A Linear Consolidation Approach for Automatically Extracting Roads of Variable Widths from Overhead Images

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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

UCRL-PRES-226133

Introductory Remarks

Goal:

- To develop an algorithm that robustly extracts lines of communication (roads) from overhead images

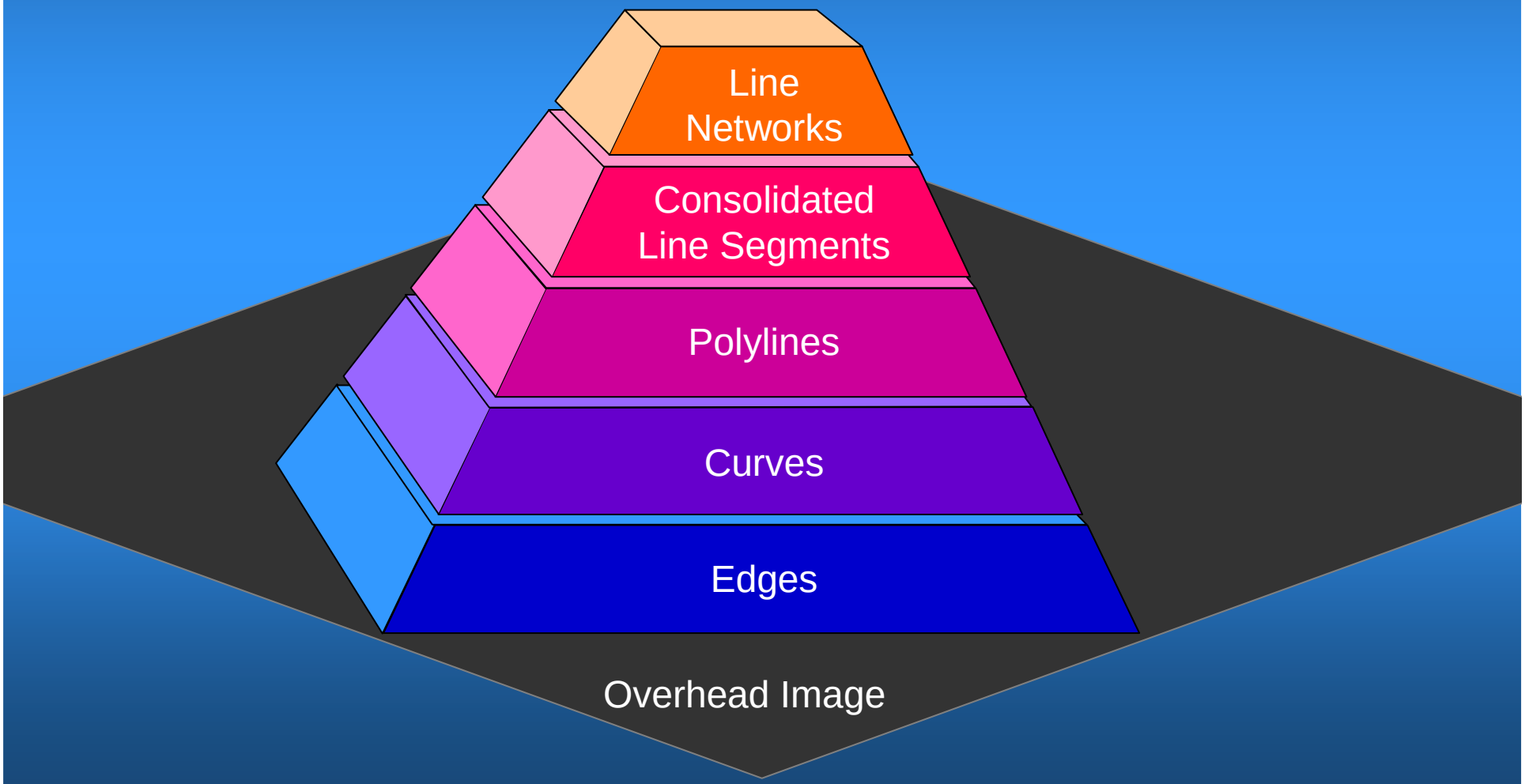
Motivating Applications:

- Assisted update of GIS road networks:
  - Track changes to road networks to detect new activity
- Detection of interesting objects using lines of communication information
  - Interconnected Facilities
  - Vehicles

Approach:

- Model roads as a set of relatively long and interconnected parallel edges
- Hierarchical “bottom-up” extraction where higher levels build on results from lower ones

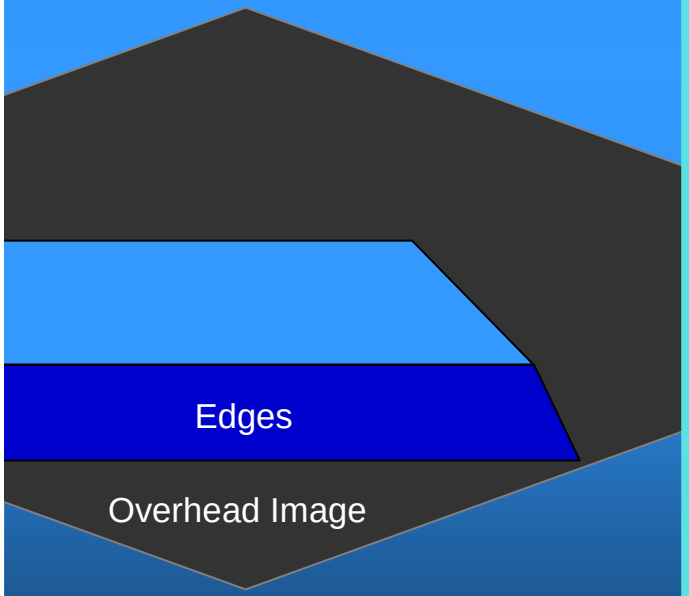
Hierarchical Approach for Extracting Lines of Communication

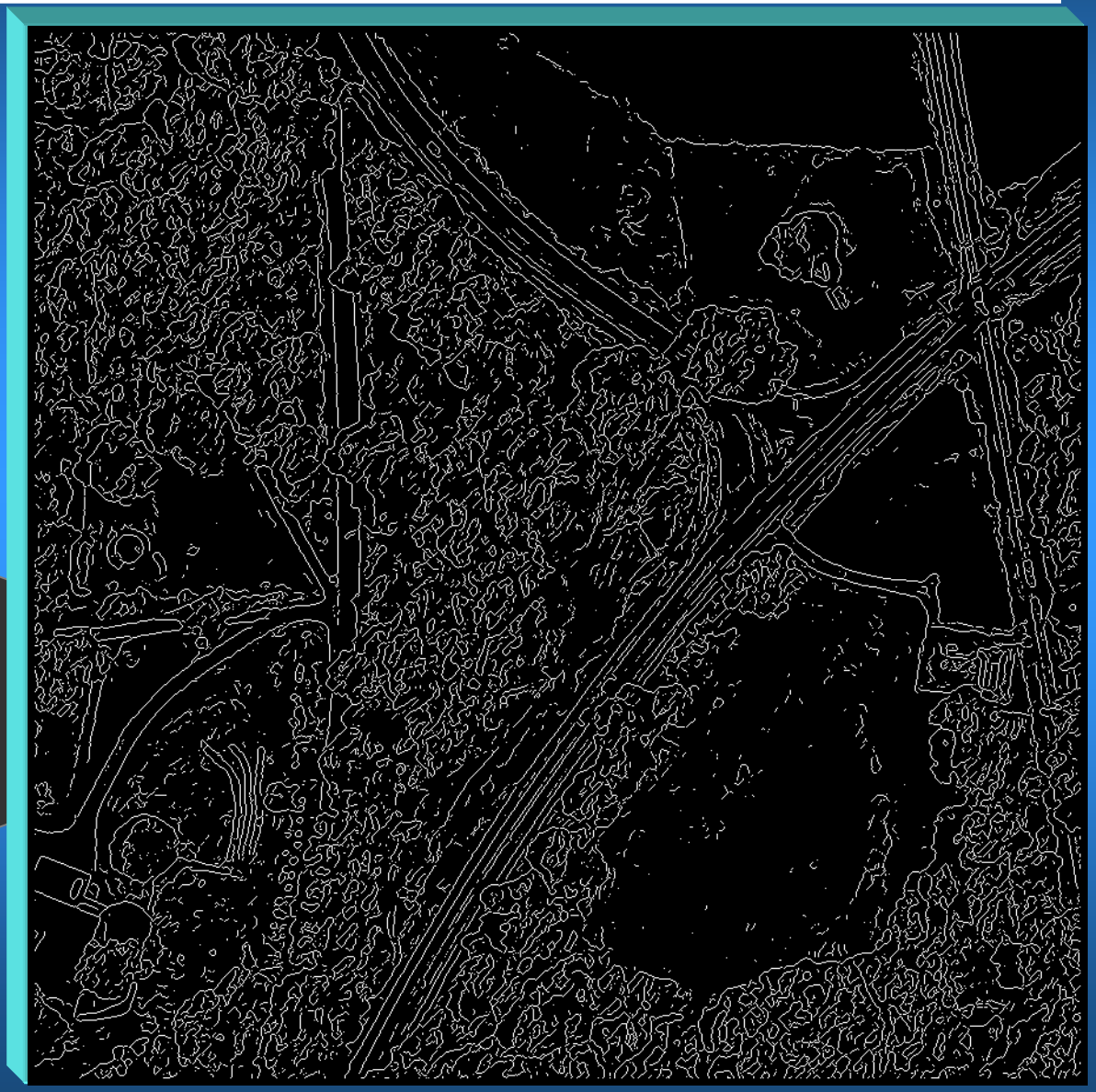


Rural Scene Example: Image

Overhead Image

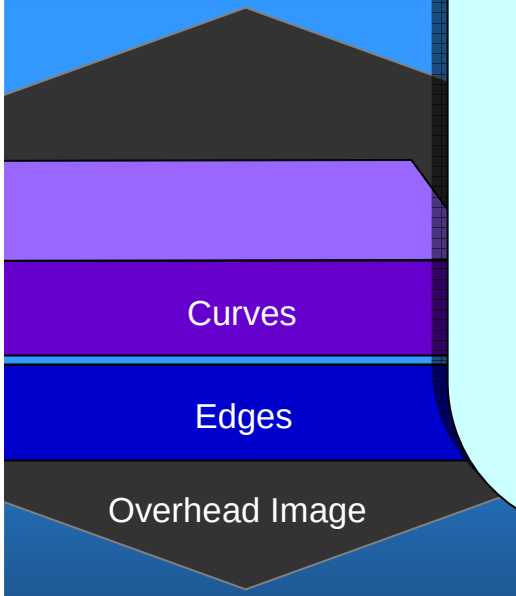
Edge Pixels from a Gradient-Based Edge Detector

