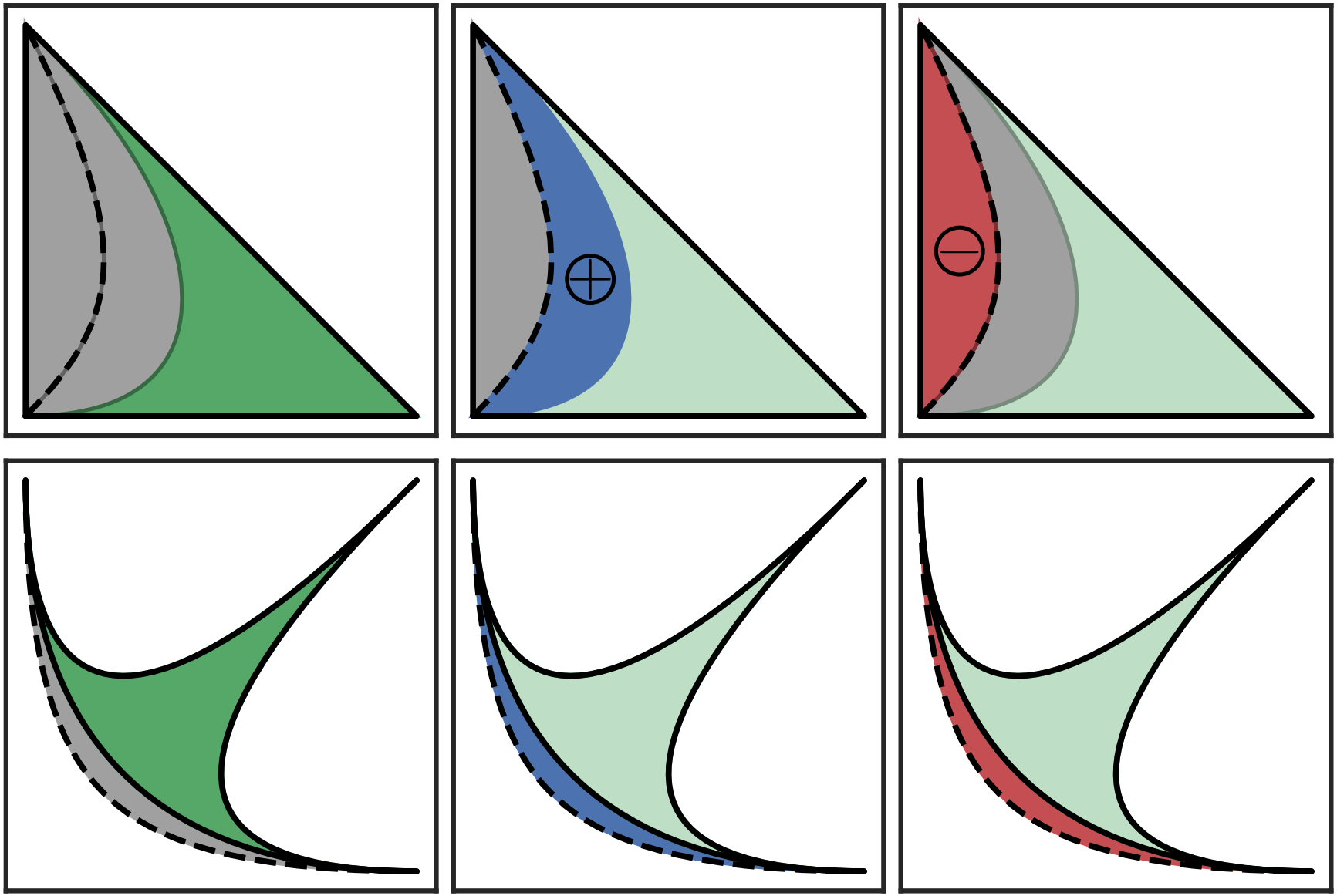

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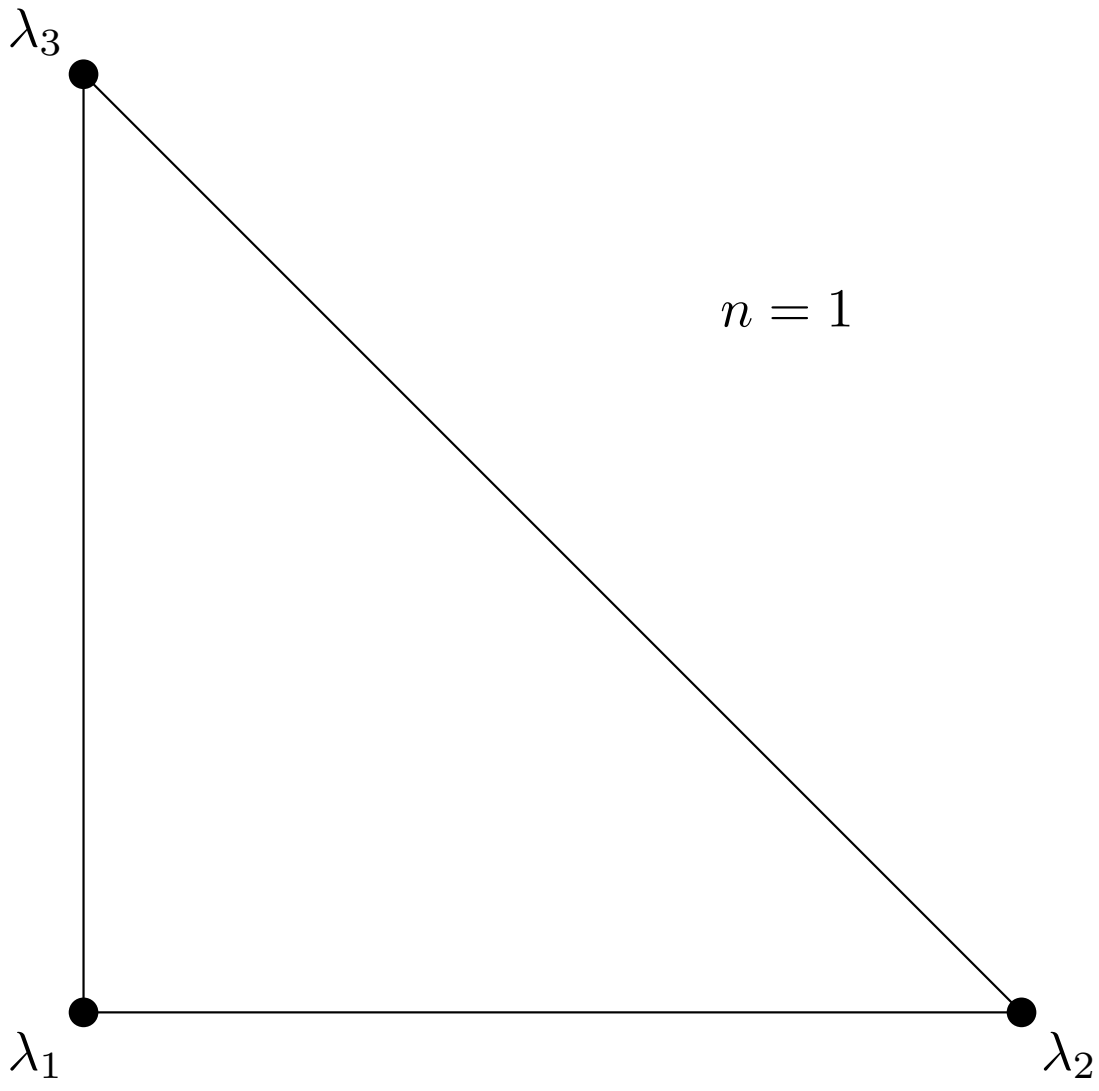

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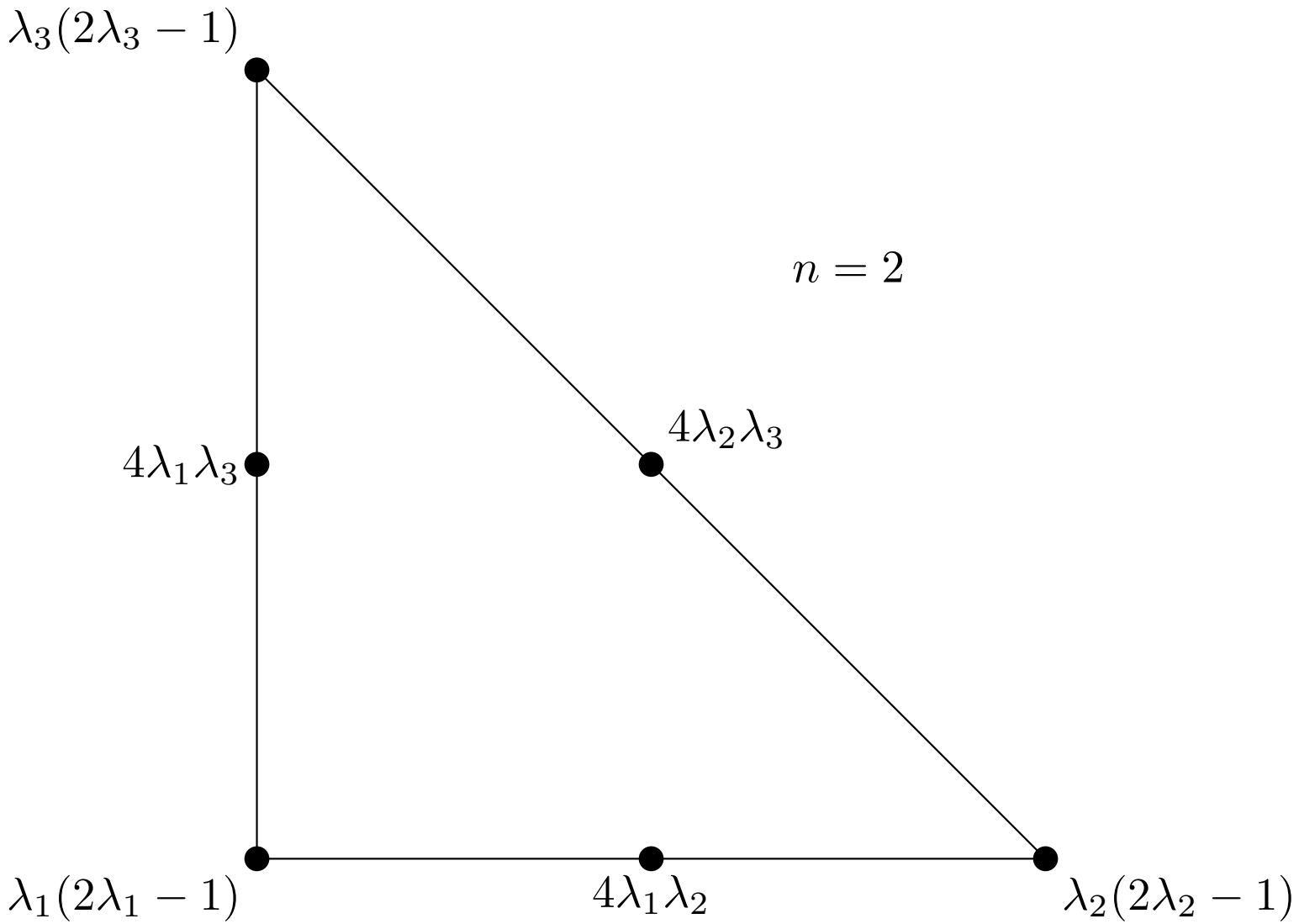

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- $\operatorname{supp}(\phi) = \mathcal{T}$

Solution Transfer

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  - Shape function bases $\phi_D^{(j)}$ and $\phi_T^{(j)}$
  - Known discrete field $\boldsymbol{q}_D = \sum_j d_j \phi_D^{(j)}$
- **Want**: L_2-optimal interpolant $\boldsymbol{q}_T = \sum_j t_j \phi_T^{(j)}$:

$$\|\boldsymbol{q}_T - \boldsymbol{q}_D\|_2 = \min_{\boldsymbol{q} \in \mathcal{V}_T} \|\boldsymbol{q} - \boldsymbol{q}_D\|_2$$

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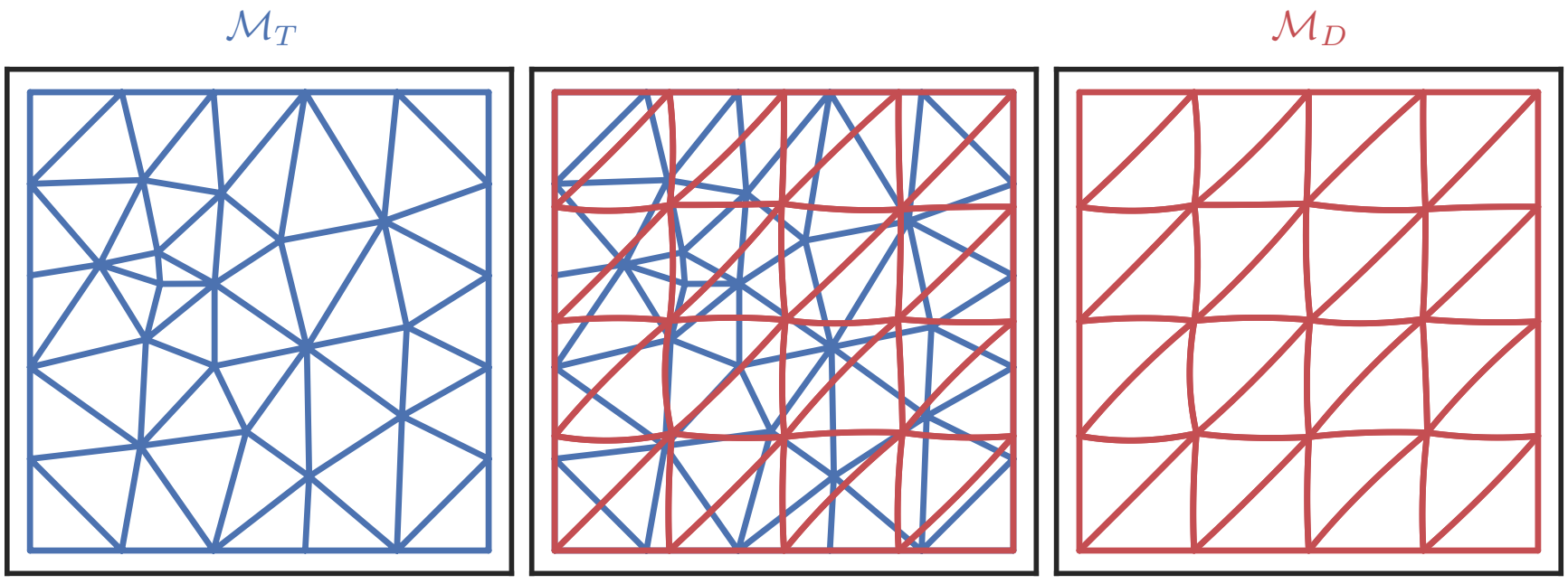

Galerkin Projection

Differentiating w.r.t. each t_j in $\boldsymbol{q}_T = \sum_j t_j \phi_T^{(j)}$ gives **weak form**

$$\int_\Omega \boldsymbol{q}_D \phi_T^{(j)} \, dV = \int_\Omega \boldsymbol{q}_T \phi_T^{(j)} \, dV, \qquad \text{for all } j.$$

Galerkin Projection

Differentiating w.r.t. each t_j in $\boldsymbol{q}_T = \sum_j t_j \phi_T^{(j)}$ gives **weak form**

$$\int_\Omega \boldsymbol{q}_D \phi_T^{(j)} \, dV = \int_\Omega \boldsymbol{q}_T \phi_T^{(j)} \, dV, \qquad \text{for all } j.$$

If $(\boldsymbol{x} \mapsto 1) \in \mathcal{V}_T$, then $\boldsymbol{q}_T$ is globally **conservative**

$$\int_\Omega \boldsymbol{q}_D \, dV = \int_\Omega \boldsymbol{q}_T \, dV.$$

Linear System

Weak form gives rise to a linear system in coefficients $\boldsymbol{d}$ and $\boldsymbol{t}$:

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$$M_T \boldsymbol{t} = M_{TD} \boldsymbol{d}.$$

Linear System

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Integrate via substitution for $F = \phi_T^{(i)} \phi_T^{(j)}$

$$\int_{b(\mathcal{U})} F(x, y) \, dx \, dy = \int_{\mathcal{U}} \det(Db) F\left(x(s,t), y(s,t)\right) \, ds \, dt$$

and then use quadrature rule on $\mathcal{U}$.