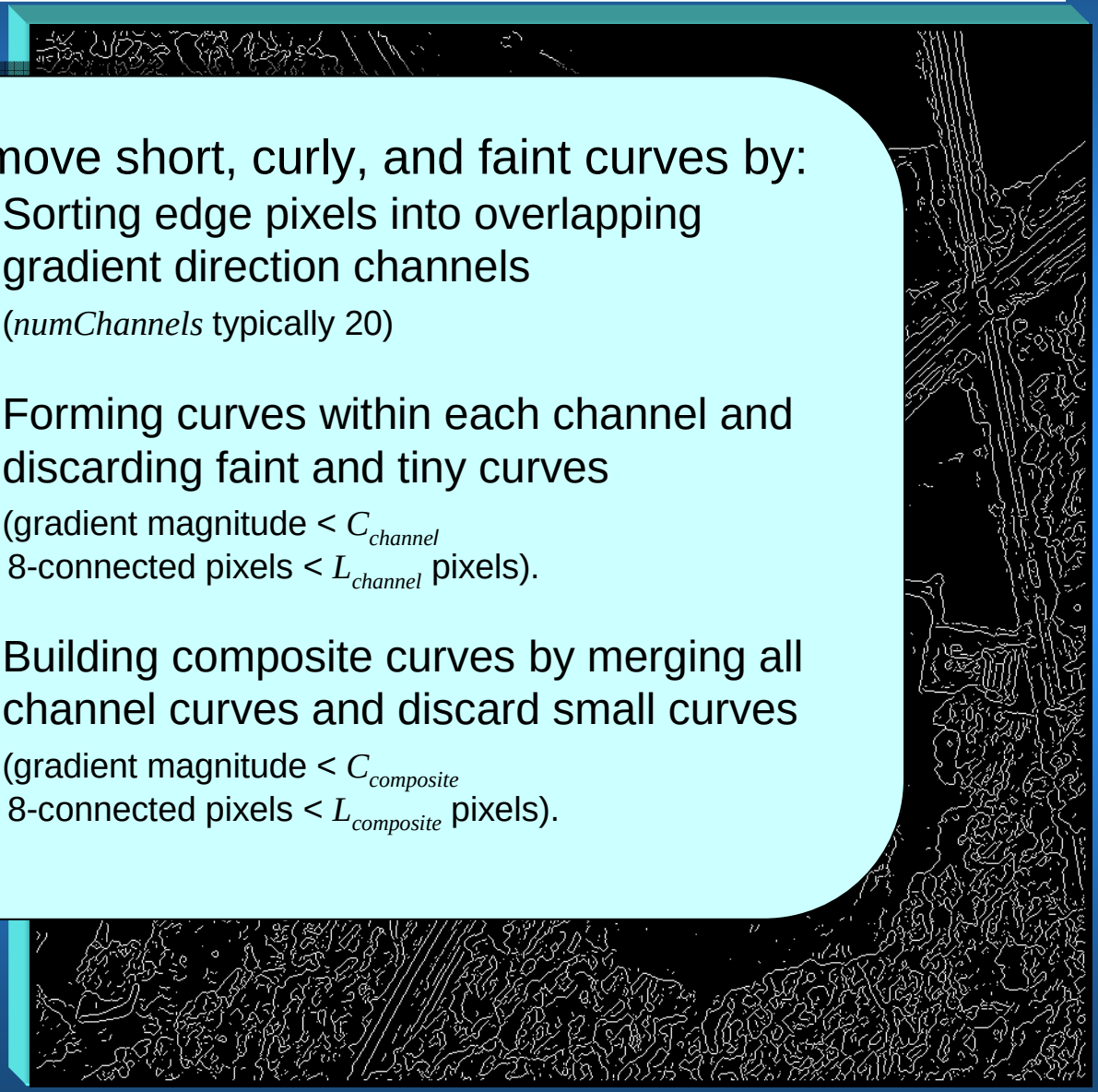




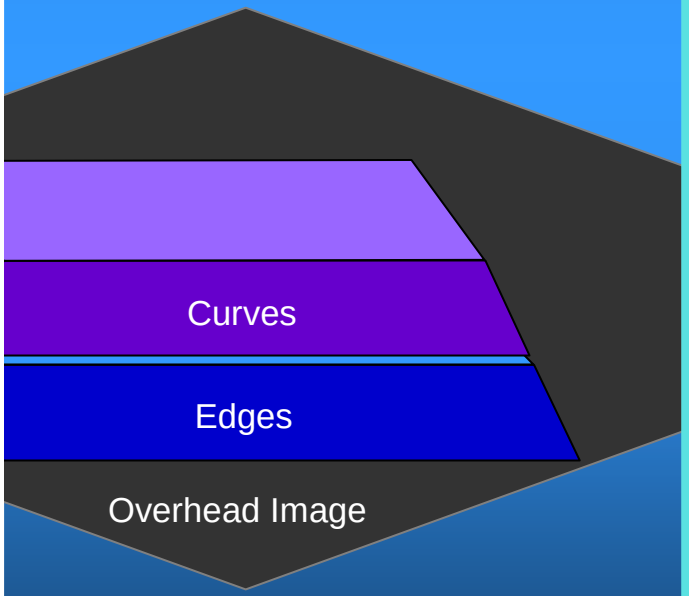
Orientation Channel De-Cluttering

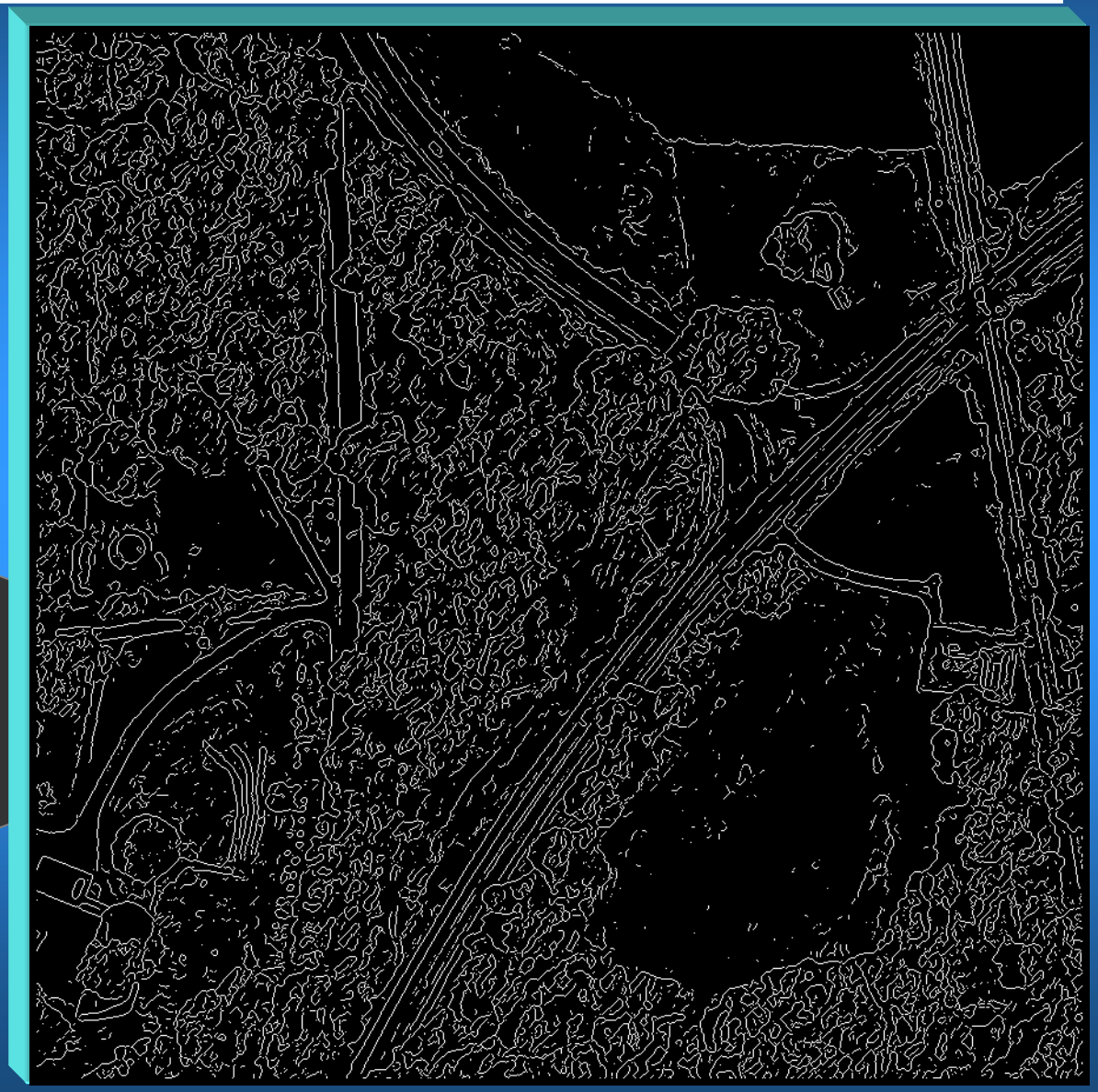
- Remove short, curly, and faint curves by:
  1. Sorting edge pixels into overlapping gradient direction channels
     (*numChannels* typically 20)
  2. Forming curves within each channel and discarding faint and tiny curves
     (gradient magnitude < $C_{channel}$
     8-connected pixels < $L_{channel}$ pixels).
  3. Building composite curves by merging all channel curves and discard small curves
     (gradient magnitude < $C_{composite}$
     8-connected pixels < $L_{composite}$ pixels).





Orientation Channel De-Cluttering

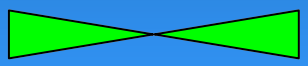


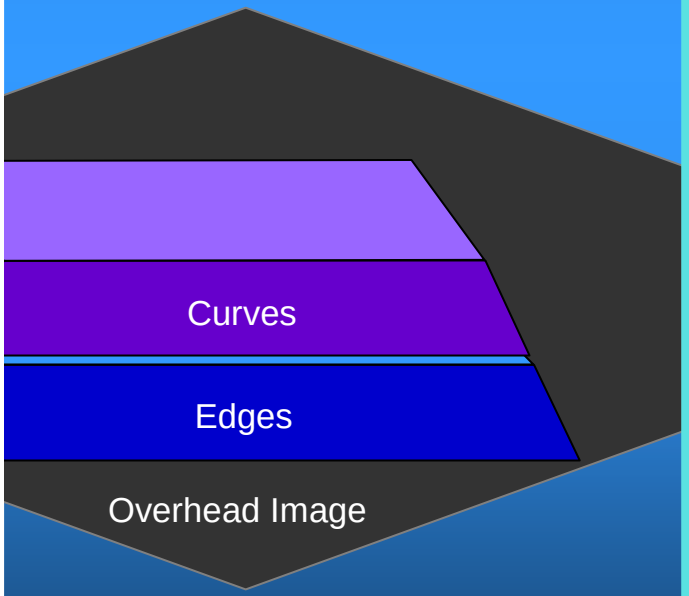


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

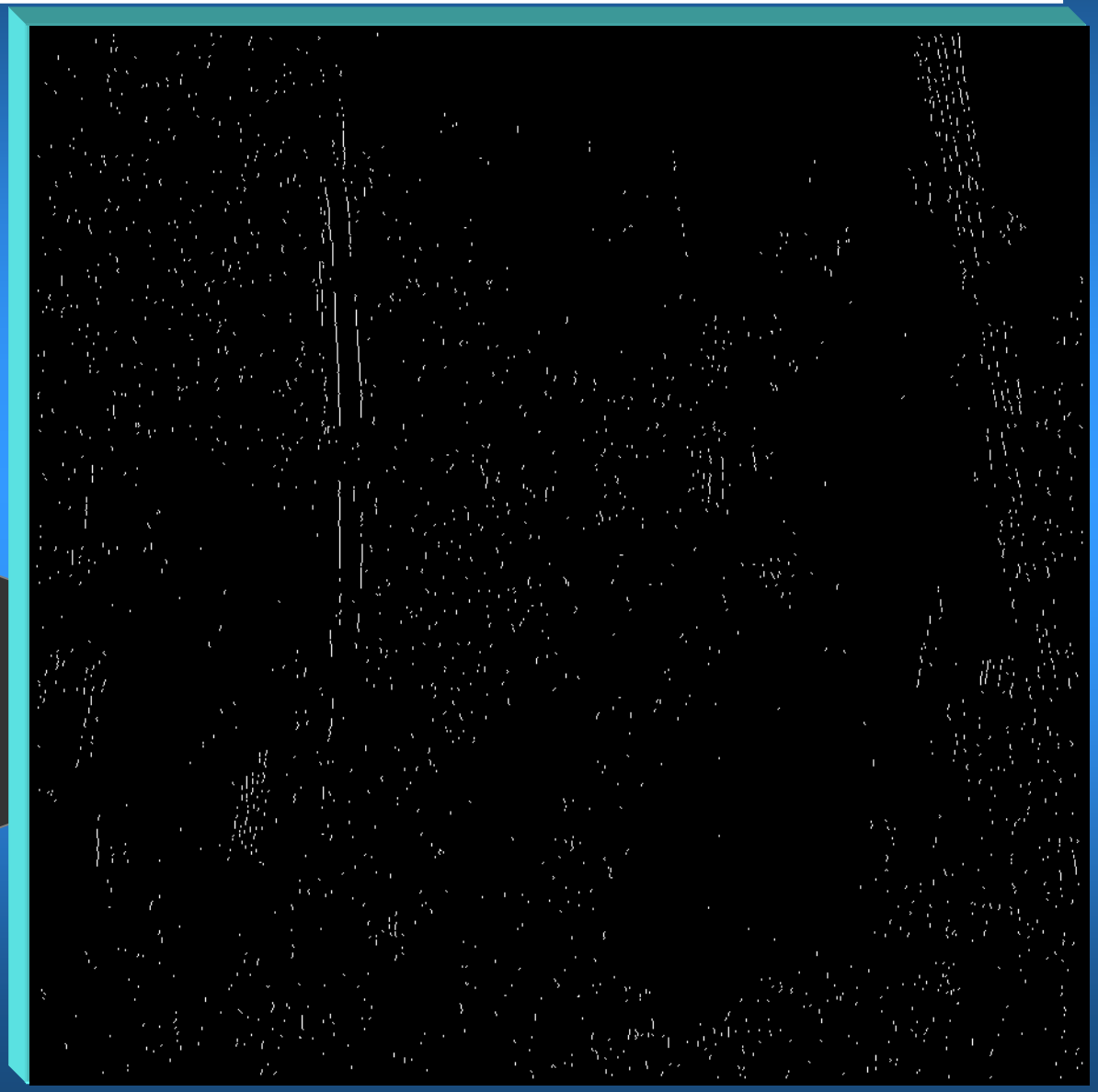
$171^\circ \le \theta \le 189^\circ$ & $-9^\circ \le \theta \le 9^\circ$





$numChannels = 20,$

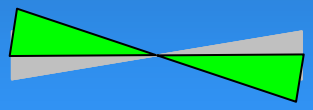
$C_{channel} = 12.0,\ L_{channel} = 2$

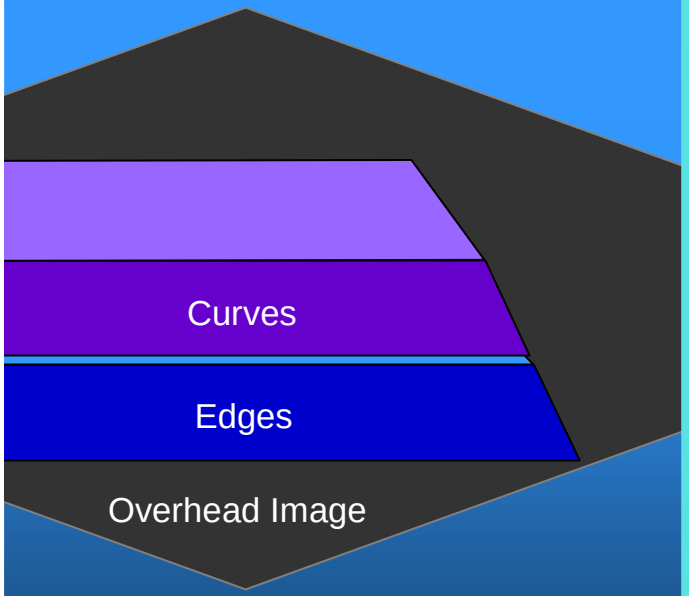


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$162^\circ \le \theta \le 180^\circ$ & $-18^\circ \le \theta \le 0^\circ$





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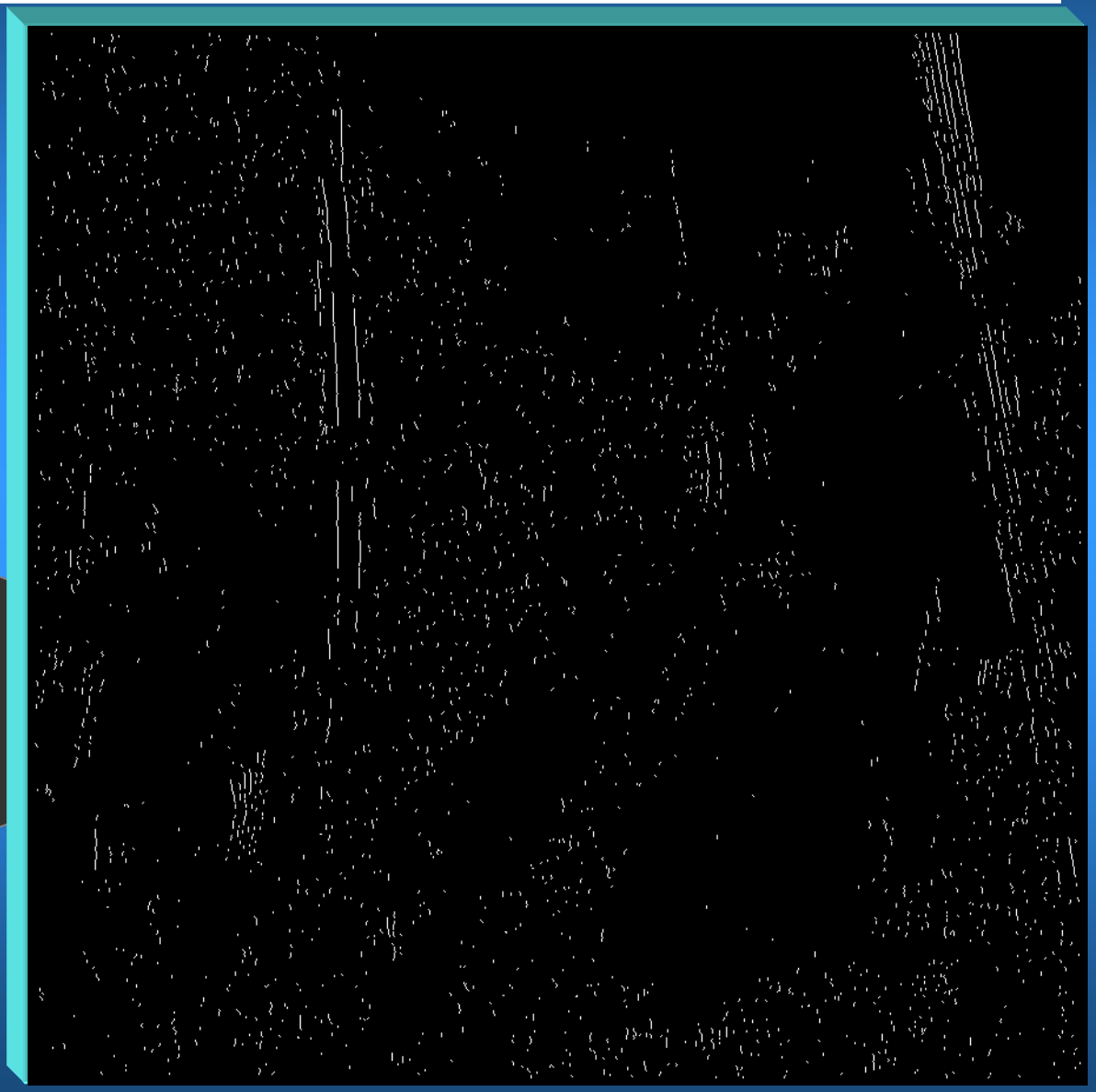
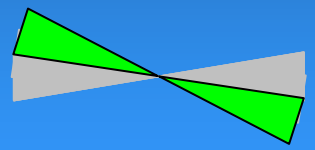
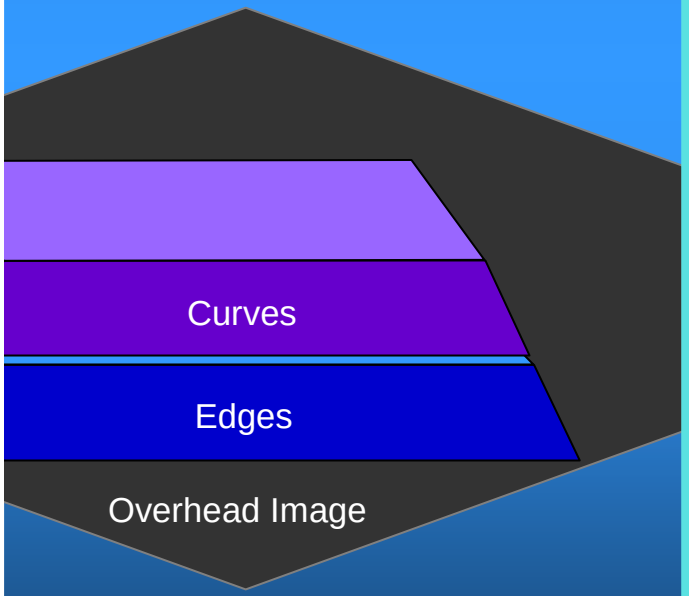


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$153^\circ \le \theta \le 171^\circ$ & $-27^\circ \le \theta \le -9^\circ$





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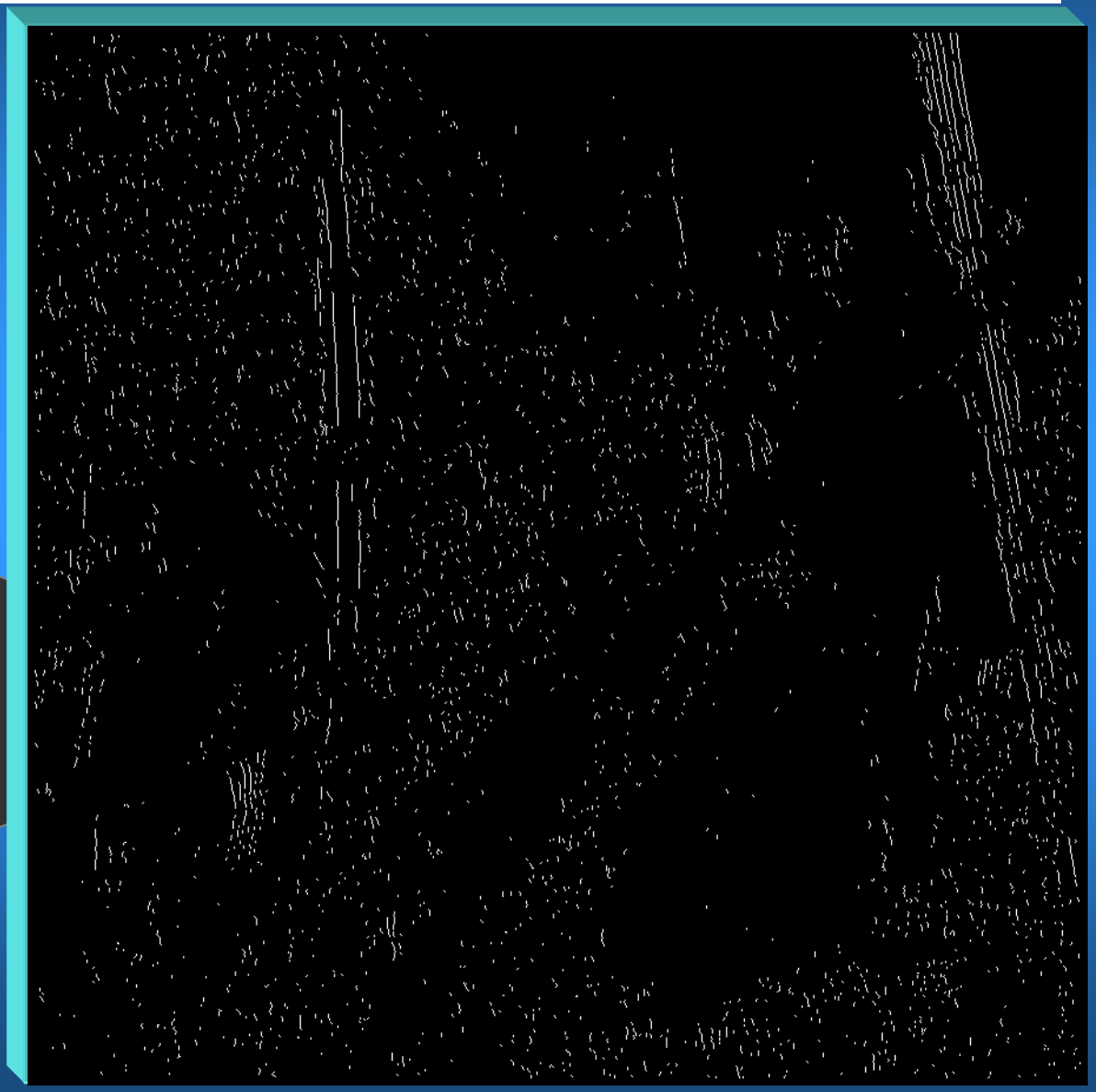
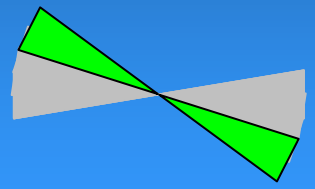
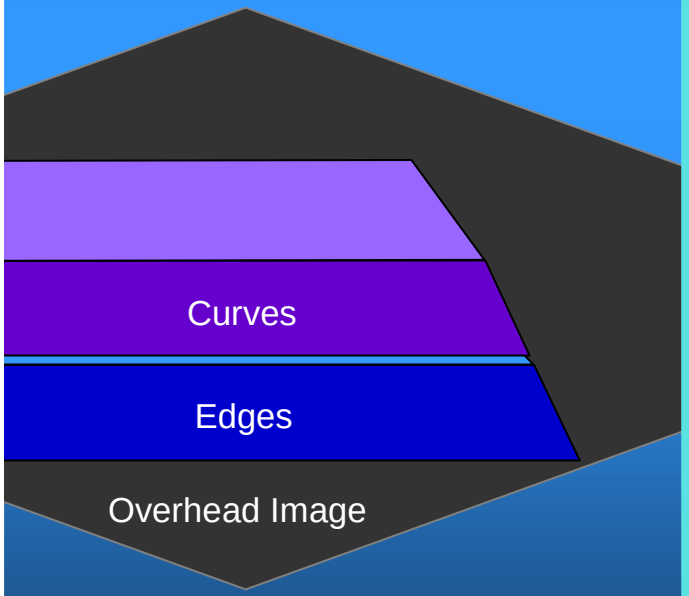