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Mixed mass matrix M_{TD}

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Instead, compute entire RHS

$$(M_{TD}\boldsymbol{d})_j = \int_\Omega \phi_T^{(j)} \boldsymbol{q}_D \, dV.$$

Common Refinement

Given ϕ supported on $\mathcal{T}$

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Common Refinement

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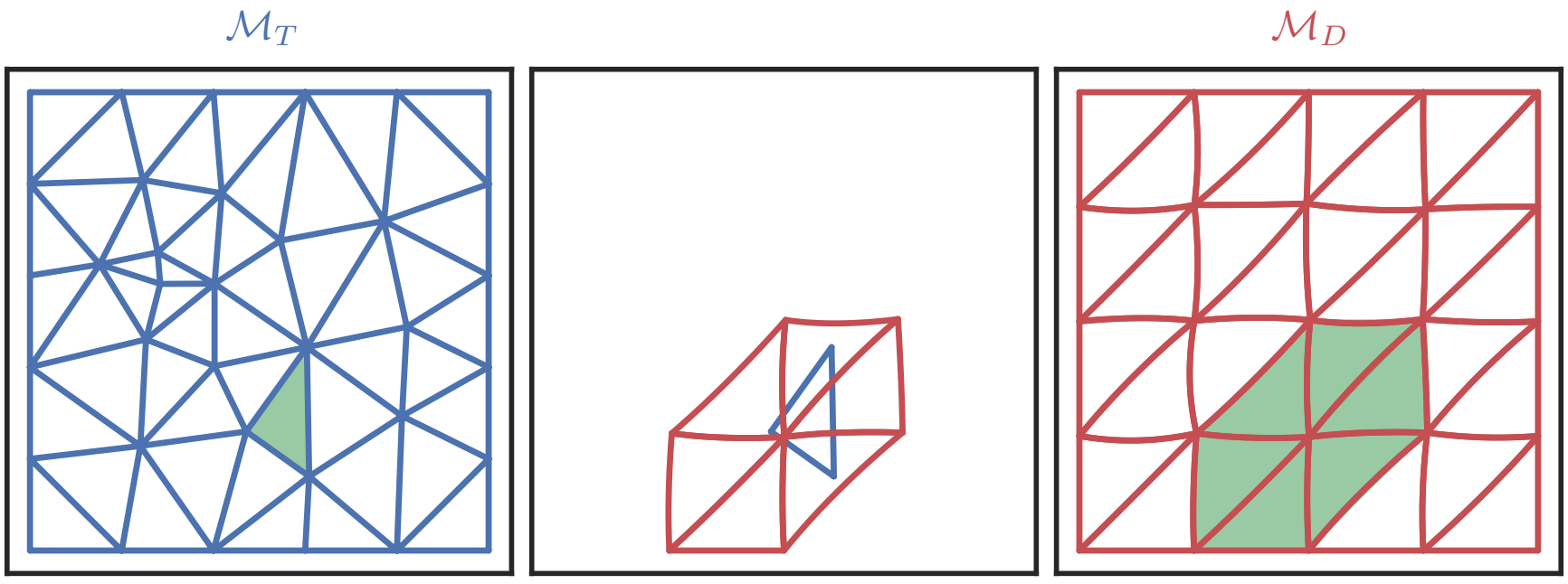
In CG, $\boldsymbol{q}_D$ need not be differentiable across elements and in DG $\boldsymbol{q}_D$ need not even be continuous

Common Refinement



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  - Integration over Curved Polygons: $\int_{\mathcal{T} \cap \mathcal{T}'} F \, dV$

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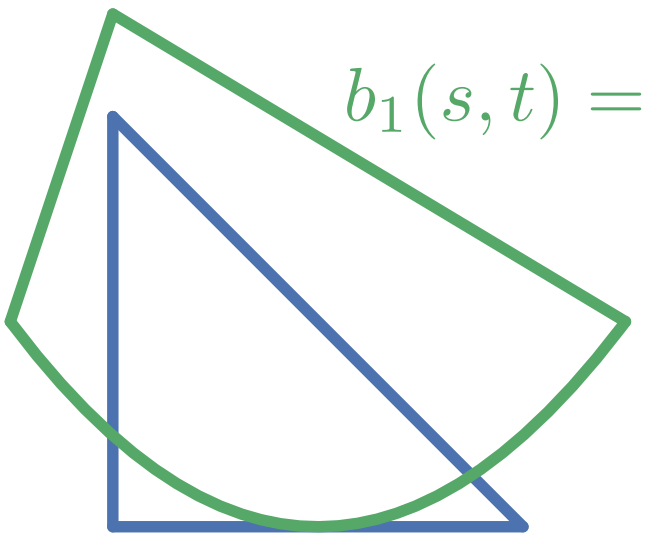
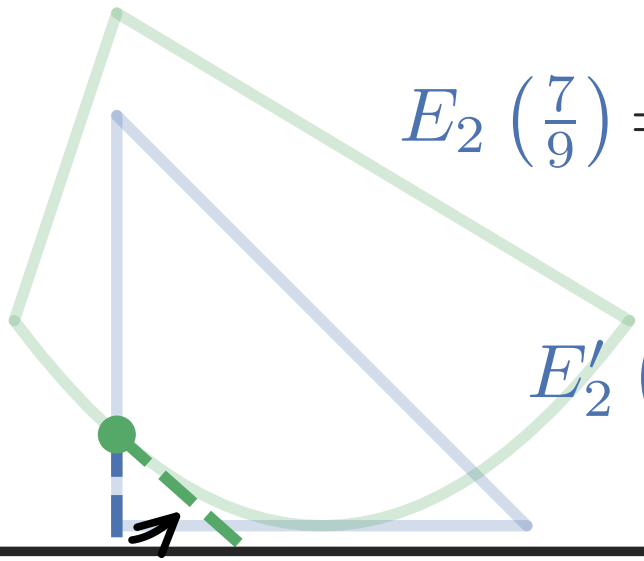
Intersecting Curved Elements



$$b_1(s,t) = \begin{bmatrix} 2(6s+t-1) \\ 2(8s^2+8st-8s+3t+2) \end{bmatrix}$$

$$b_0(s,t) = \begin{bmatrix} 8s \\ 8t \end{bmatrix}$$

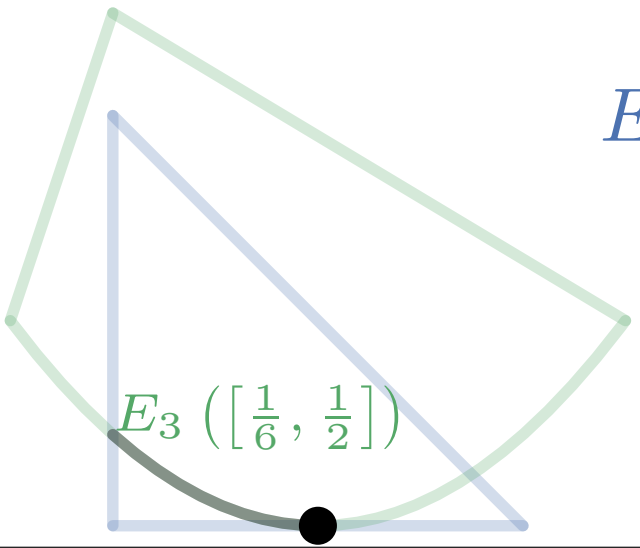
Intersecting Curved Elements



$$E_2\left(\tfrac{7}{9}\right) = E_3\left(\tfrac{1}{6}\right) = \tfrac{16}{9}\begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$E_2'\left(\tfrac{7}{9}\right) \times E_3'\left(\tfrac{1}{6}\right) = 96 > 0$$

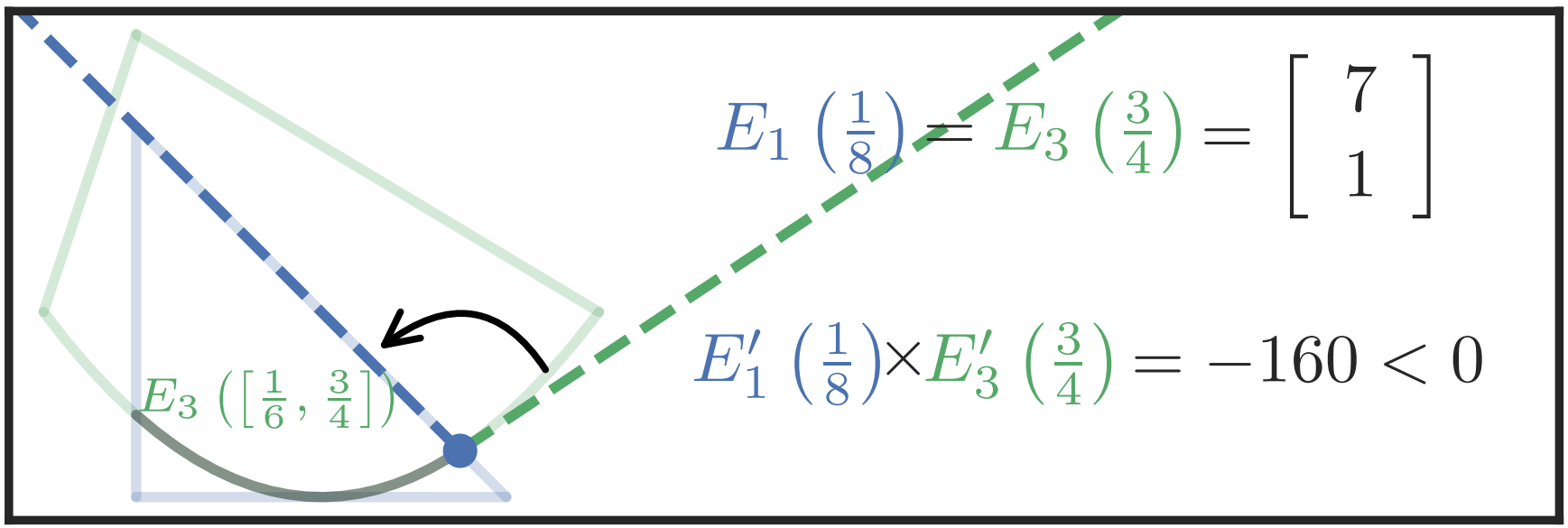
Intersecting Curved Elements



$$E_0\left(\frac{1}{2}\right) = E_3\left(\frac{1}{2}\right) = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$$

$$E_0'\left(\frac{1}{2}\right) \times E_3'\left(\frac{1}{2}\right) = 0$$

Intersecting Curved Elements



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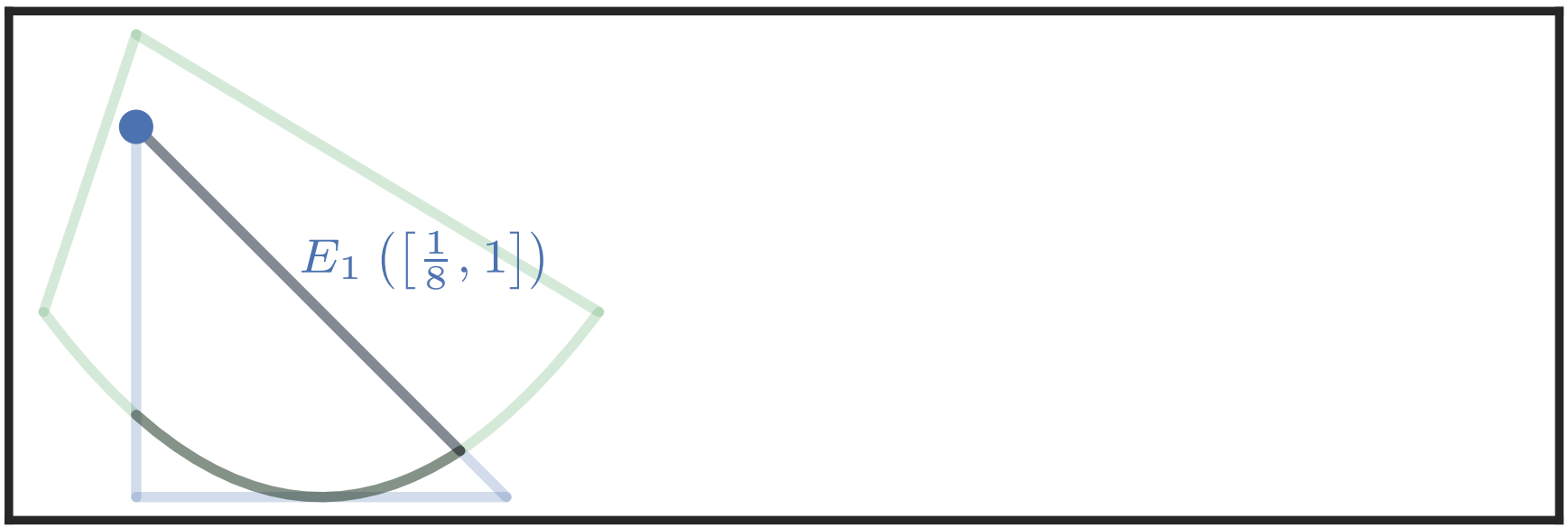

Intersecting Curved Elements

Intersecting Curved Elements

- $\mathcal{P} = \mathcal{T}_0 \cap \mathcal{T}_1$
- $\partial\mathcal{P} = E_3\left(\left[\frac{1}{6}, \frac{3}{4}\right]\right) \cup E_1\left(\left[\frac{1}{8}, 1\right]\right) \cup E_2\left(\left[0, \frac{7}{9}\right]\right)$

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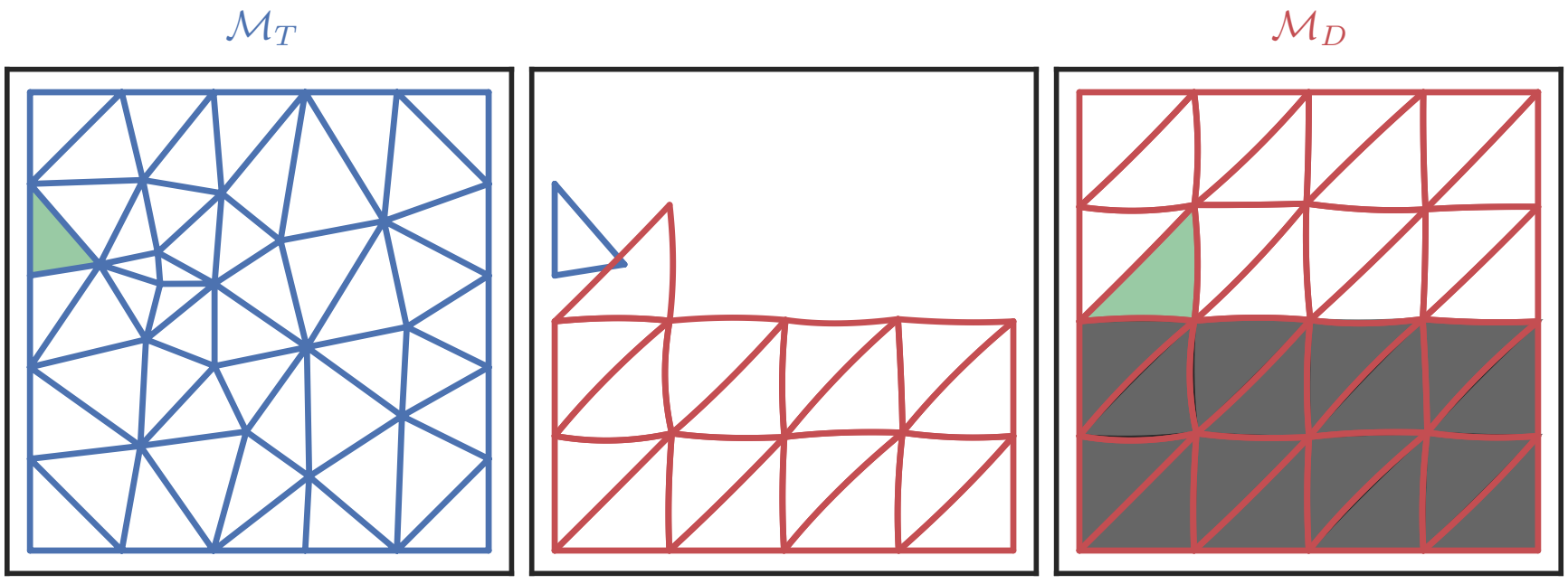