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$144^\circ \le \theta \le 162^\circ$ & $-36^\circ \le \theta \le -18^\circ$





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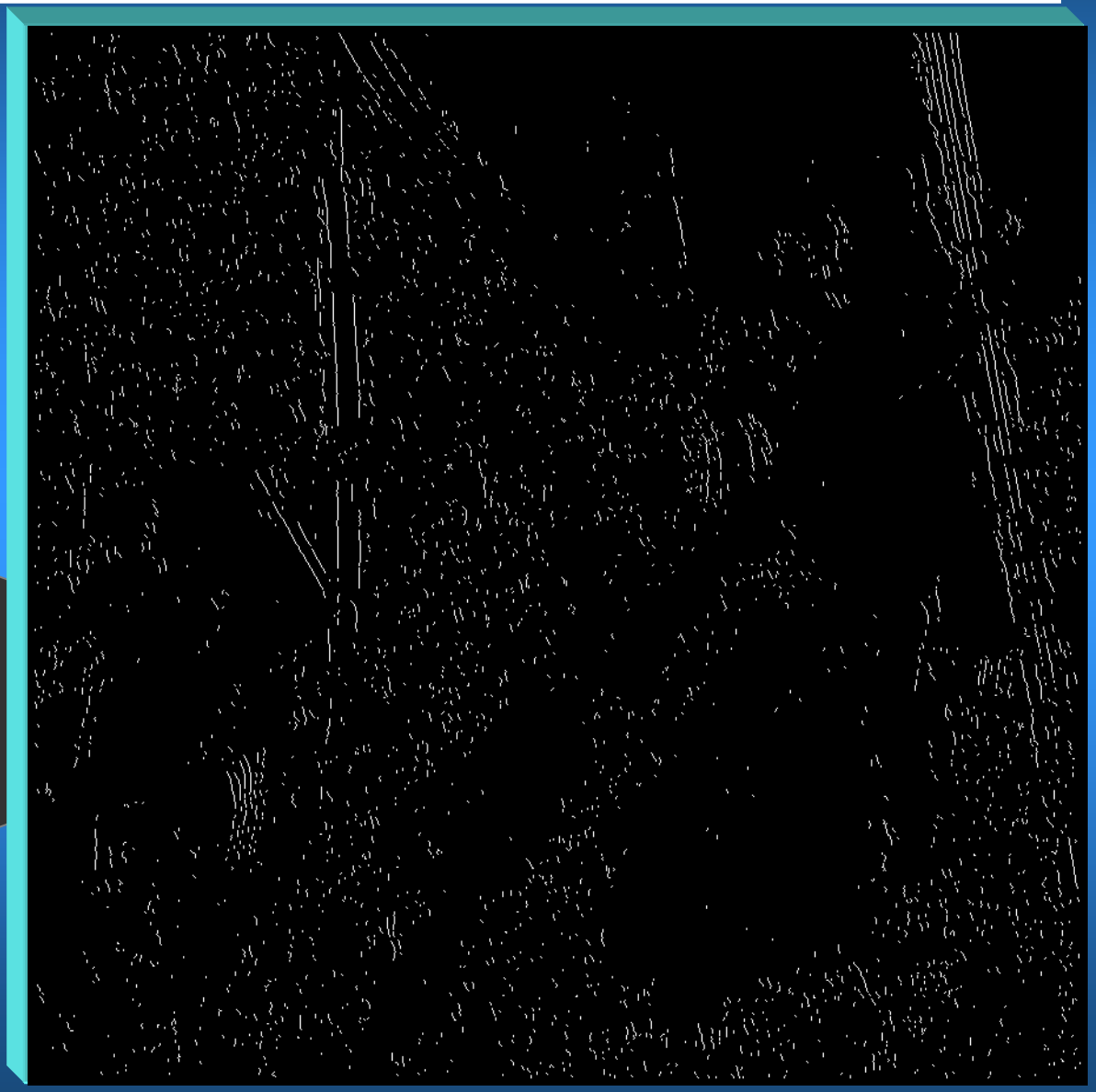
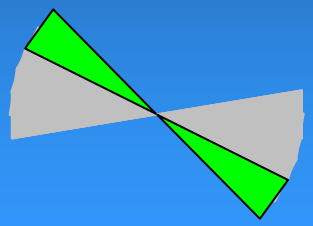
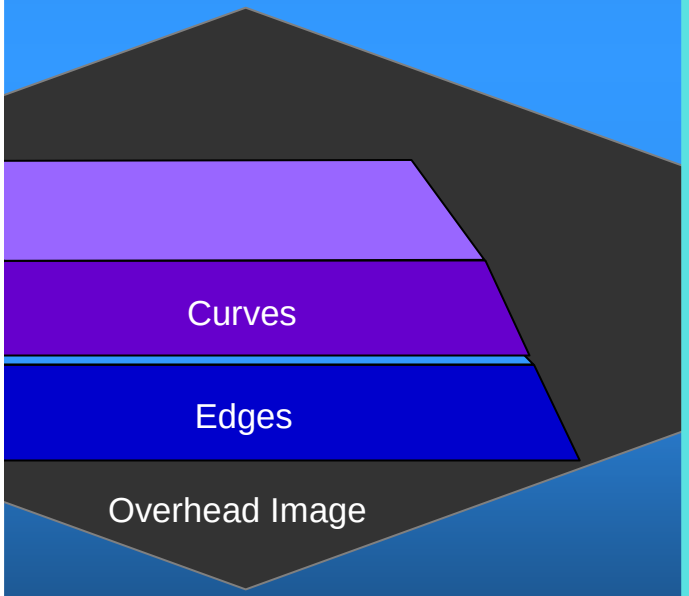


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$136^\circ \le \theta \le 153^\circ$ & $-45^\circ \le \theta \le -27^\circ$





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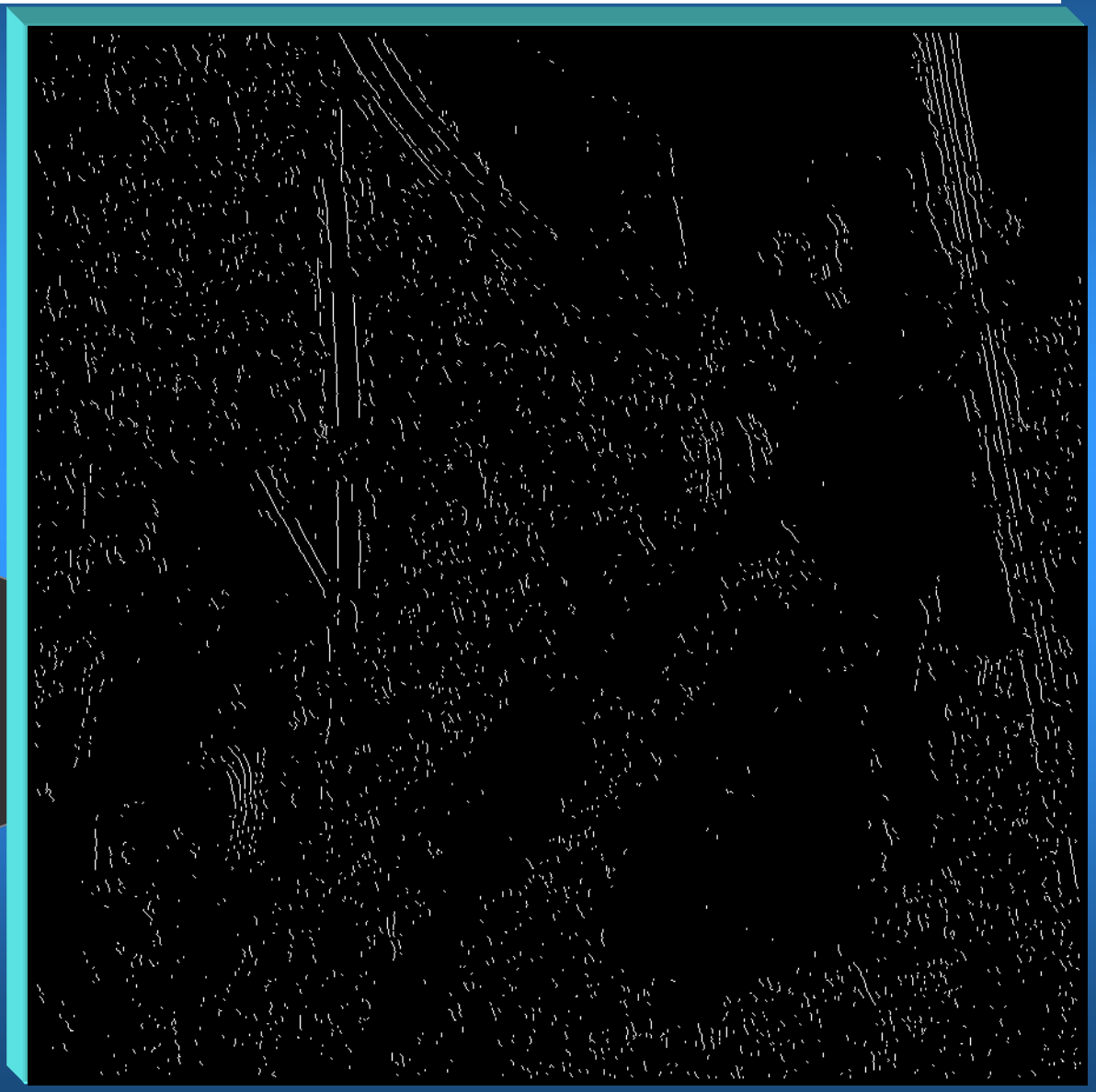
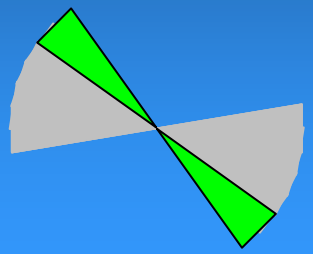
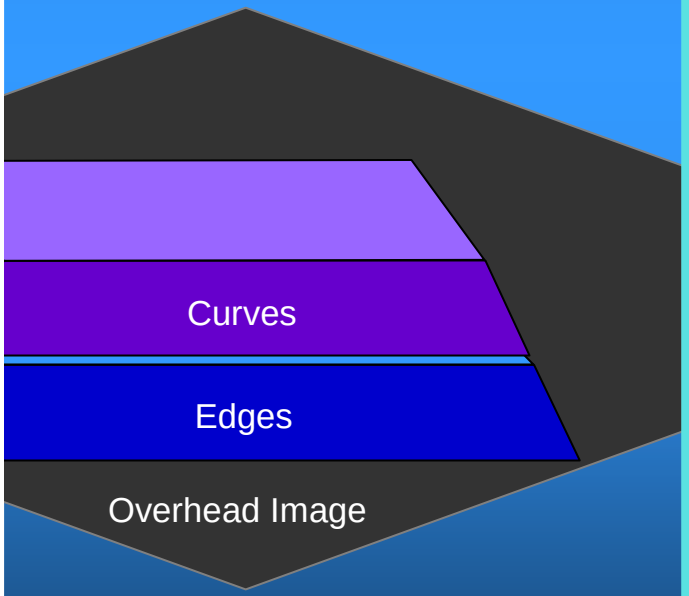


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$126^\circ \le \theta \le 145^\circ$ & $-54^\circ \le \theta \le -36^\circ$





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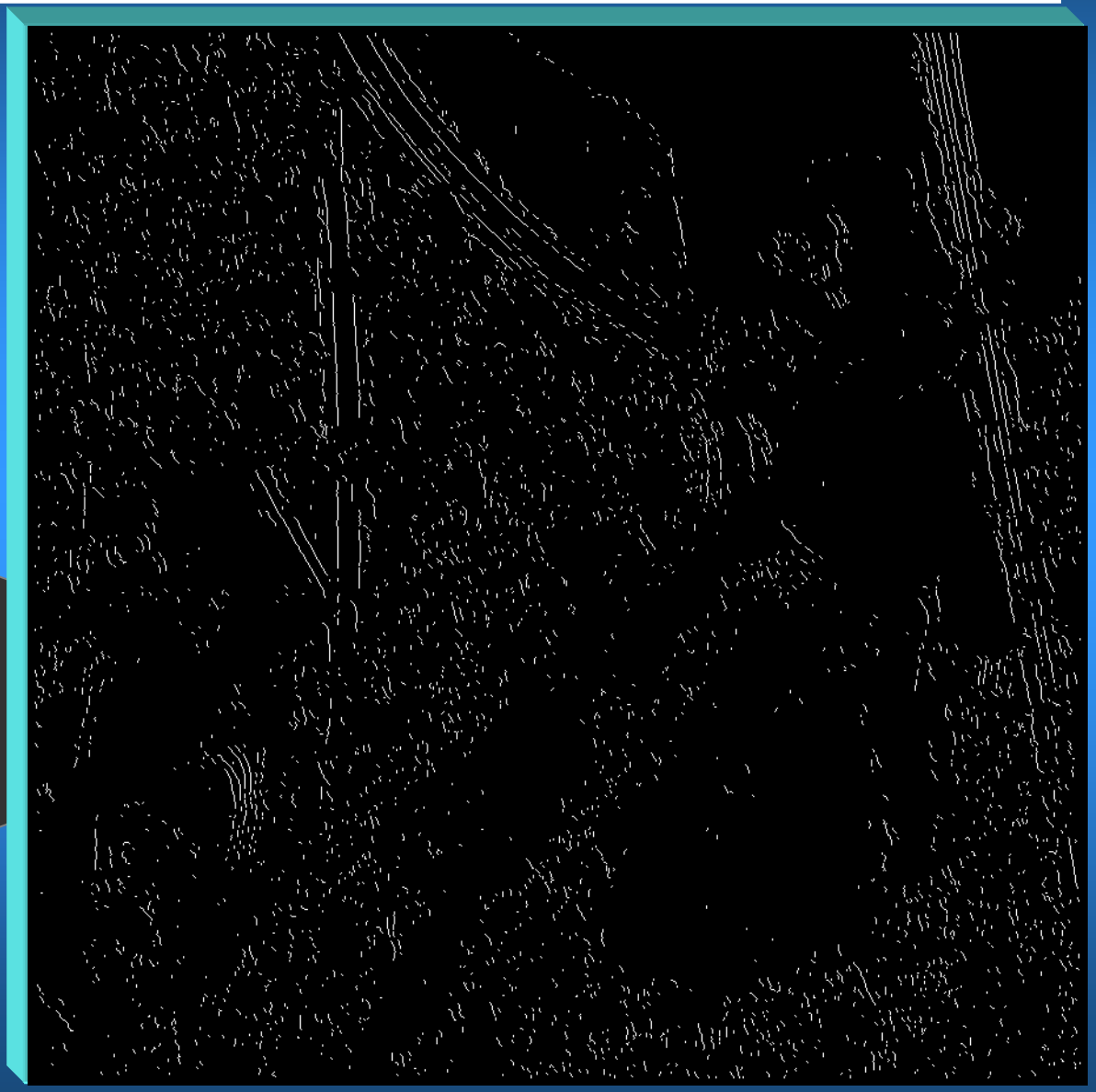
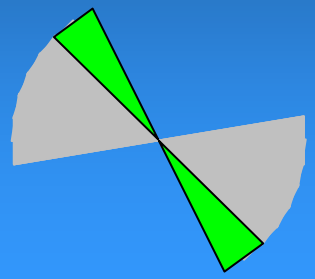
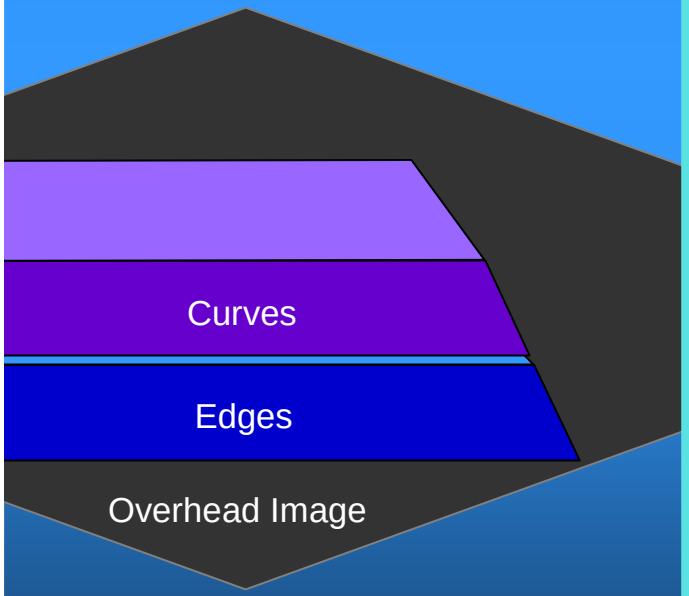


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$117^\circ \le \theta \le 136^\circ$ & $-63^\circ \le \theta \le -45^\circ$





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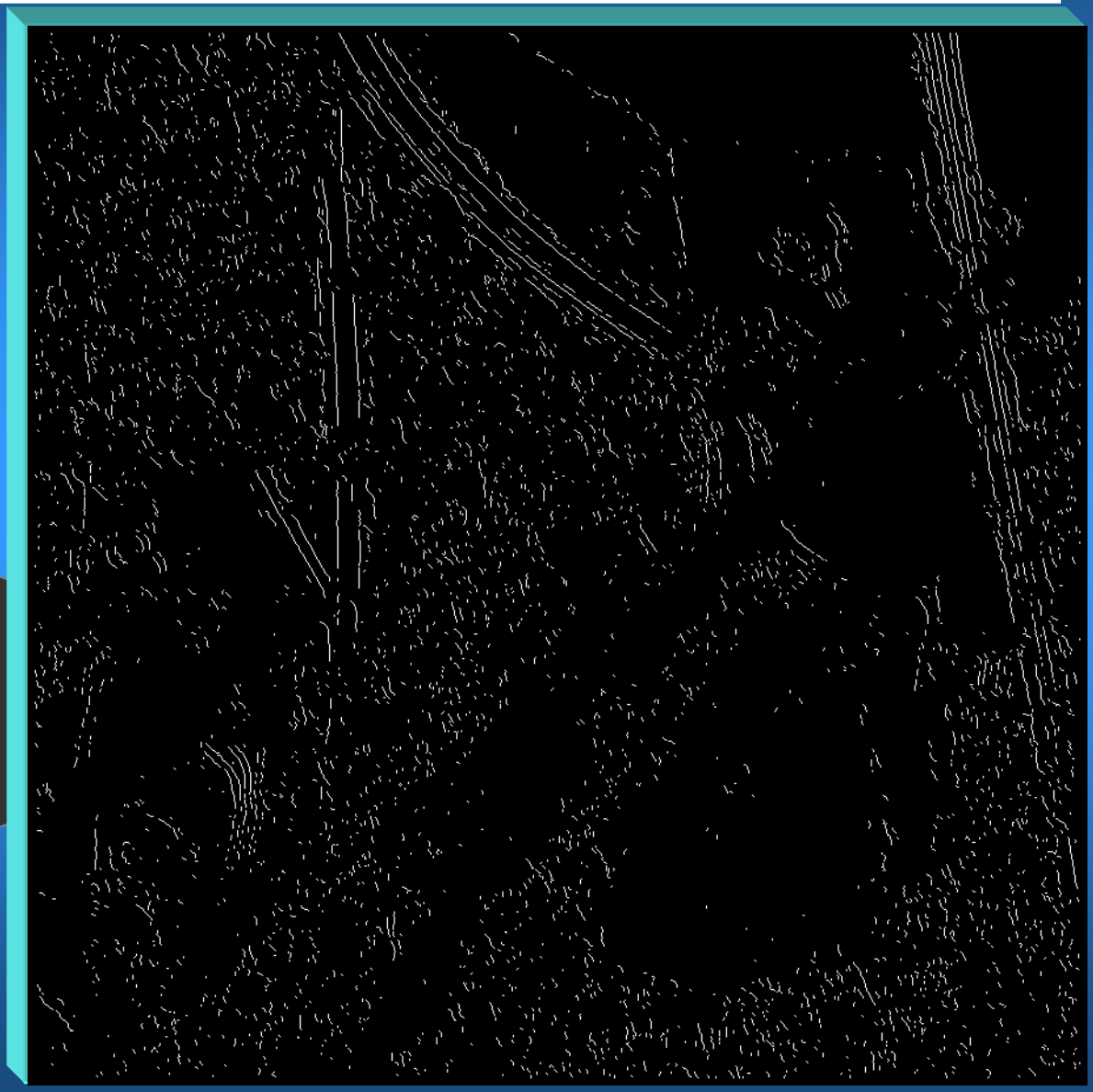
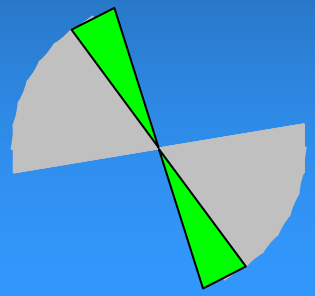
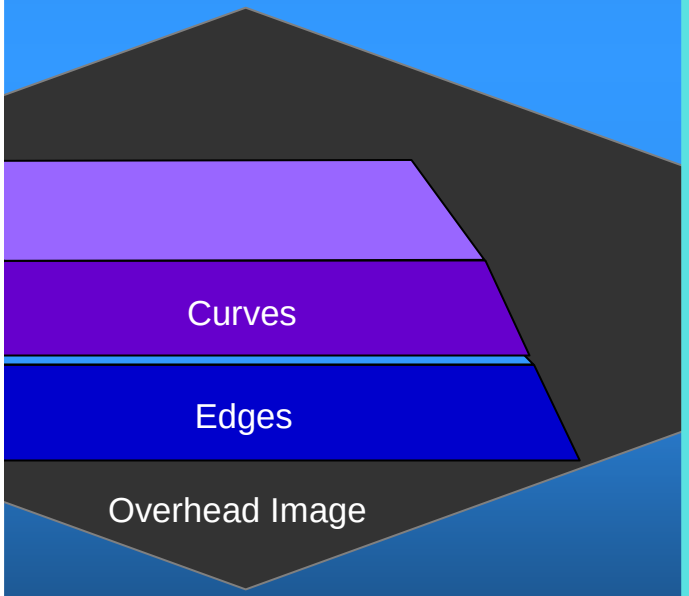