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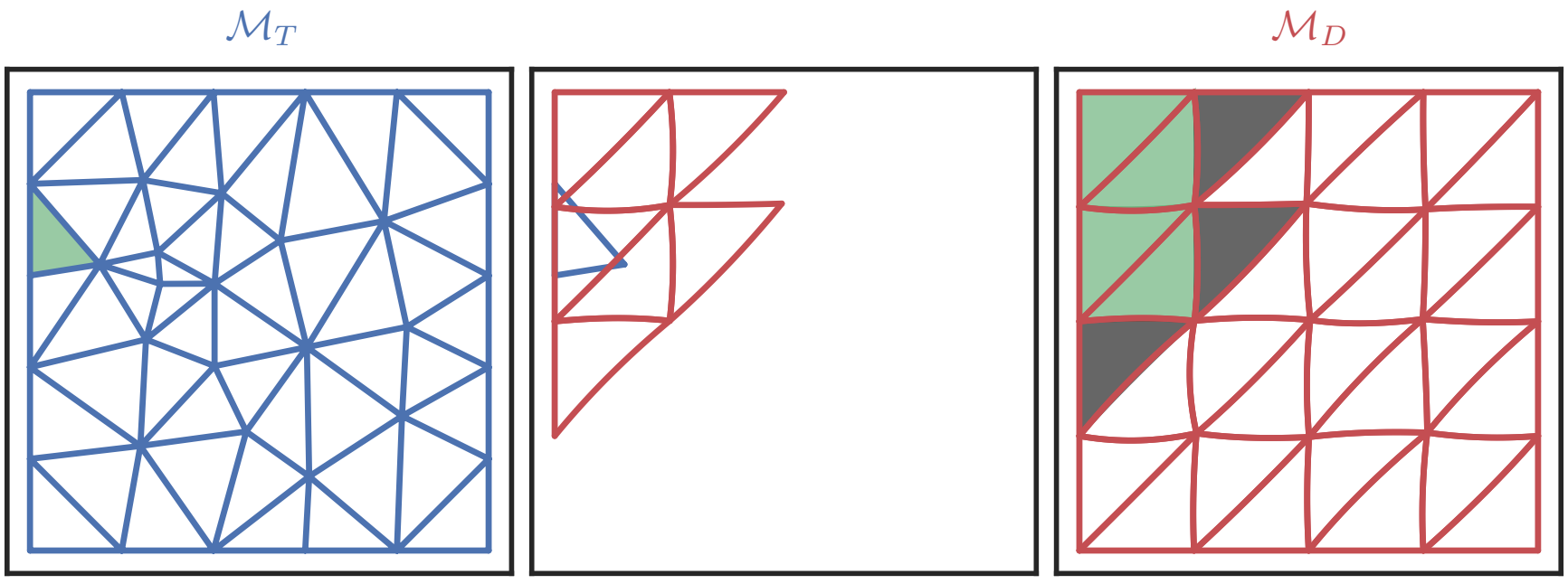

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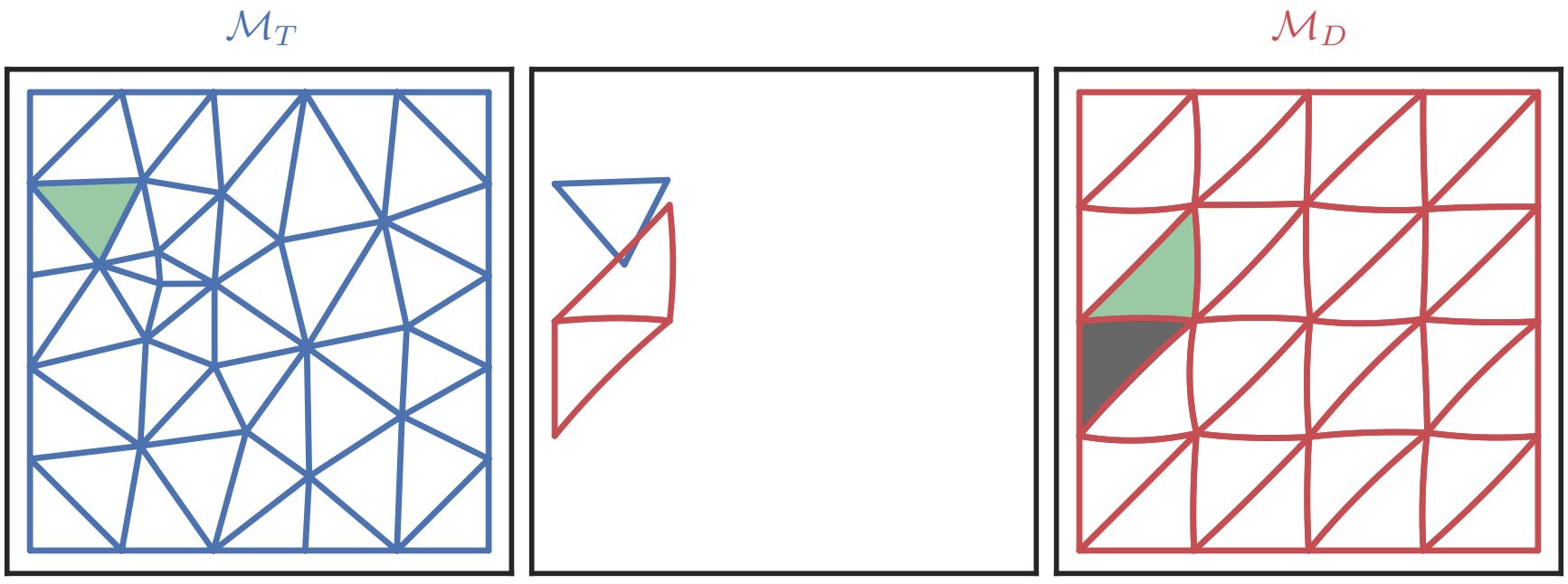

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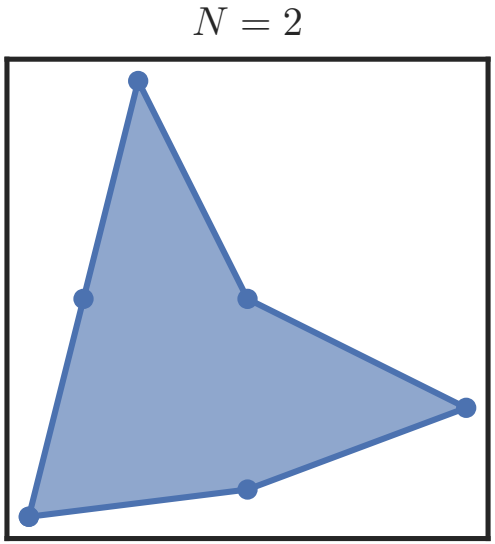
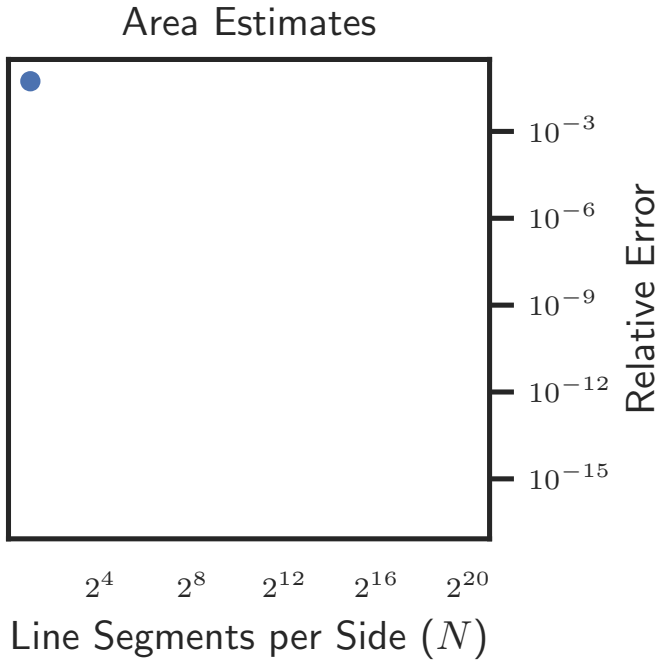
- Total $\mathcal{O}\left(|\mathcal{M}_D| + |\mathcal{M}_T|\right)$

Integration over Curved Polygons

$$\int_{\mathcal{P}} F(x, y)\, dV, \qquad \mathcal{P} = \mathcal{T}_0 \cap \mathcal{T}_1, \qquad F = \phi_0\, \phi_1$$

Integrate via Polygonal Approximation





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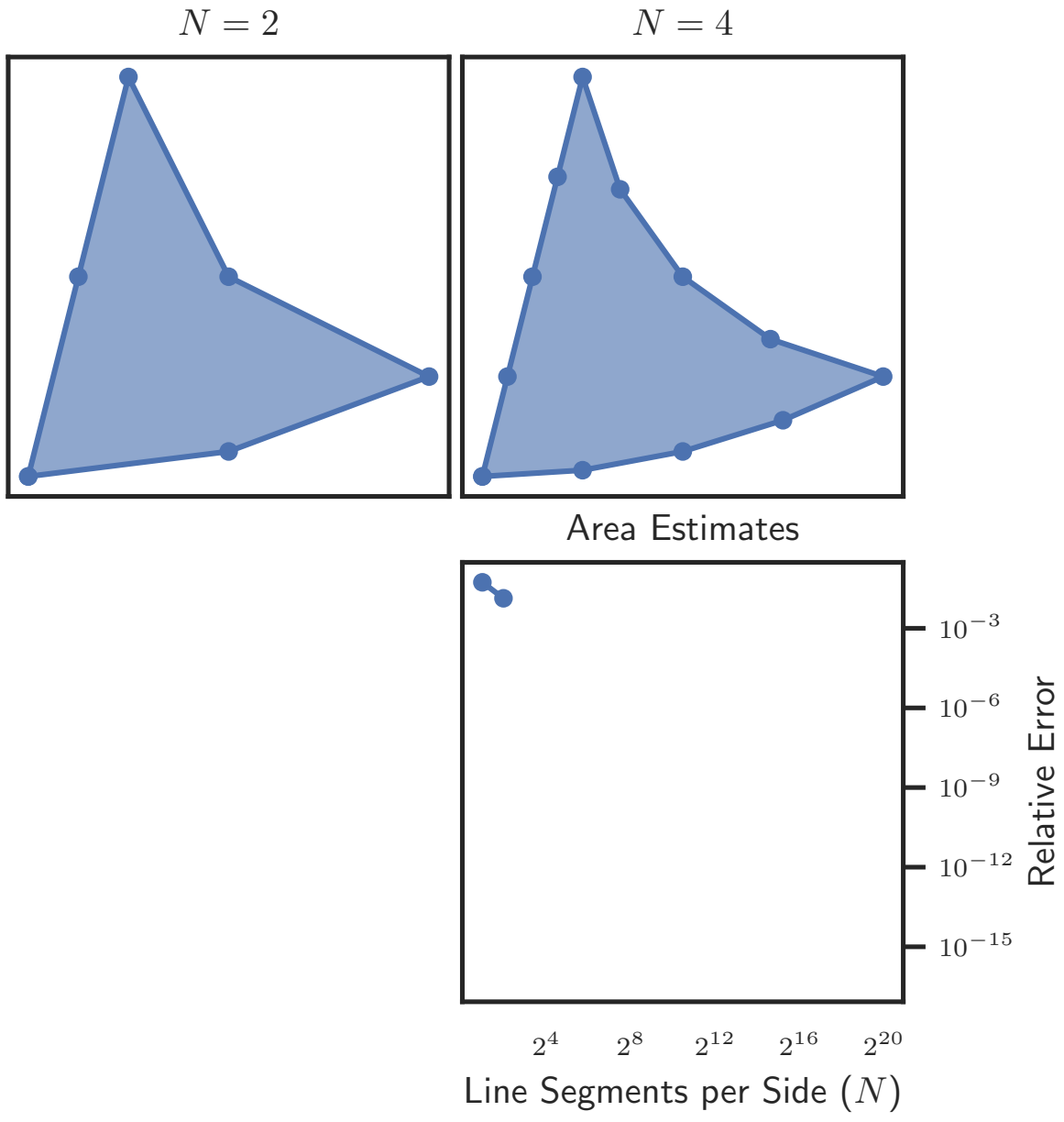

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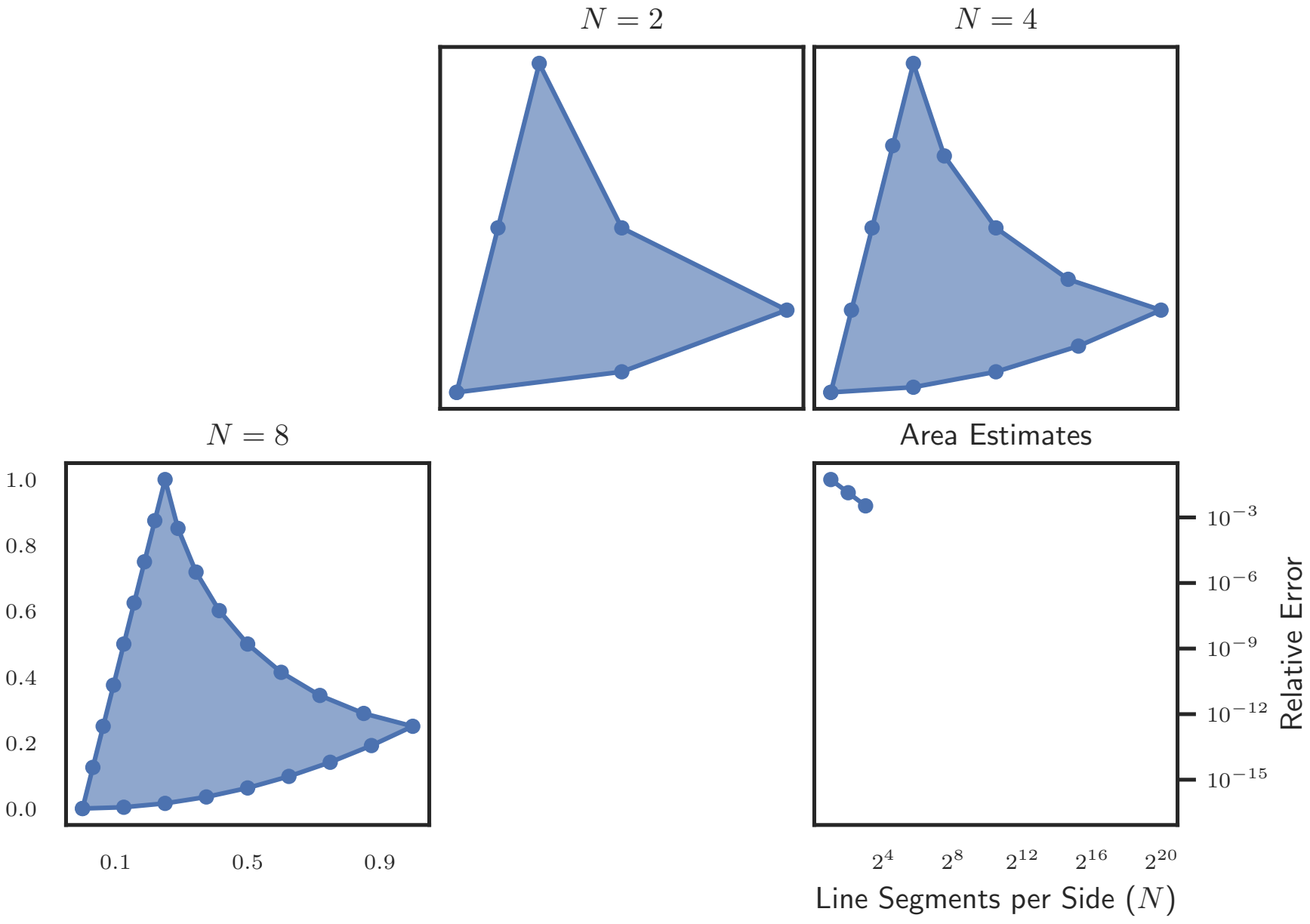