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$108^\circ \le \theta \le 126^\circ$ & $-72^\circ \le \theta \le -54^\circ$





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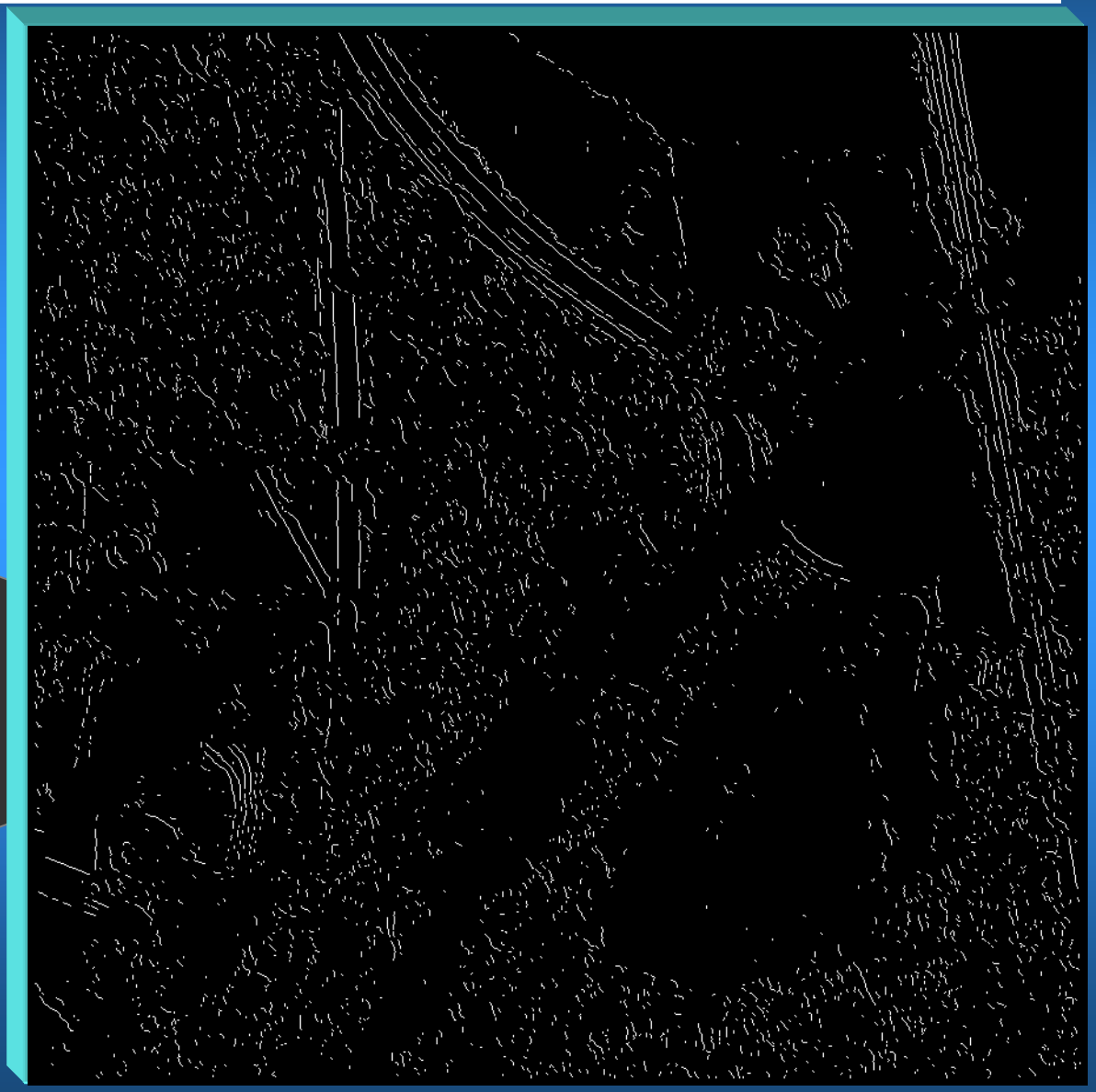
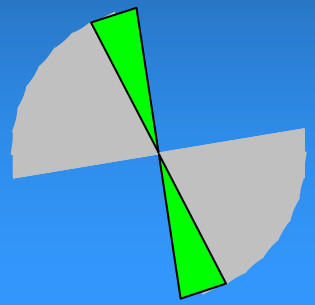
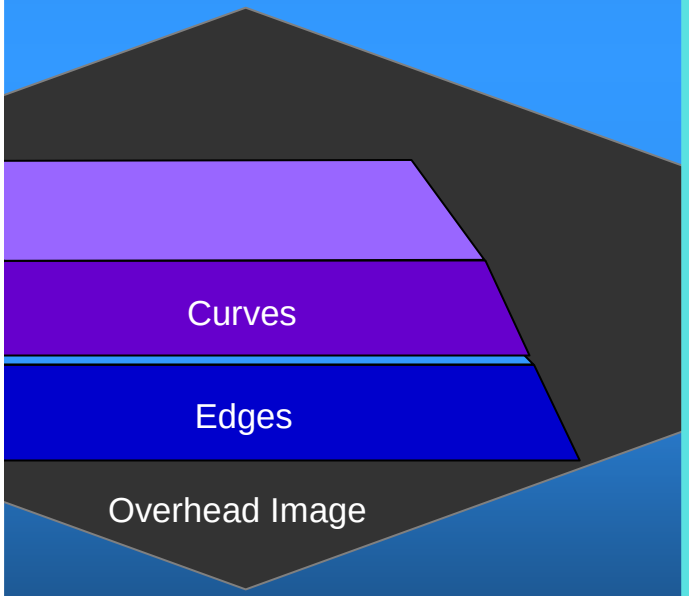


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$99^\circ \le \theta \le 117^\circ$ & $-81^\circ \le \theta \le -63^\circ$





$numChannels = 20,$

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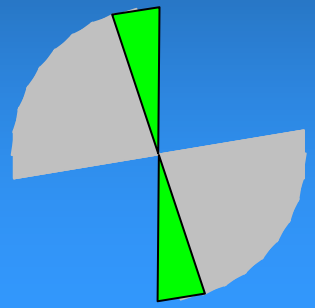
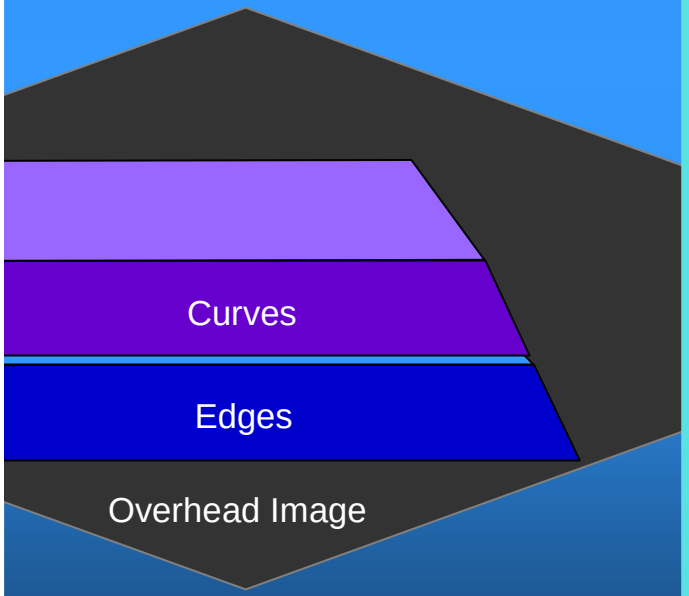
Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$90^\circ \le \theta \le 108^\circ$ & $-90^\circ \le \theta \le -72^\circ$



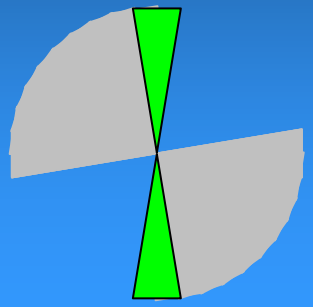


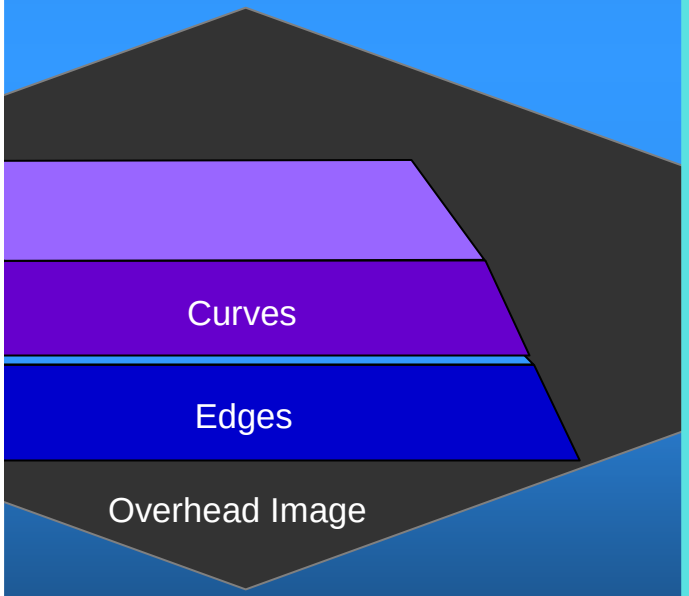
$$numChannels = 20,$$
$$C_{channel} = 12.0,\ L_{channel} = 2$$

Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$81^\circ \le \theta \le 99^\circ$ & $-99^\circ \le \theta \le -81^\circ$





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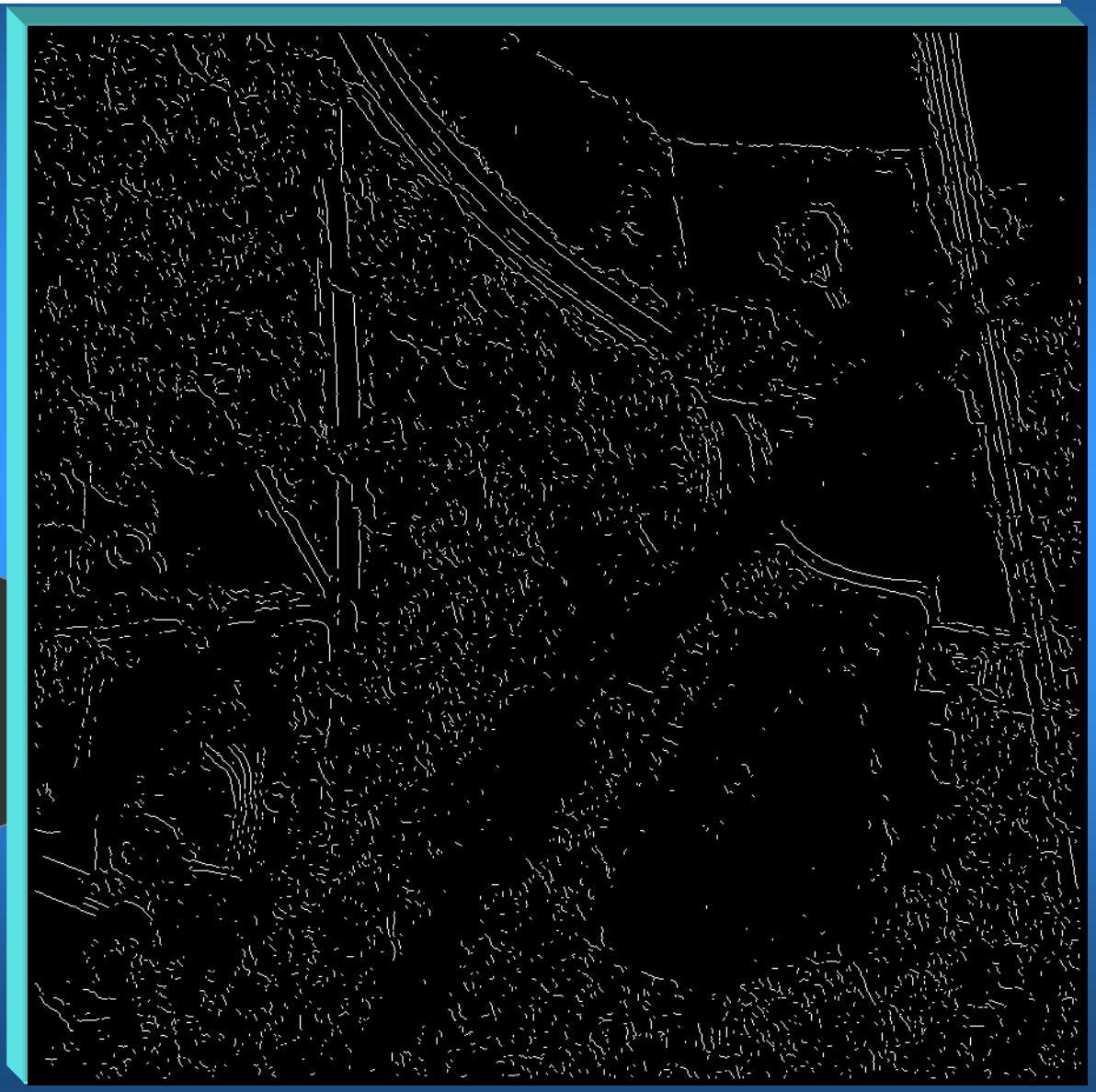
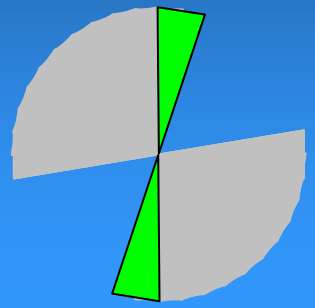
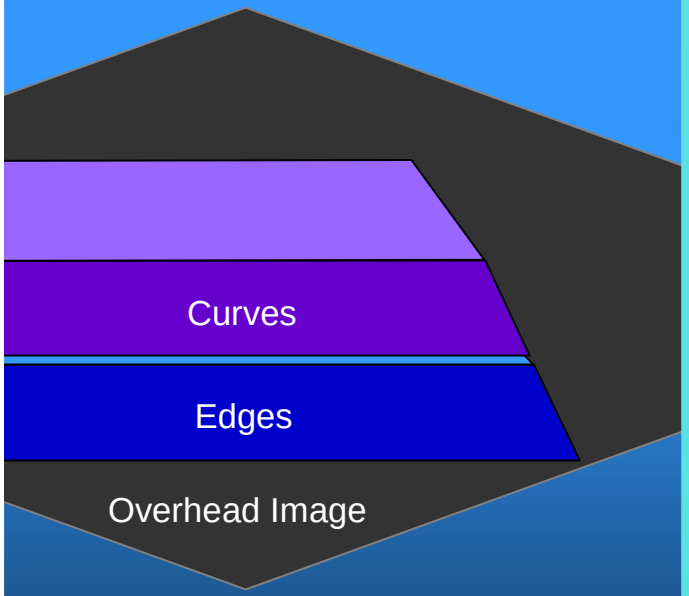


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$72^\circ \le \theta \le 90^\circ$ & $-108^\circ \le \theta \le -90^\circ$





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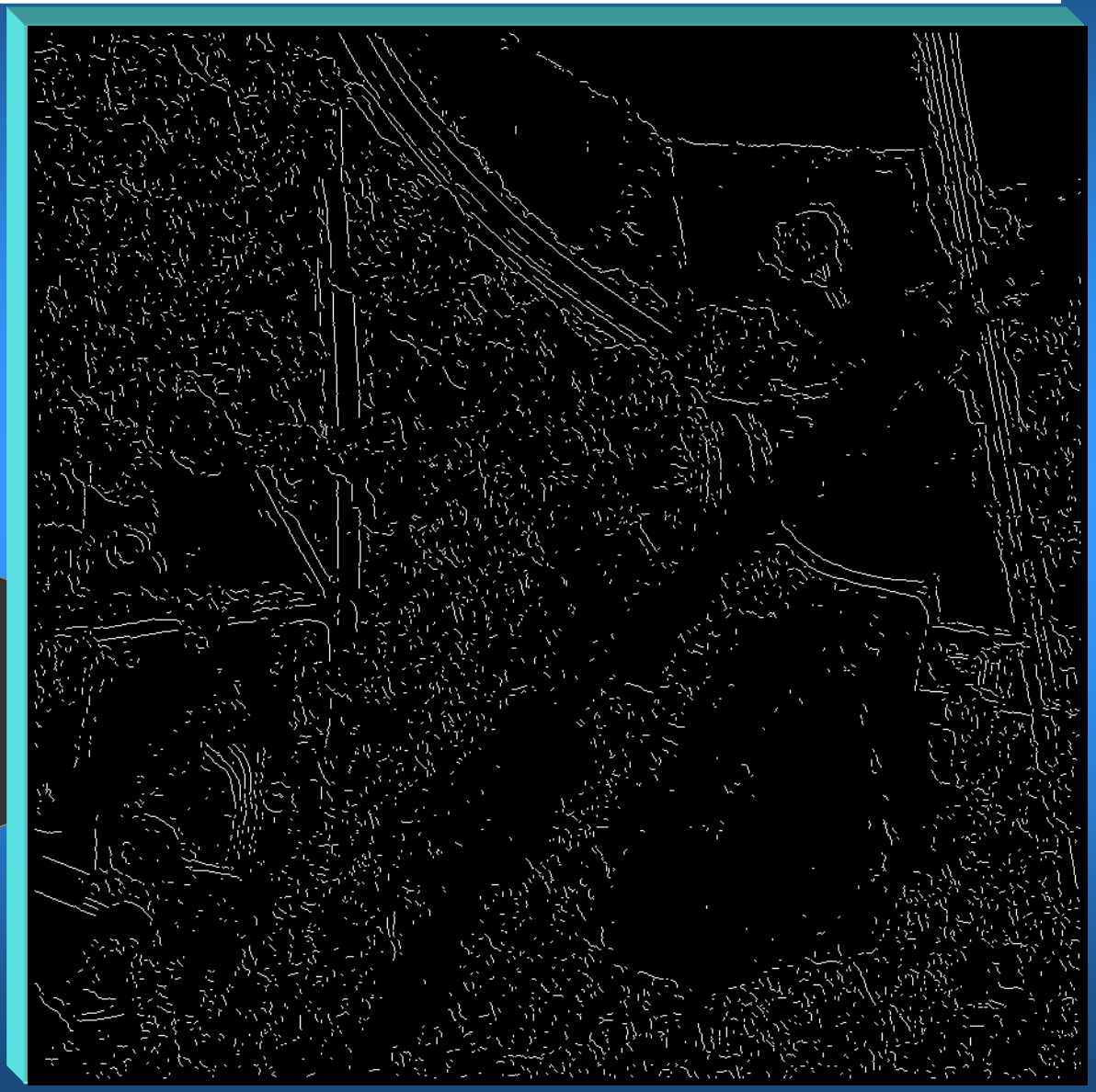
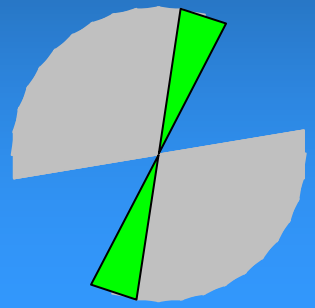
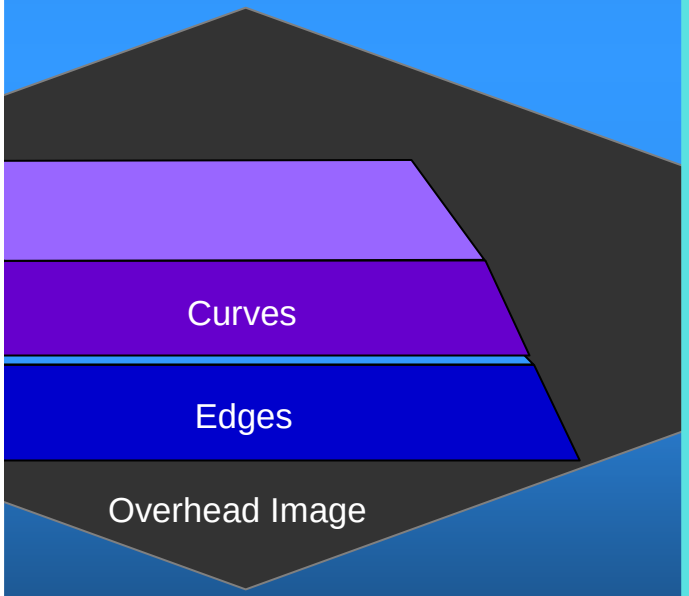


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$63^\circ \le \theta \le 81^\circ$ & $-117^\circ \le \theta \le -99^\circ$





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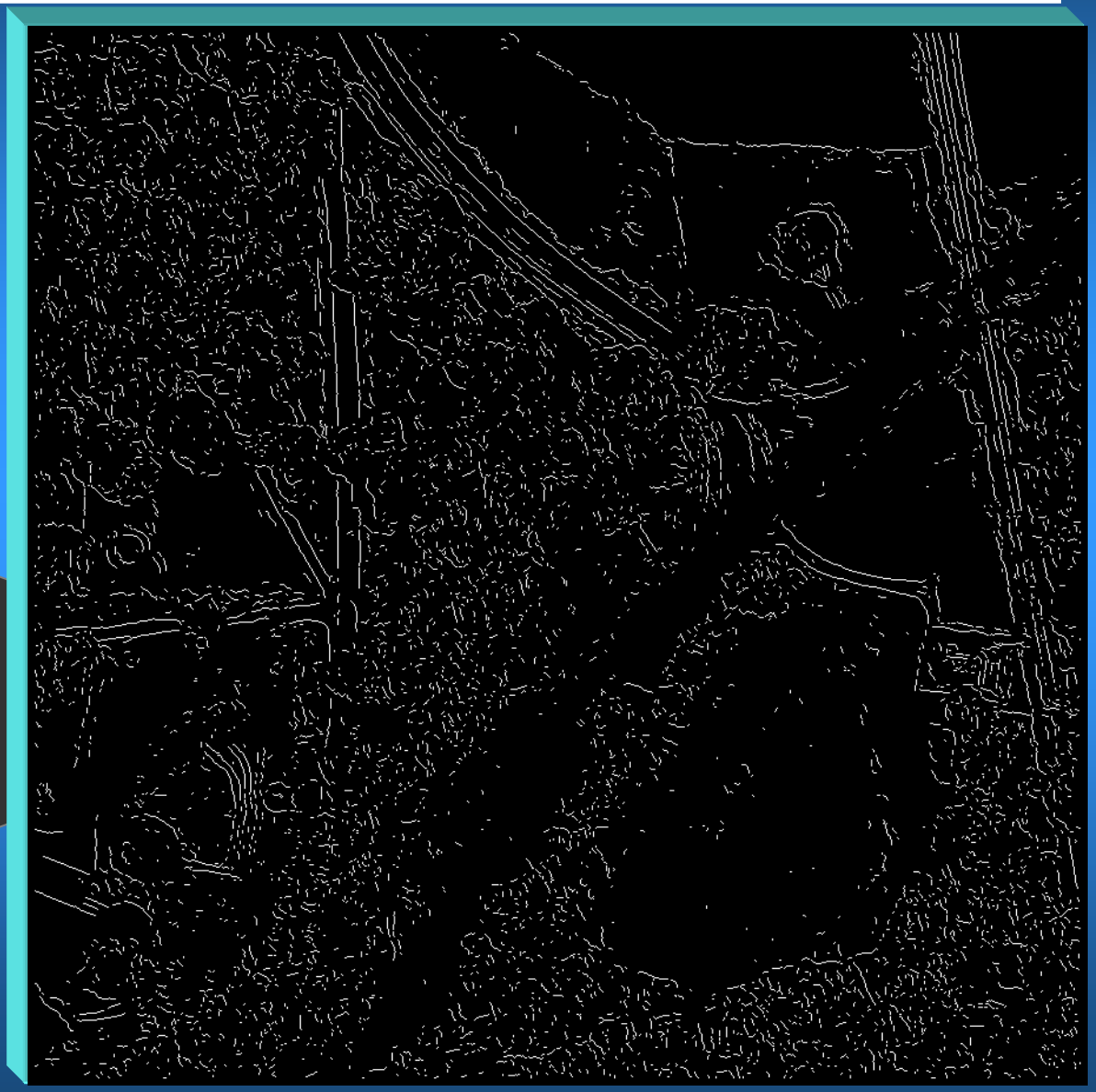
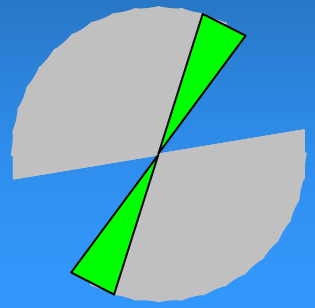
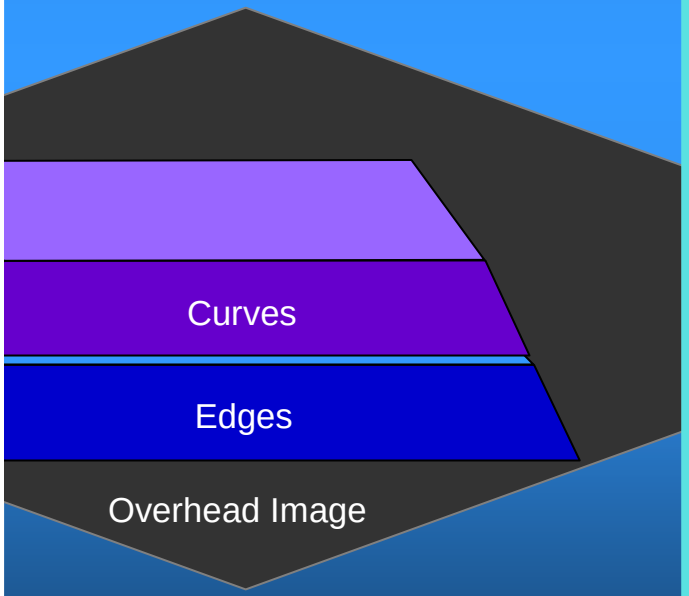