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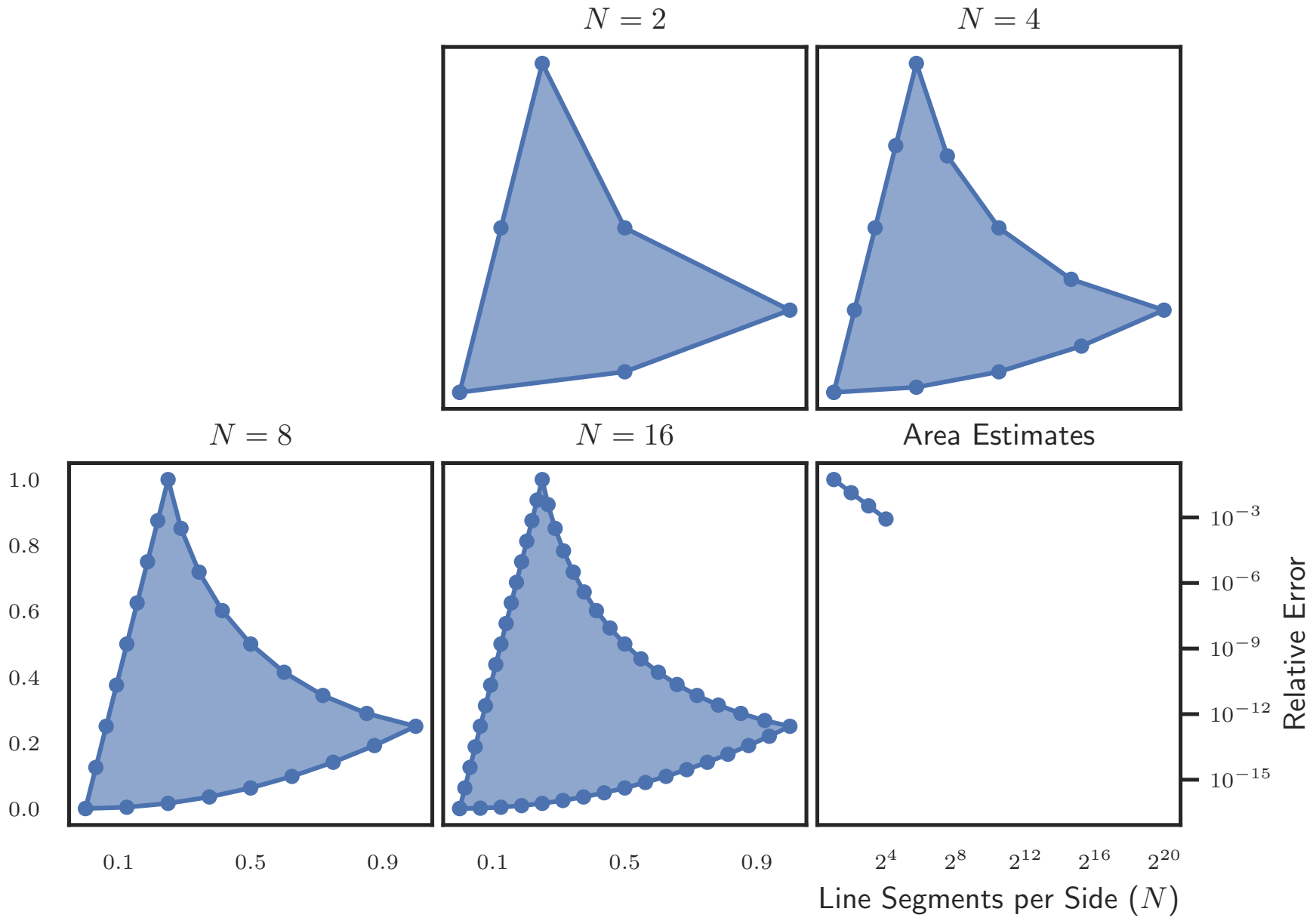

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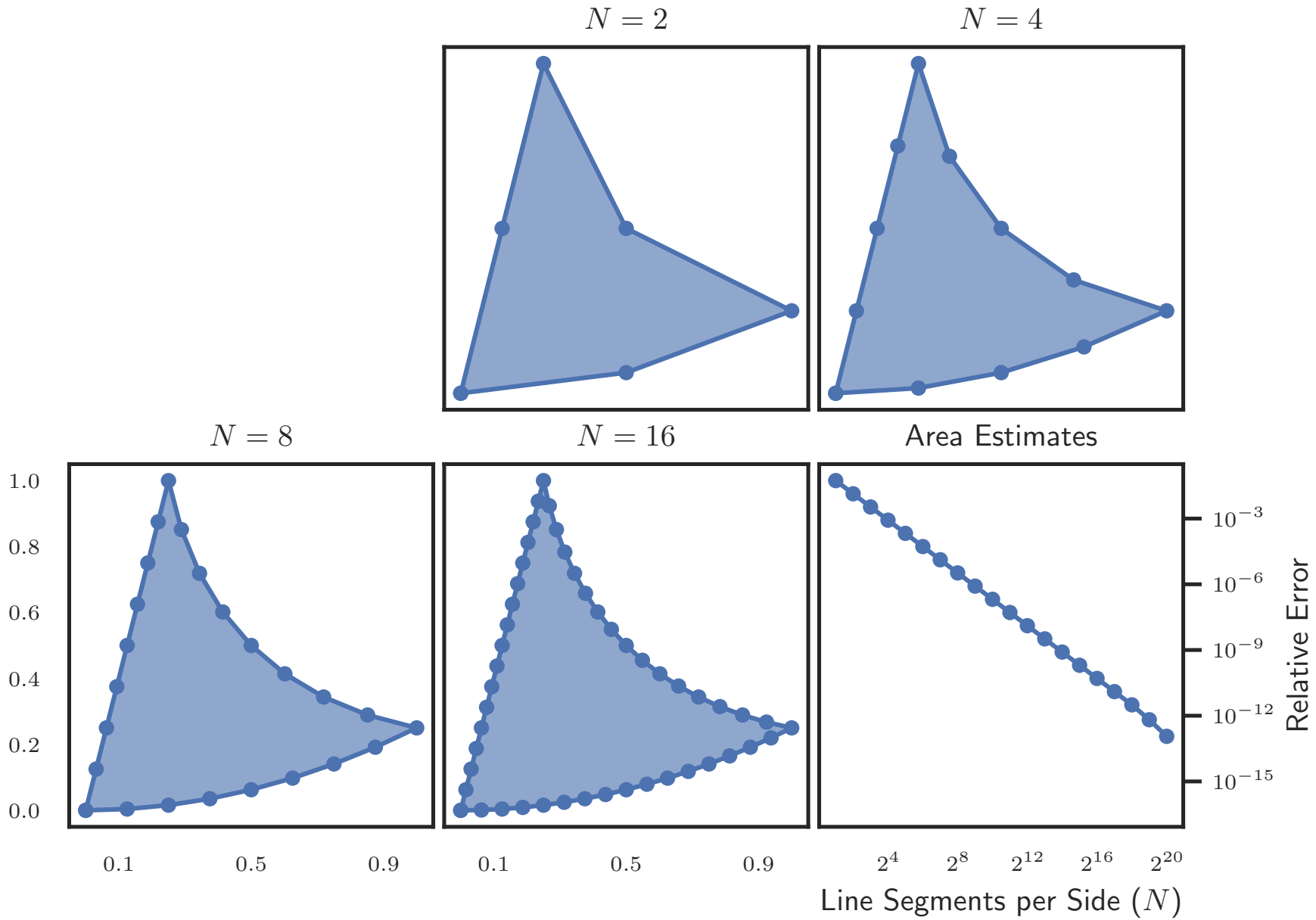

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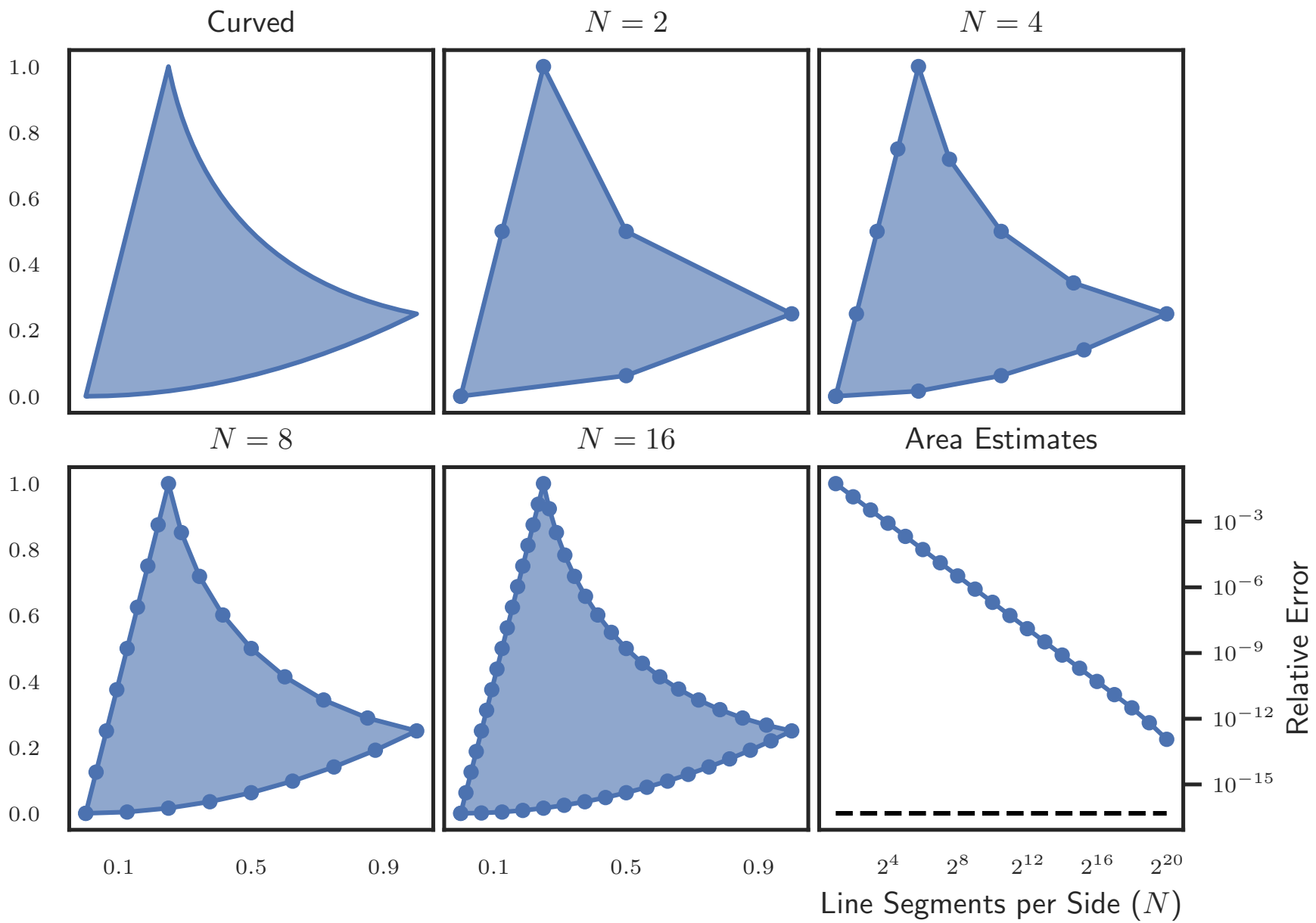

Integrate via Polygonal Quadrature

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  - Maps from (straight sided) reference domain, but increase degree or are not bijective

Integrate via Tessellation

- Triangular quadrature rules simple and well established

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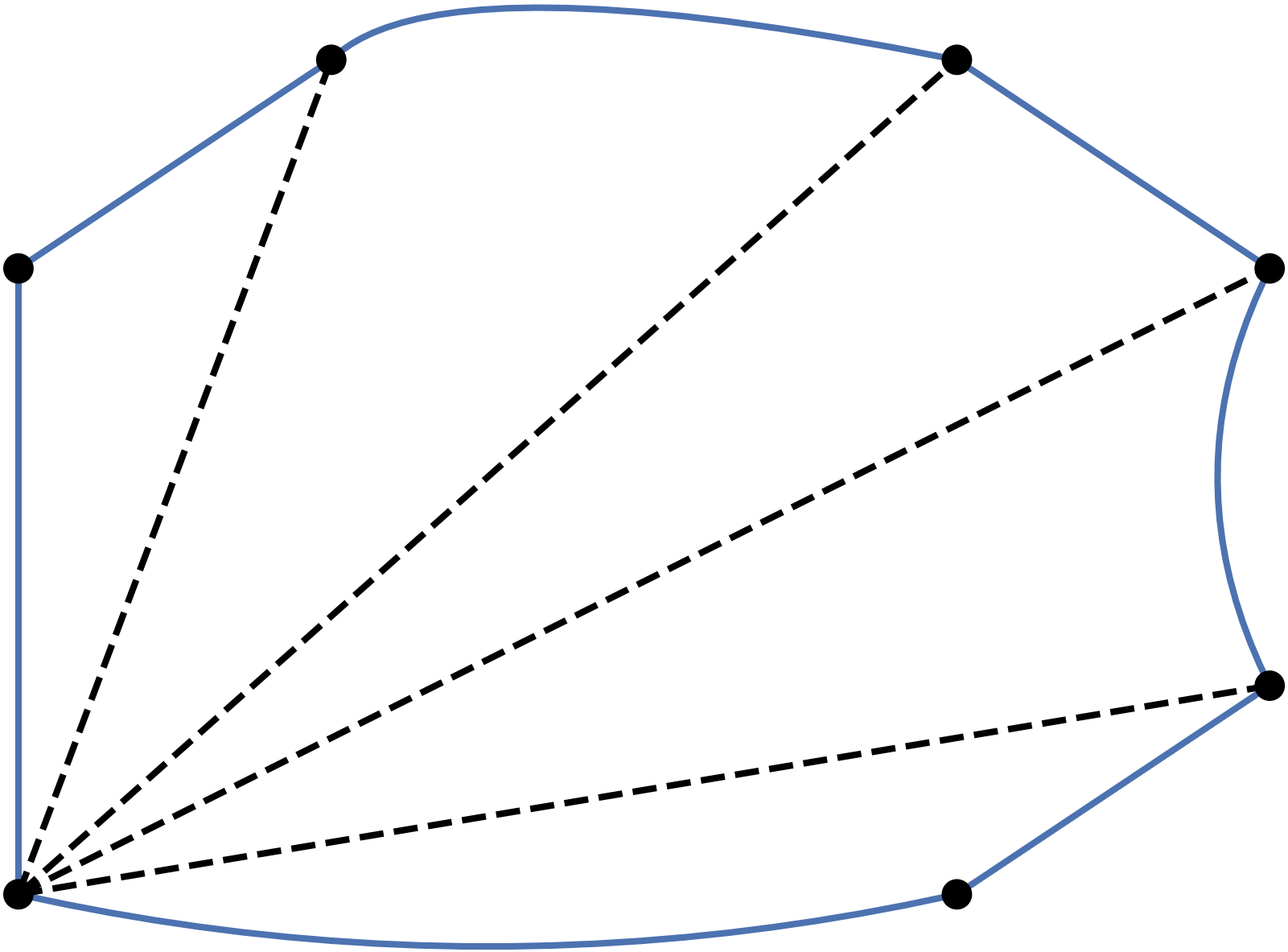
- Tessellate $\mathcal{P}$ into disjoint union of Bézier triangles

Integrate via Tessellation



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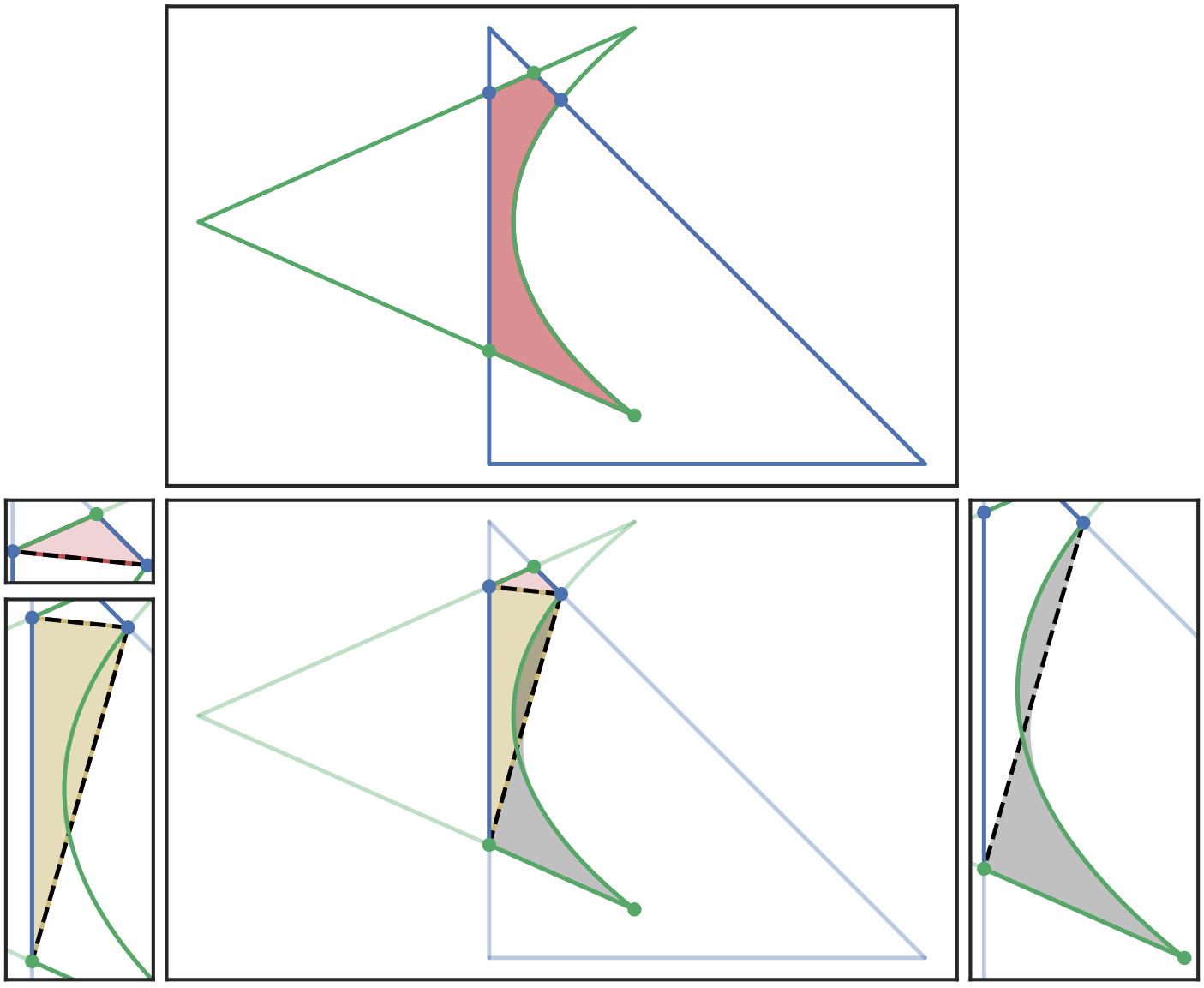
- If diagonals are valid, high degree Bézier triangles need interior control points introduced that don't cause triangle to invert

Integrate via Tessellation

- Tessellate with inverted Bézier triangles?

Integrate via Tessellation



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- $\mathcal{T}_2$ inverted, $b(s, t) \notin \mathcal{P}$ is possible but b_0^{-1} need not need be defined outside of $\mathcal{T}_0$

Integrate via Green's Theorem

- Horizontal antiderivative H and vertical antiderivative V s.t. $H_x = V_y = F$

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- Each C given by $x(r), y(r)$, 1D quadrature on unit interval of

$$G(r) = H(x(r), y(r))y'(r) - V(x(r), y(r))x'(r)$$

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- Fundamental theorem of calculus

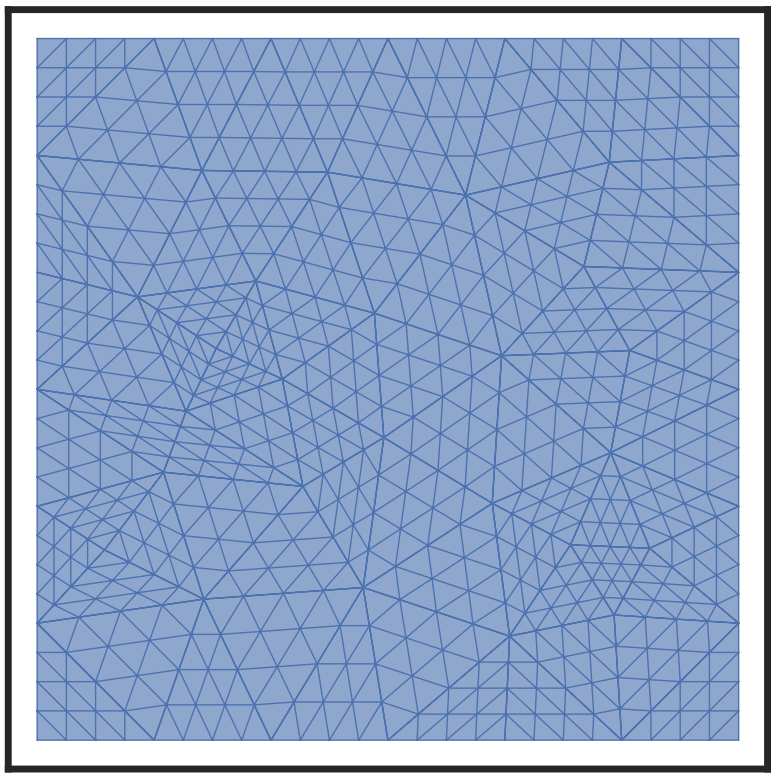
$$H(\alpha, \beta) = H(\alpha, \beta) - H(0, \beta) = \int_0^\alpha F(x, \beta)\ dx$$

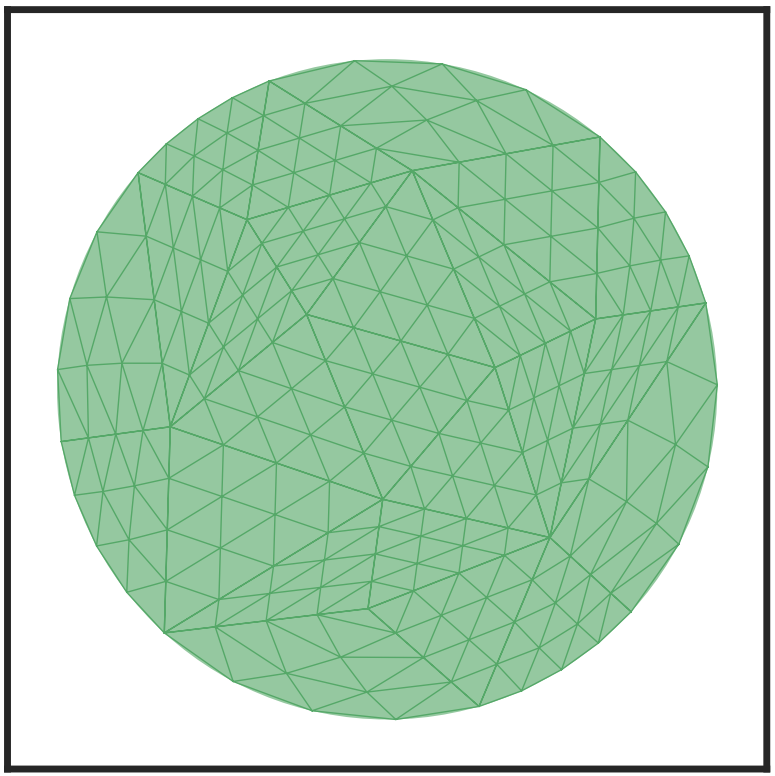
- Quadrature points $F(x_j, \beta)$ may fall outside $\mathcal{P}$, so pre-image basis cannot be used
- Global coordinates basis means F is a polynomial on $\mathbf{R}^2$, so quadrature is exact

Numerical Experiments

- Three meshes ($p = 1, 2, 3$)

Numerical Experiments





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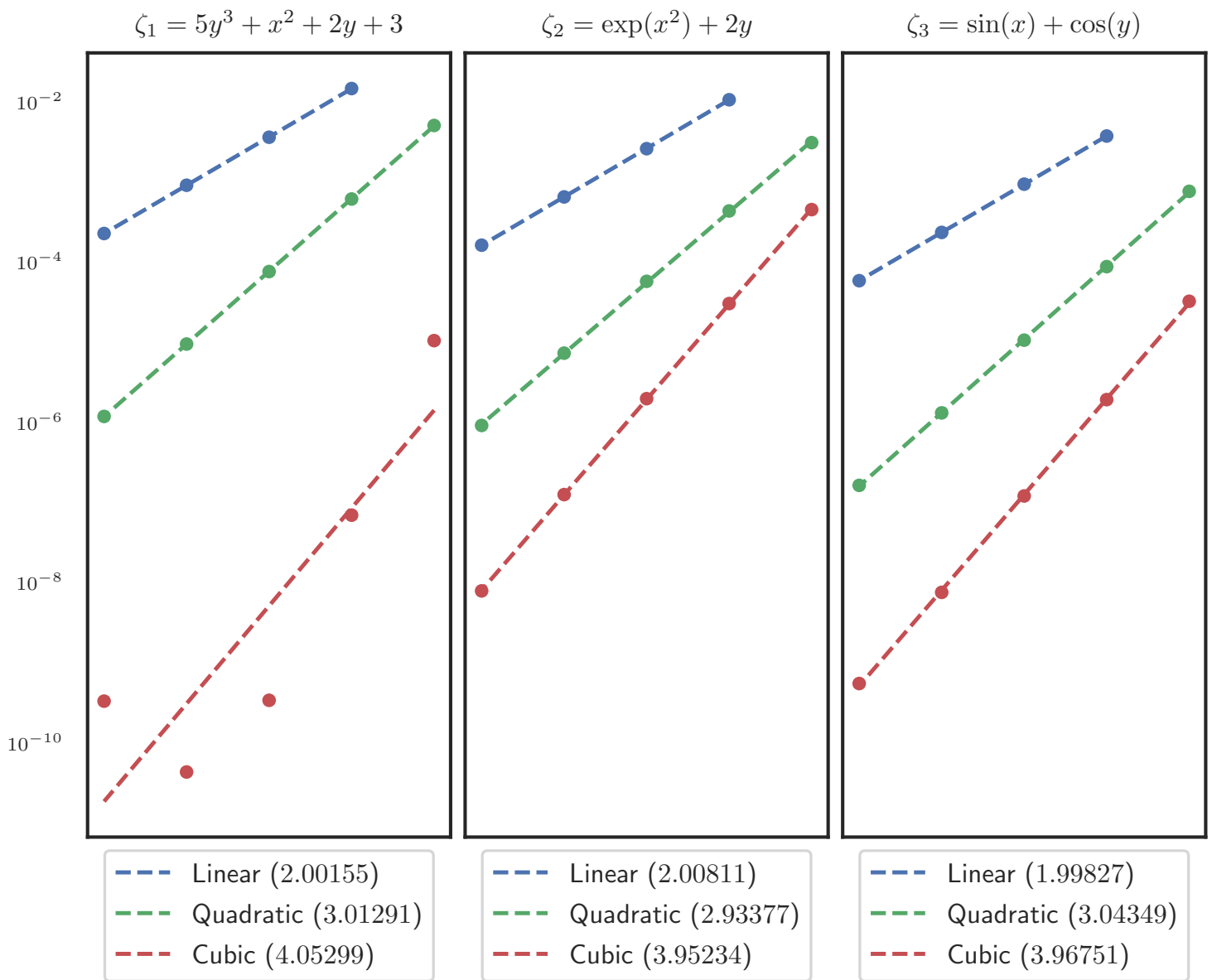
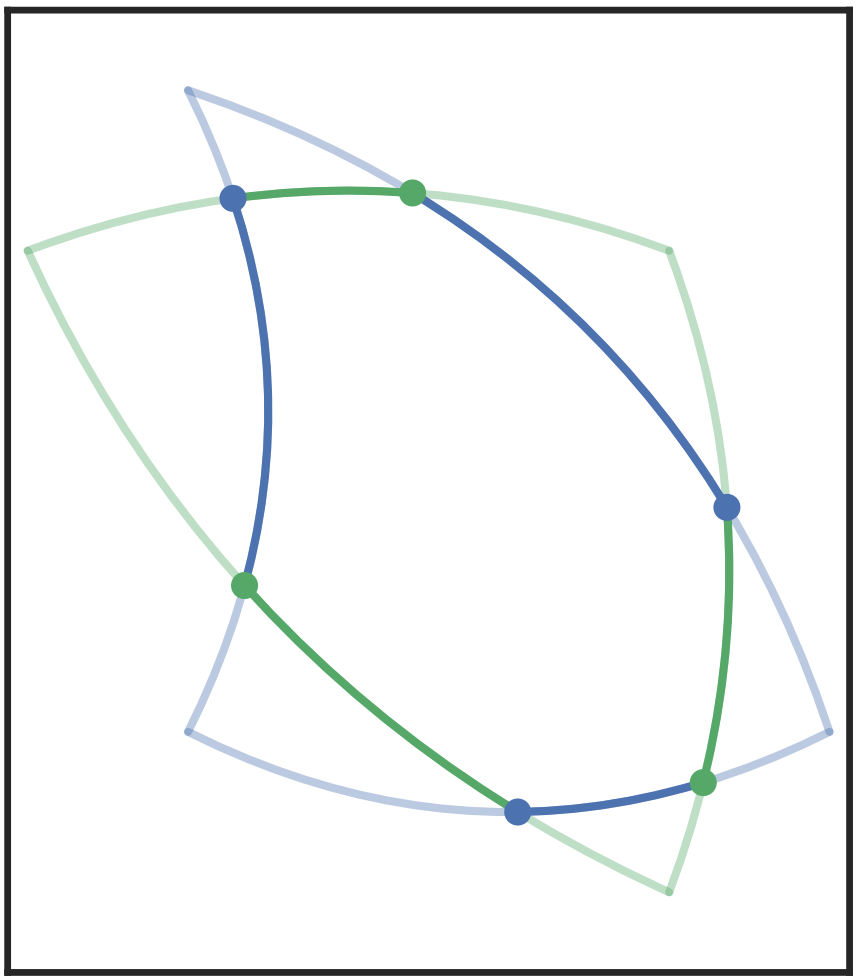
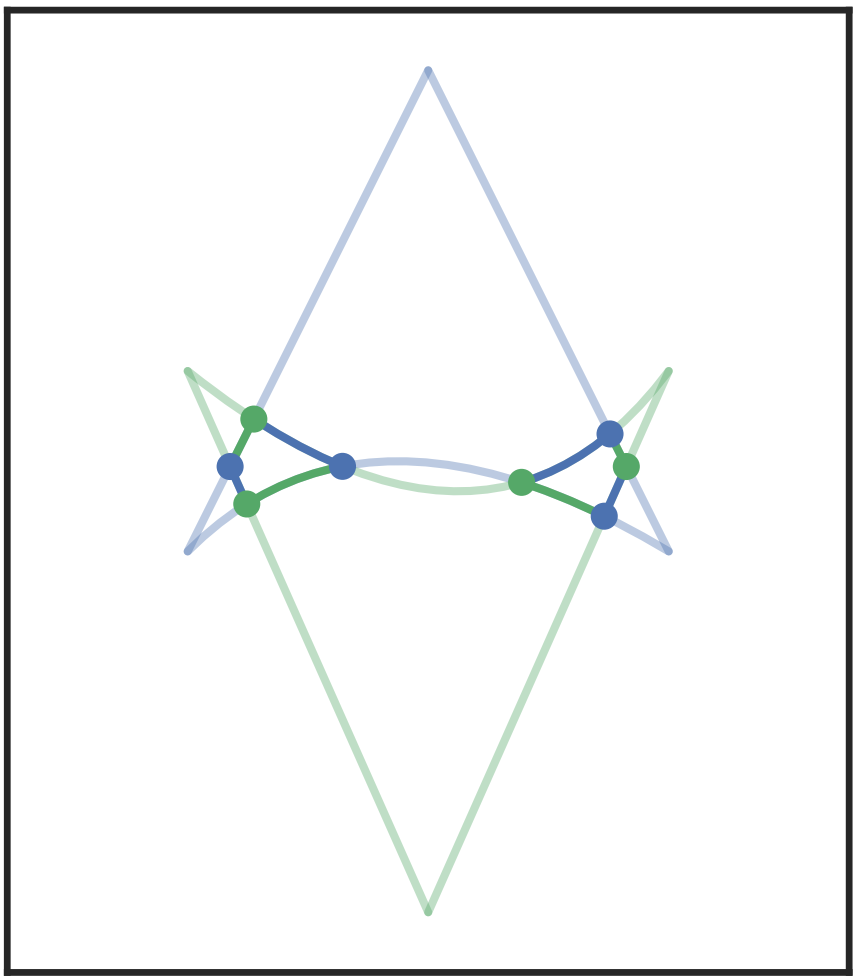
Numerical Experiments



Ill-conditioned Bézier Curve Intersection

Ill-Conditioned Intersections





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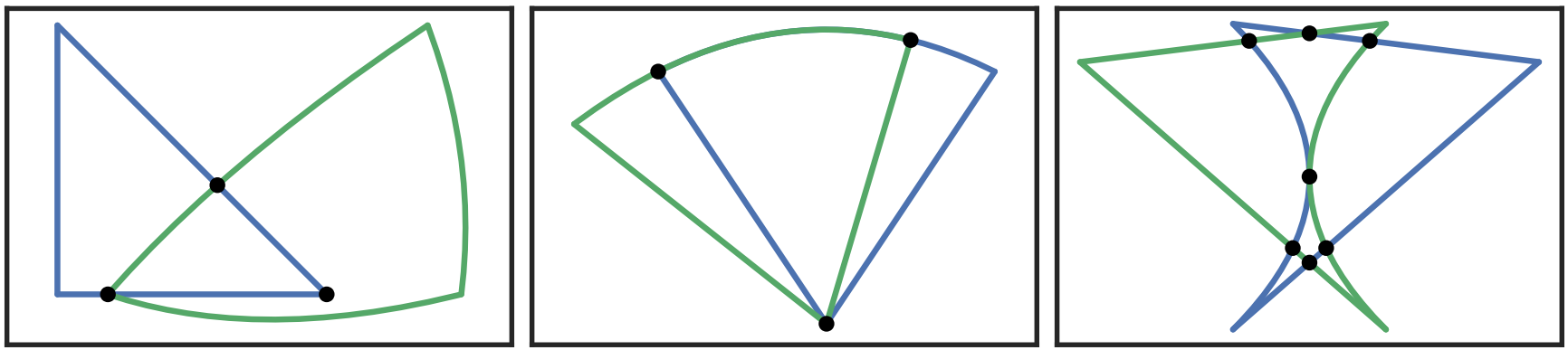

Ill-Conditioned Intersections

- Edges are Bézier curves, e.g. $b(r, 0) = \sum_{j=0}^{n} \binom{n}{j} (1 - r)^{n-j} r^j \, \boldsymbol{p}_{n-j,j,0}$

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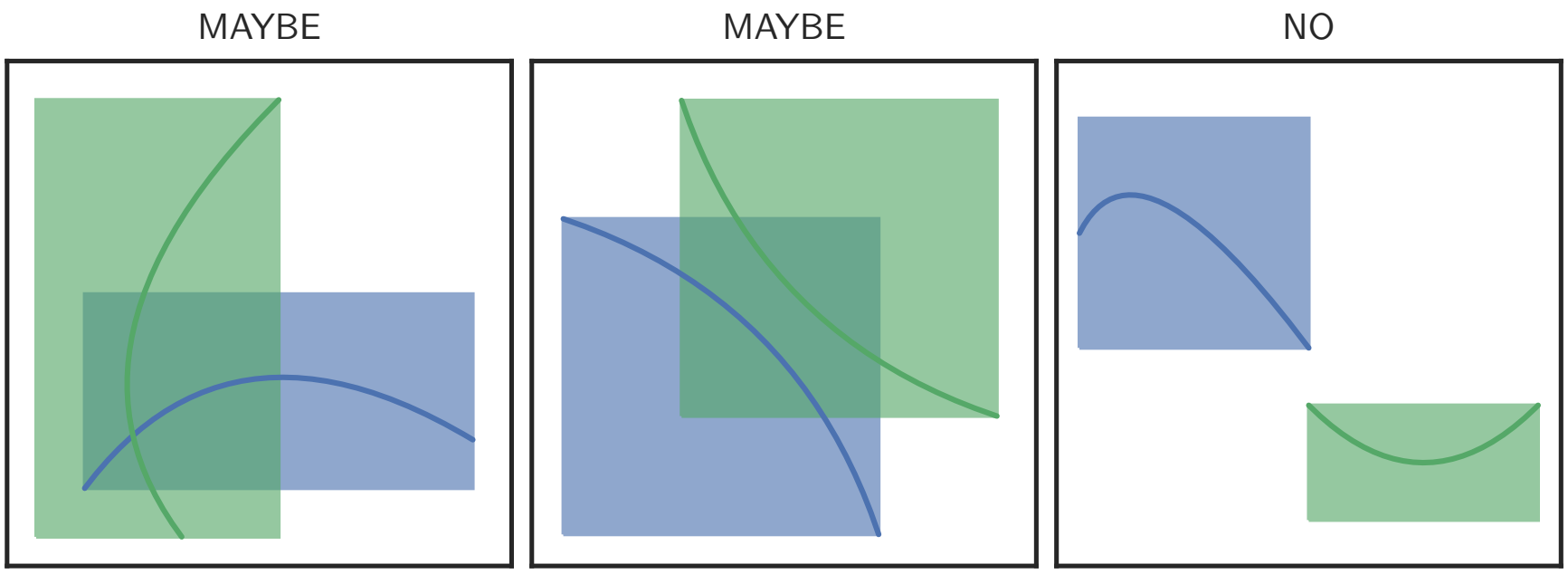
- Random pair of meshes, “almost tangent” intersections increasingly frequent as $h \longrightarrow 0^+$

Intersection Algorithm

- Bounding box check

Intersection Algorithm



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- Curve subdivision

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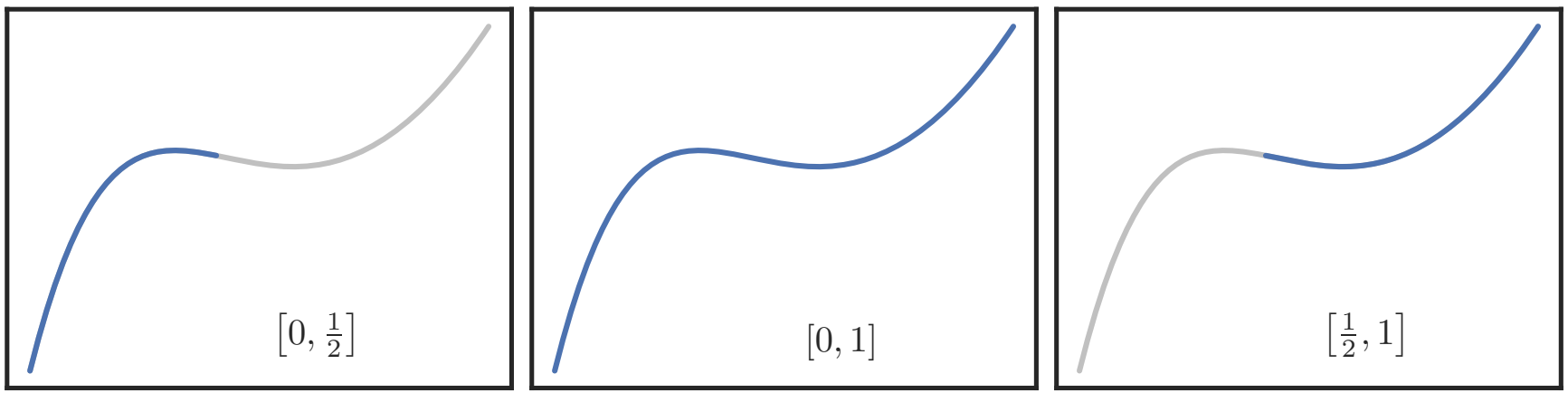

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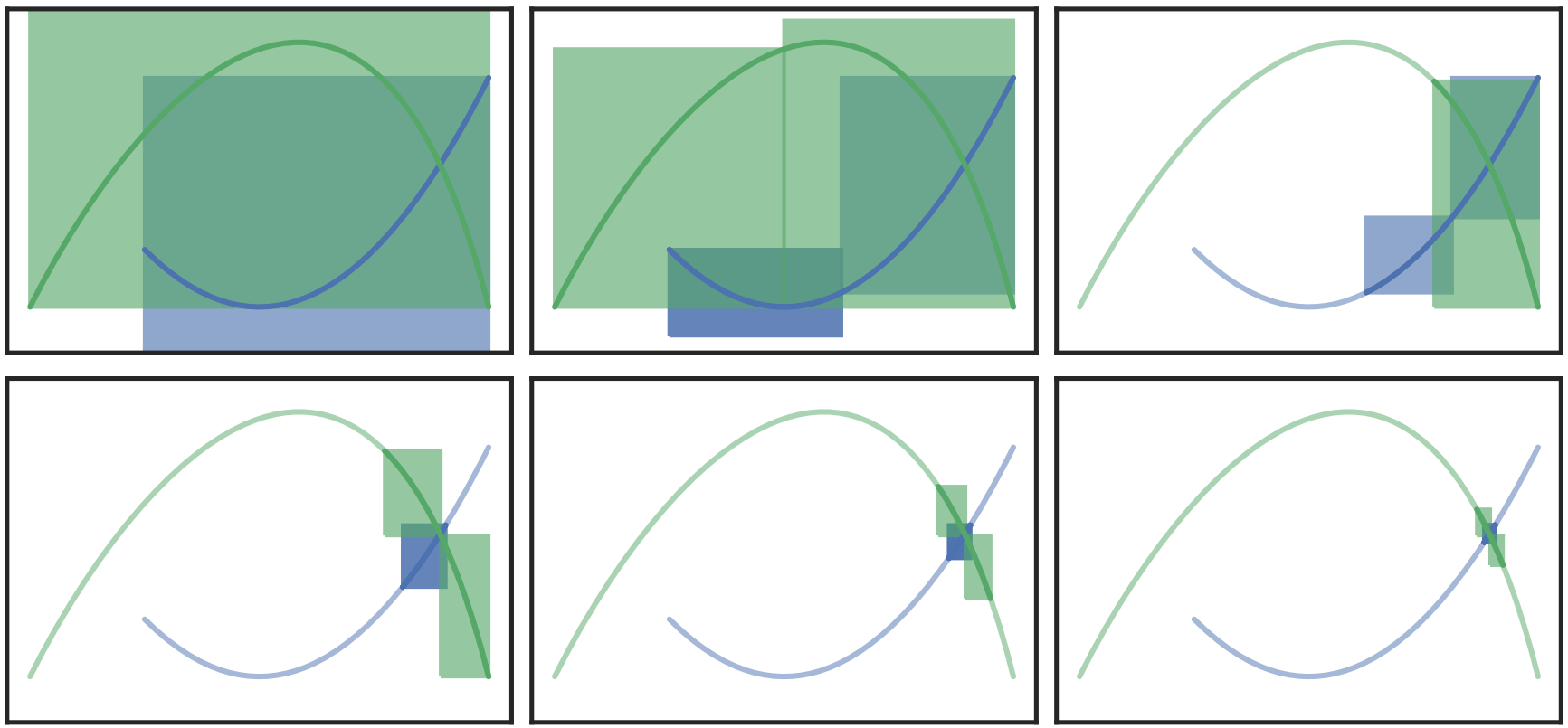

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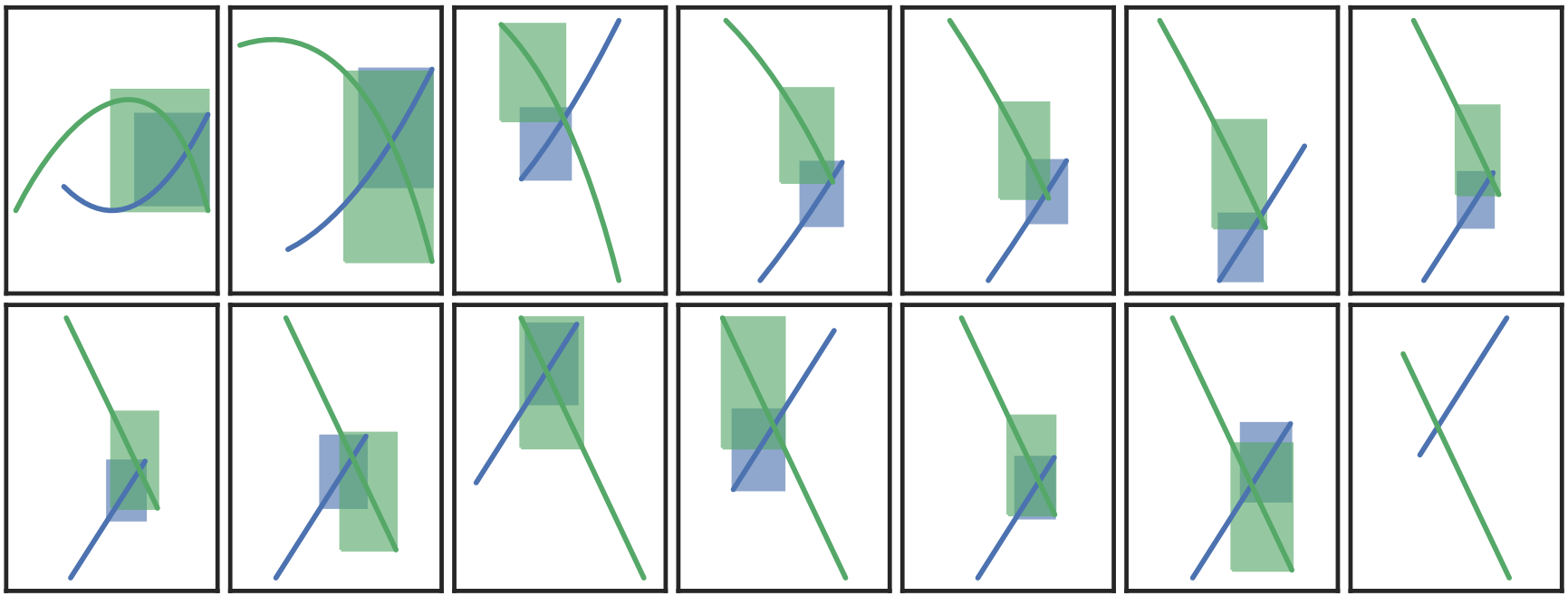

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- Check subdivided pairs
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- Use intersection of lines as seed for Newton’s method

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- At ill-conditioned intersections, J is almost singular and evaluation of F is typically ill-conditioned as well

Modified Newton's Method

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  - Tisseur (2001) showed this generically and applied to iterative refinement for generalized eigenvalue problem

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- **Compensated** algorithm uses $\widehat{f} \oplus \widehat{e}$; better approximation of $f(x)$ than $\widehat{f}$ (usually)

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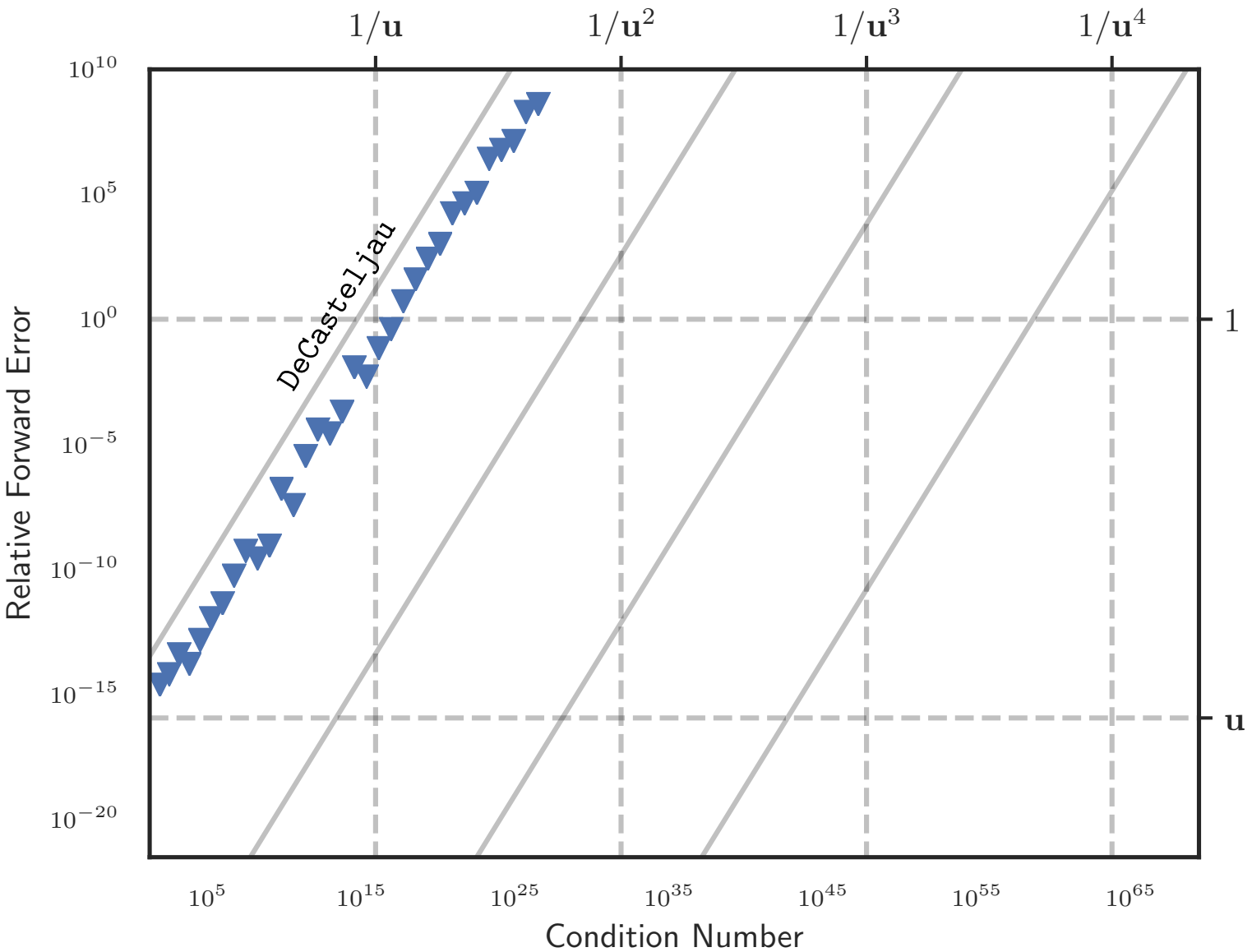
- Test polynomial $p(s) = (s-1)\left(s-\frac{3}{4}\right)^7$; evaluation at $s = \frac{3}{4}$ has infinite condition, very ill-conditioned nearby

Compensated de Castlejau

$$\frac{|p(s) - \texttt{DeCasteljau}\,(p, s)|}{|p(s)|} \leq \operatorname{cond}(p, s) \cdot \mathcal{O}(\mathbf{u})$$

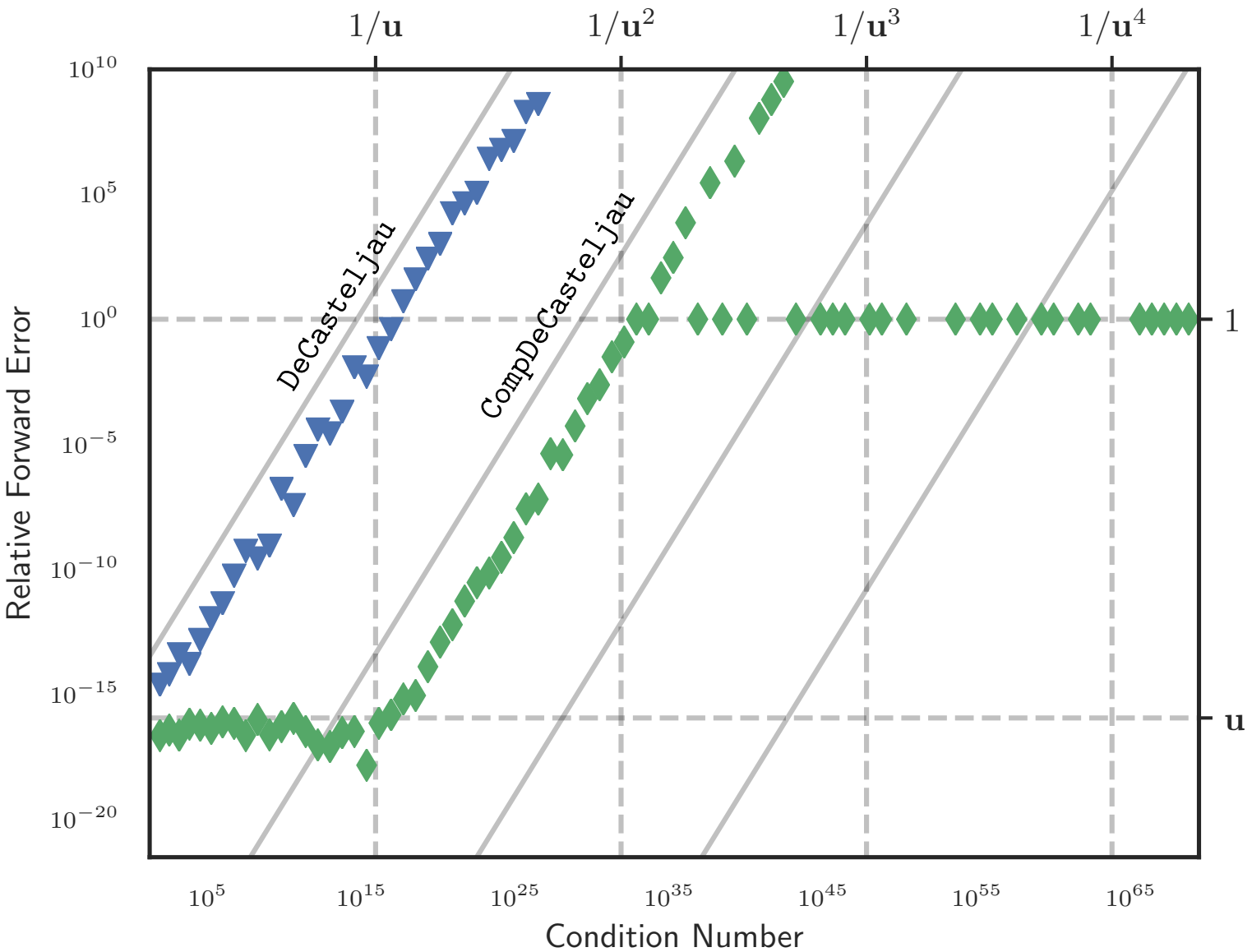
Compensated de Castlejau



Compensated de Castlejau

$$\frac{|p(s) - \texttt{CompDeCasteljau}\,(p, s)|}{|p(s)|} \leq \mathcal{O}\left(\mathbf{u}\right) + \operatorname{cond}\left(p, s\right) \cdot \mathcal{O}\left(\mathbf{u}^2\right)$$

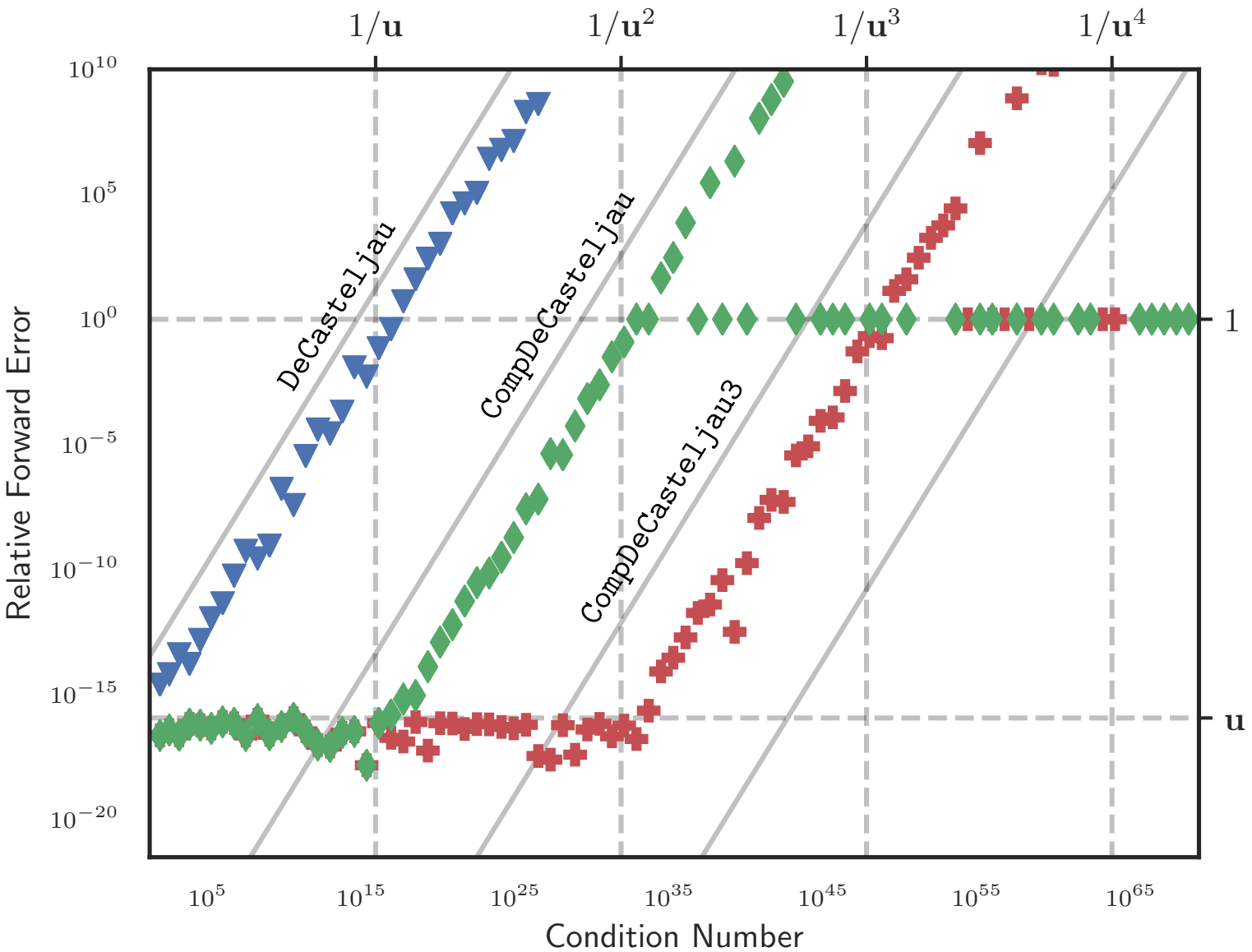
Compensated de Castlejau



Compensated de Castlejau

$$\frac{|p(s) - \texttt{CompDeCasteljauK}\,(p, s)|}{|p(s)|} \leq \mathcal{O}\,(\mathbf{u}) + \mathrm{cond}\,(p, s) \cdot \mathcal{O}\left(\mathbf{u}^K\right)$$

Compensated de Castlejau



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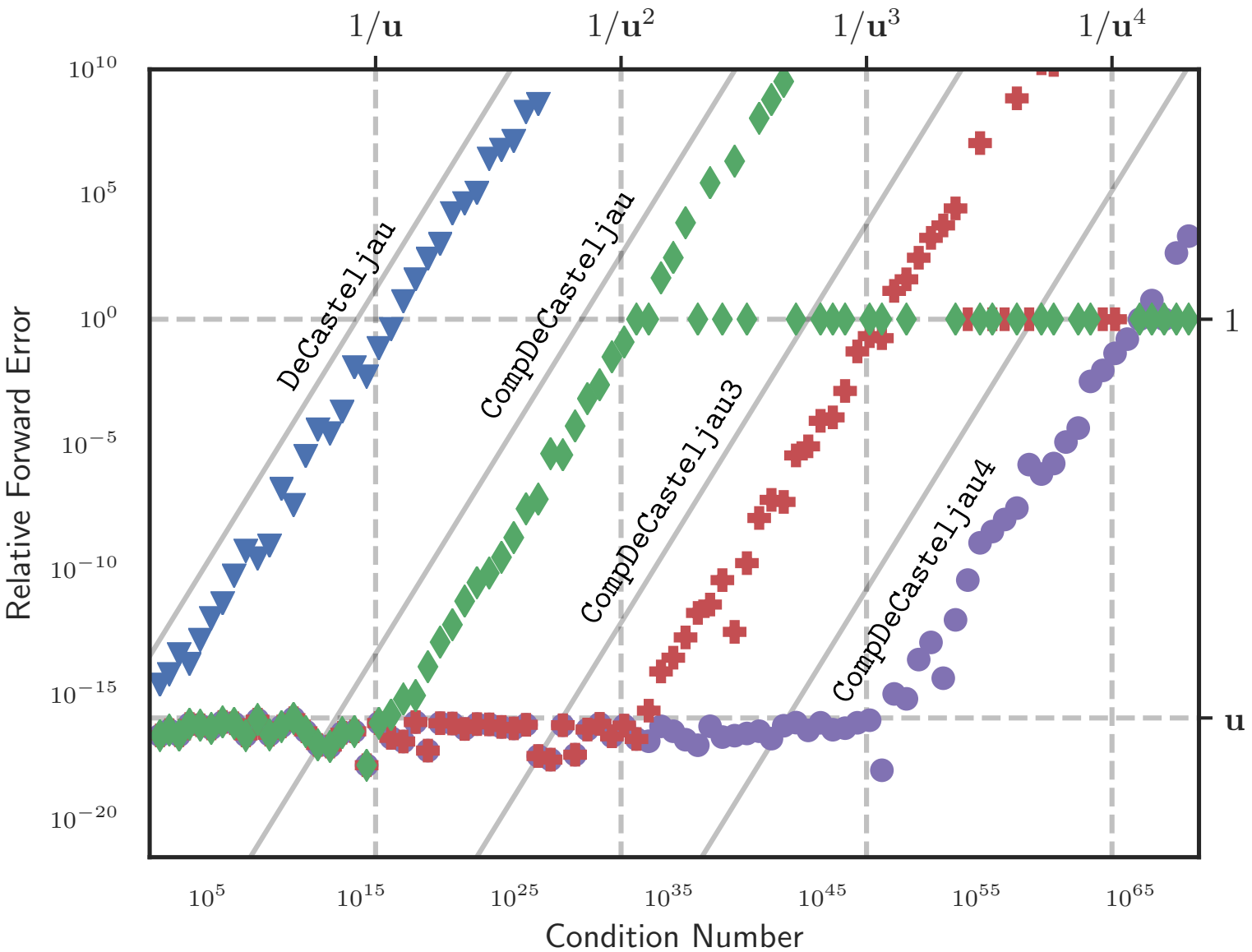

Modified Newton's for Intersection

Polynomial Roots

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  - `DNewtonFull`: `CompDeCasteljau` for residual and Jacobian

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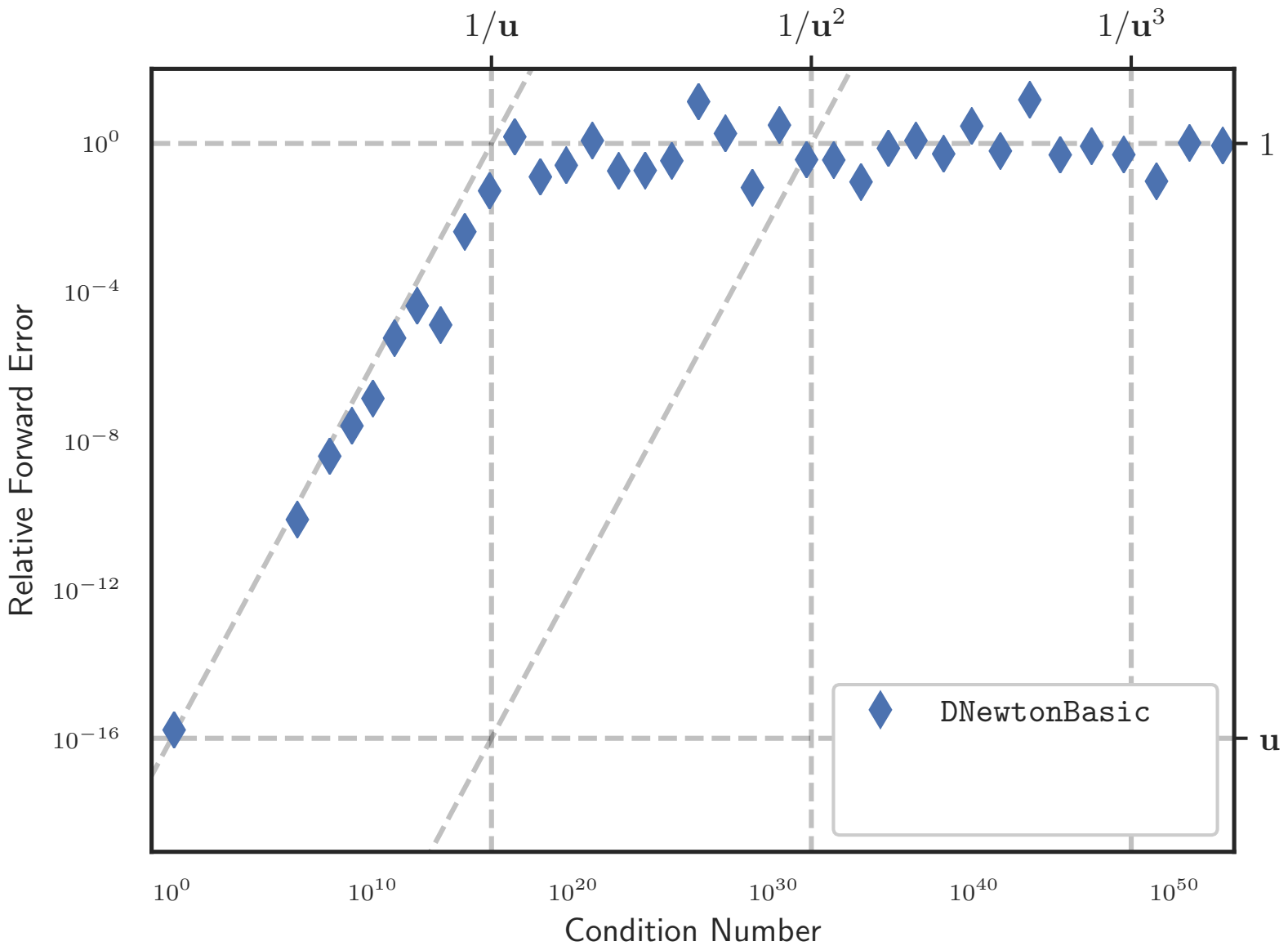
- Root $\alpha = \dfrac{1 + 2^{30/n}}{5 + 3 \cdot 2^{30/n}} \in \left[\dfrac{1}{4}, \dfrac{1}{3}\right]$

Polynomial Roots



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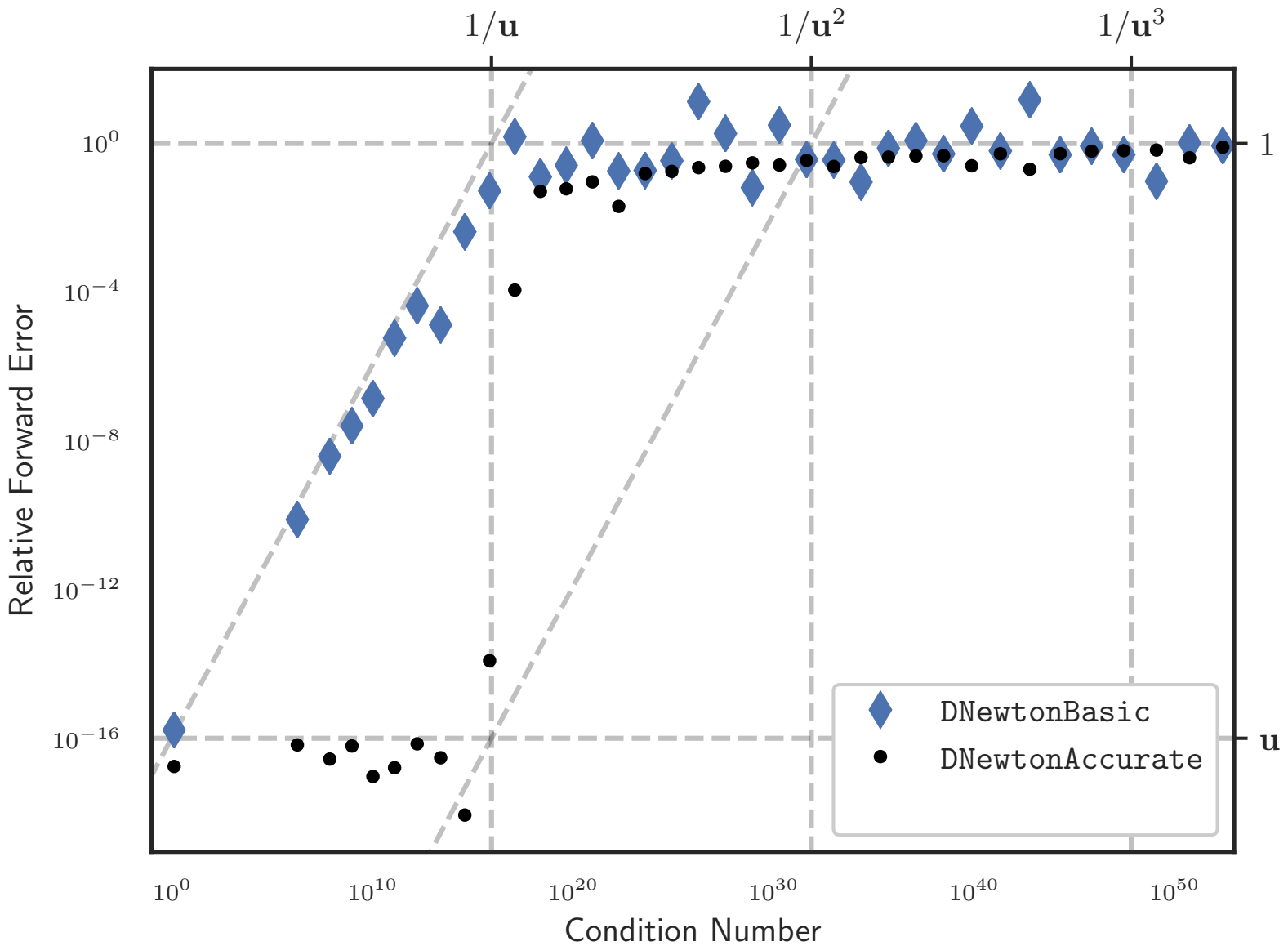

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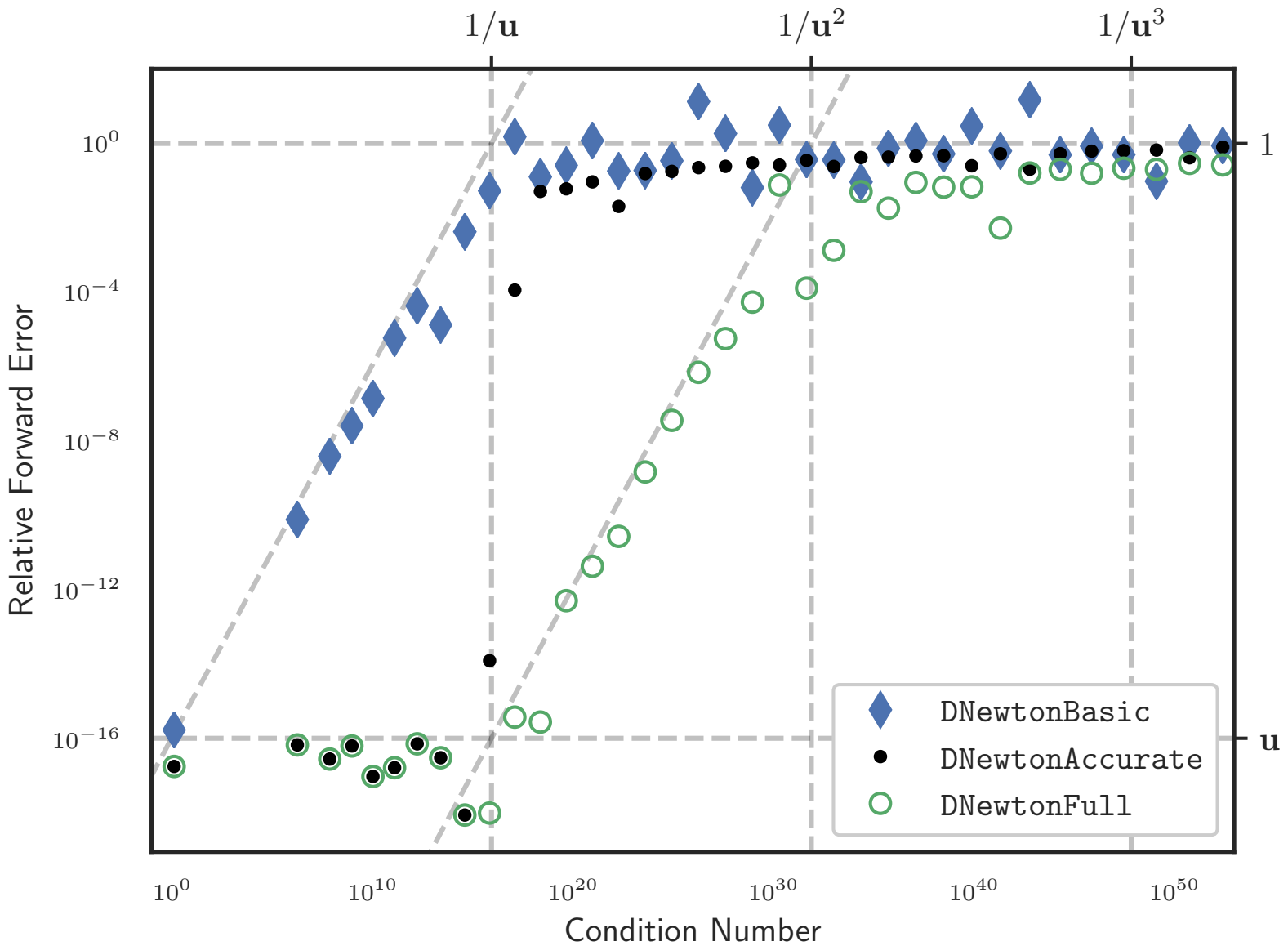

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- Evaluate $x_0(s), y_0(s), x_1(t), y_1(t)$ via de Casteljau
- Modify Newton's method by using "extended precision" (i.e. compensated method) for $\widehat{F}$

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- Fails; $x_0(s), x_1(t)$ may not be near zero, e.g. $\widehat{x}_0 \oplus \widehat{e}_0 = \widehat{x}_0$

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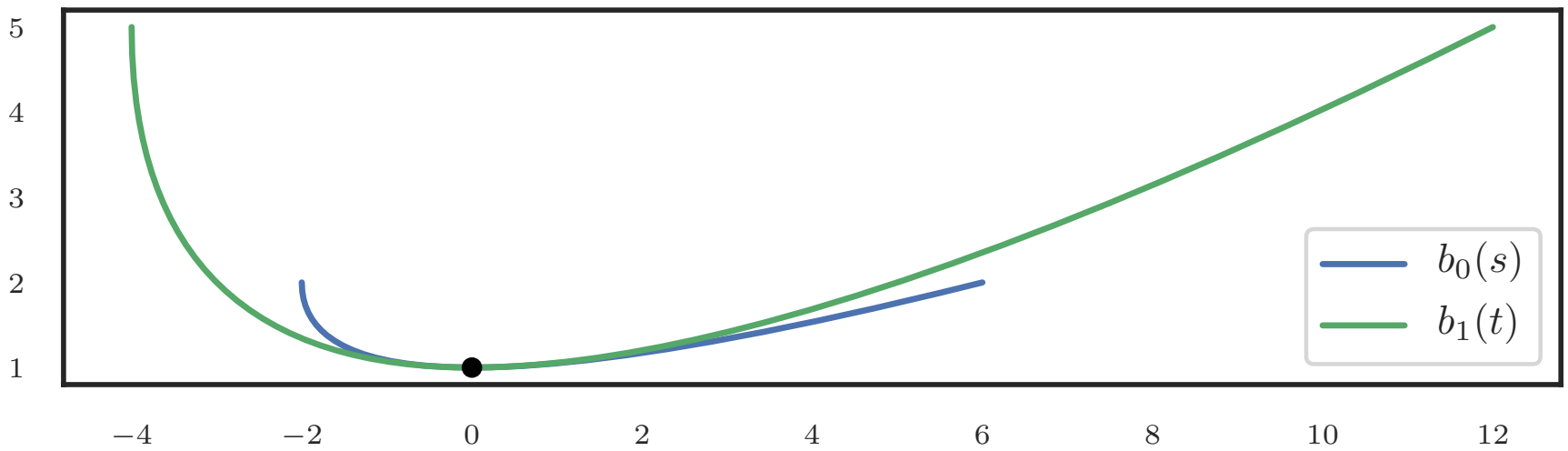

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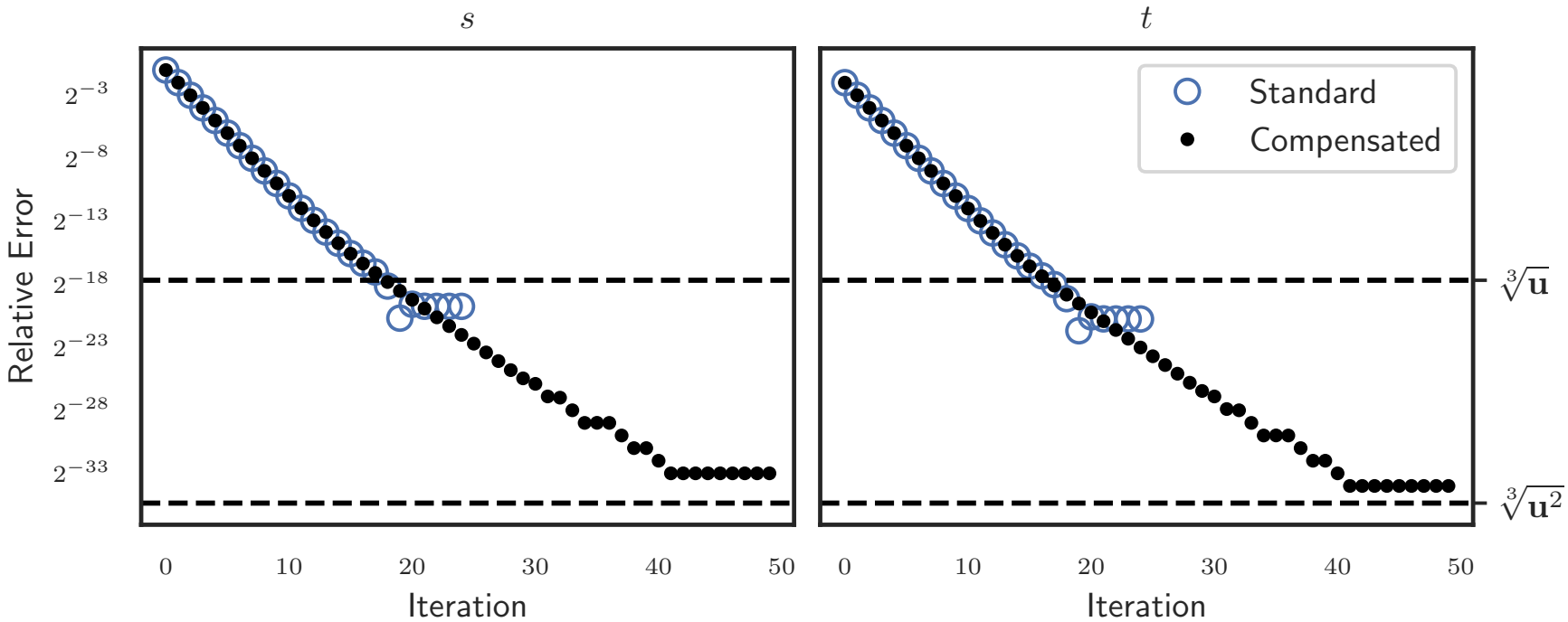

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Approaches triple root as $r \longrightarrow 0^+$, $F\left(\frac{1+\sqrt{r}}{2}, \frac{2+\sqrt{r}}{4}\right)$

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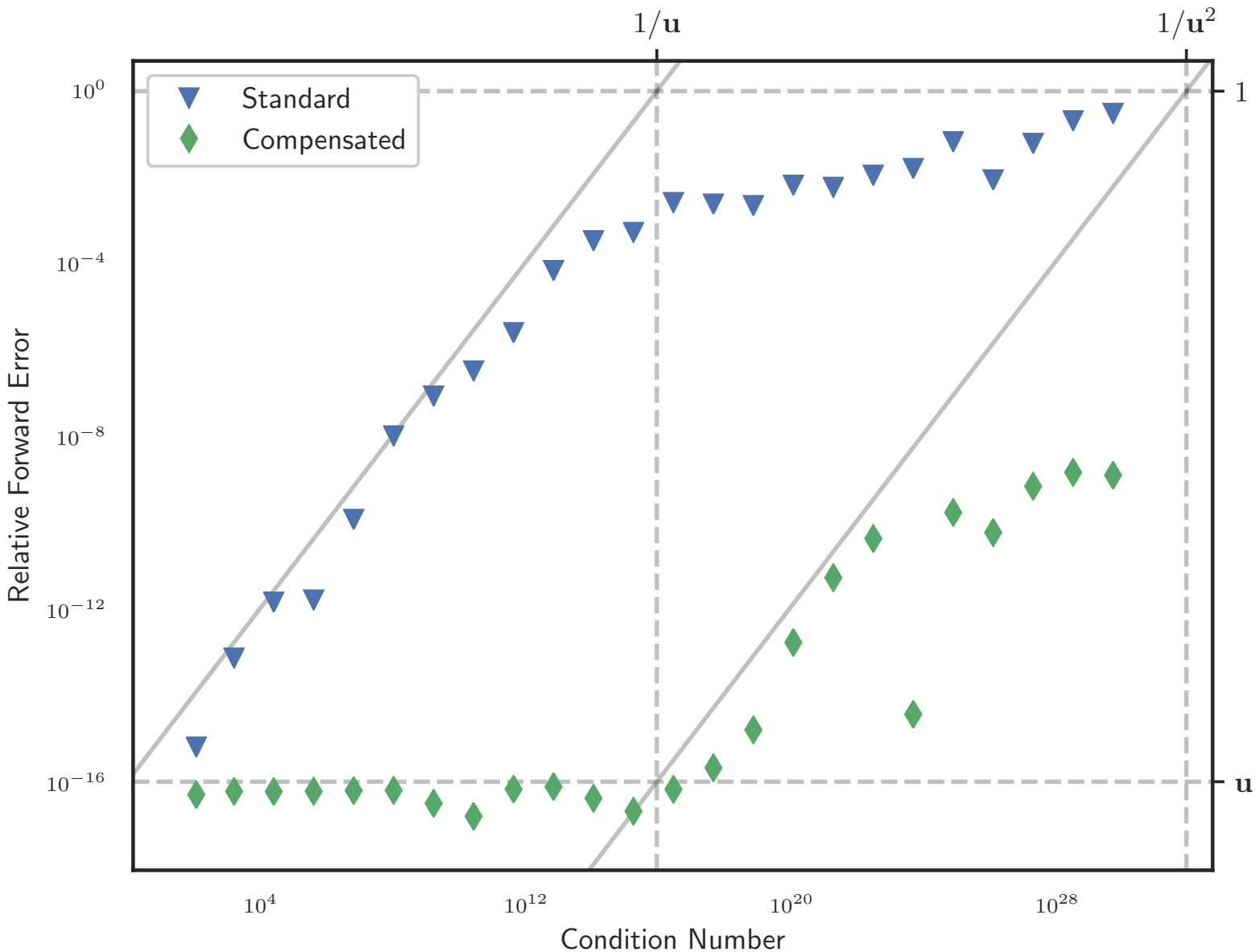

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  - Modified Newton's method; computes residual $F(s, t)$ as if in extended precision

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- Parallelize via domain decomposition (inherently local)