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

$54^\circ \le \theta \le 72^\circ$ & $-126^\circ \le \theta \le -108^\circ$





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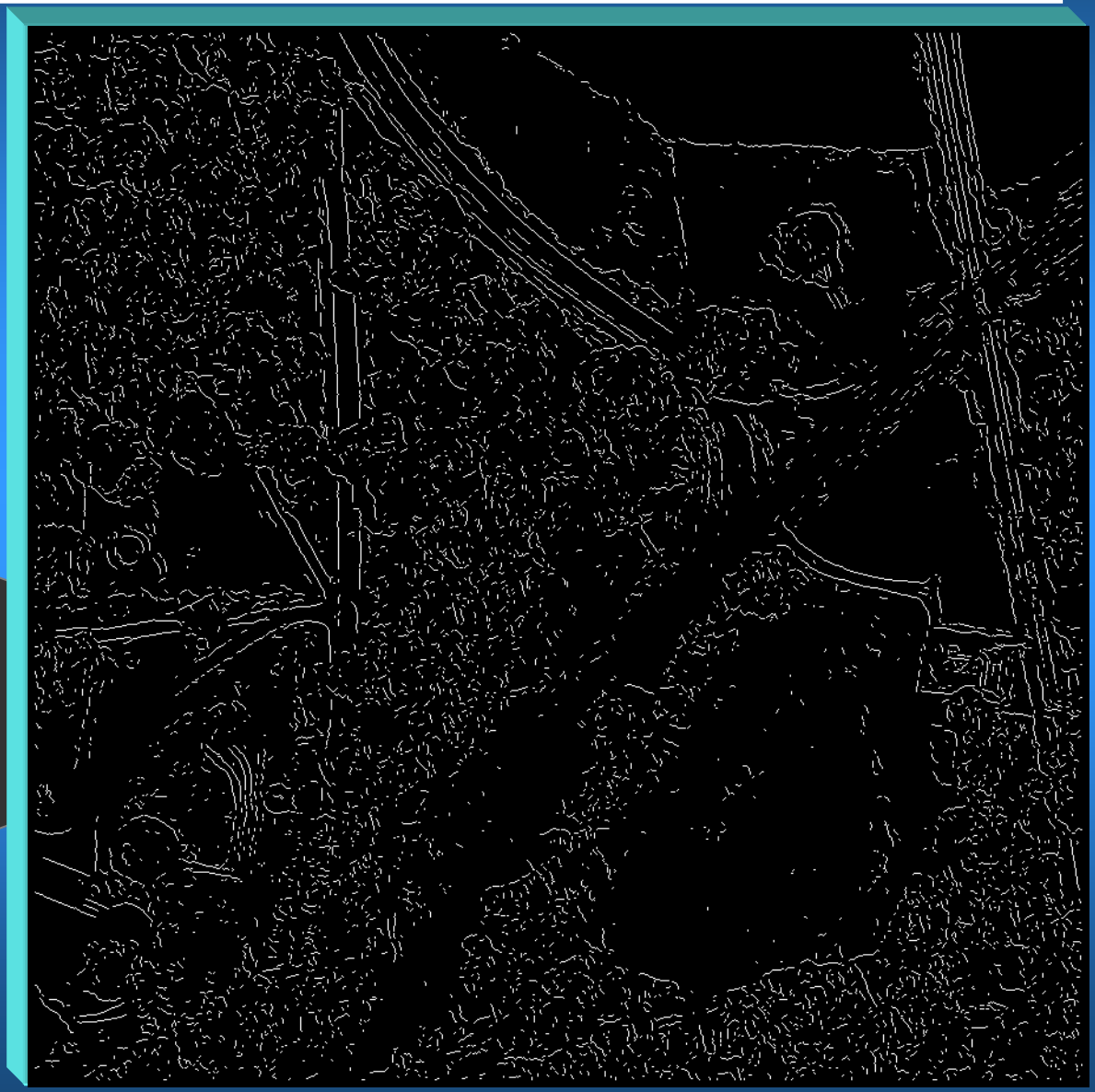
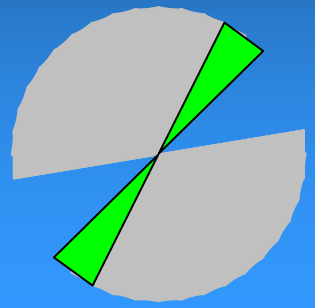
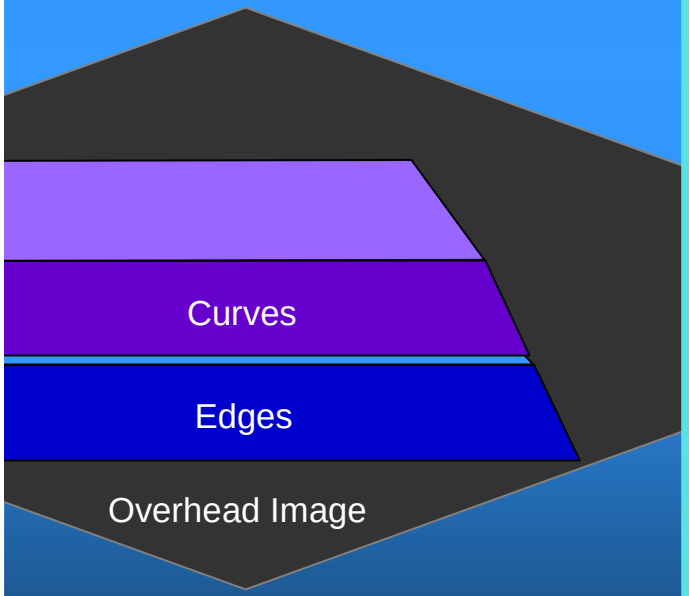


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

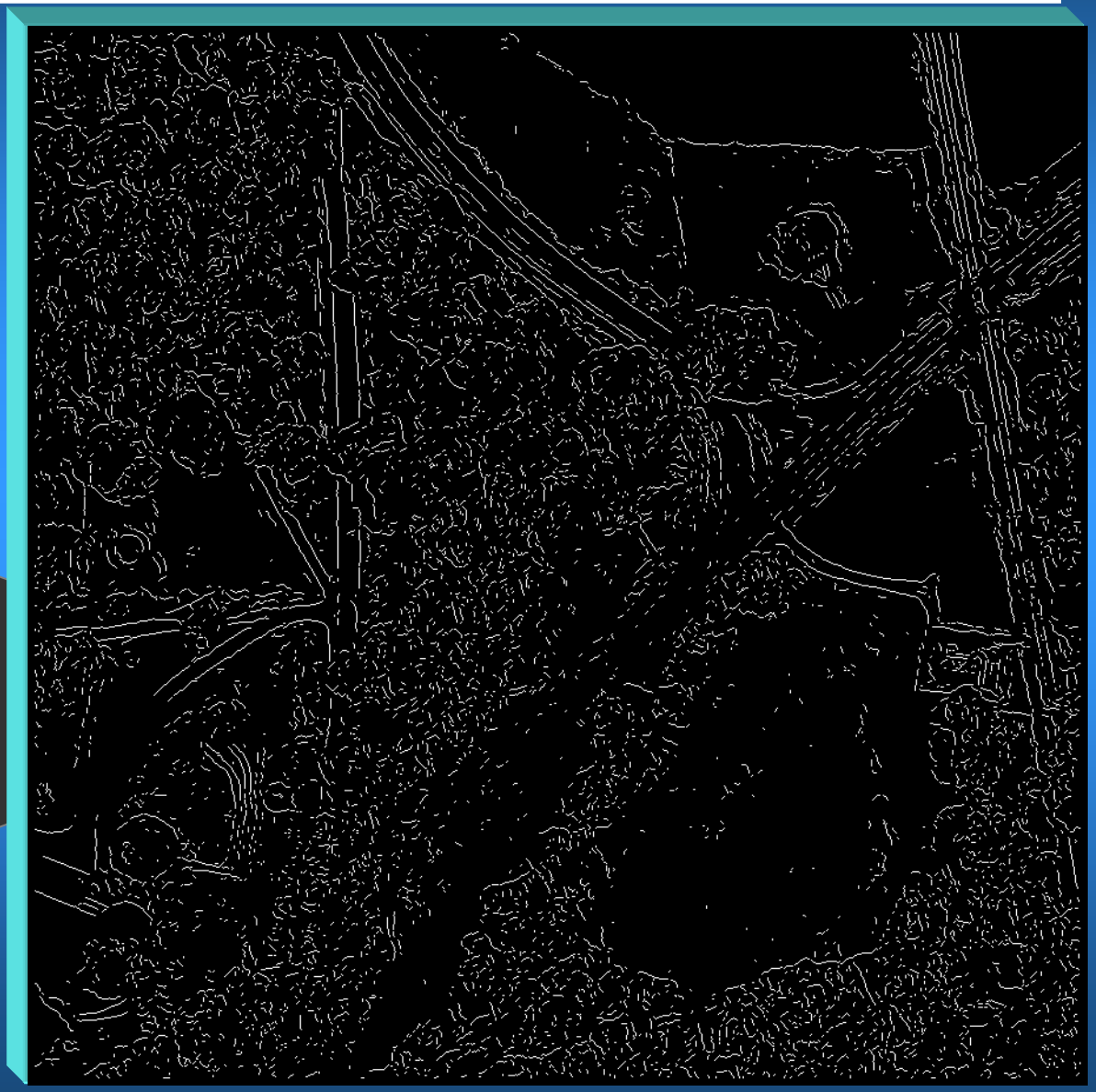
$45^\circ \le \theta \le 63^\circ$ & $-135^\circ \le \theta \le -117^\circ$





$numChannels = 20,$

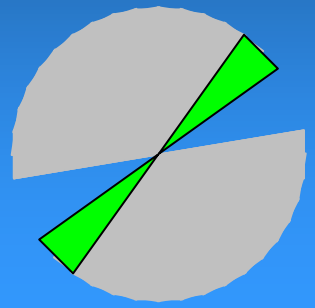
$C_{channel} = 12.0,\ L_{channel} = 2$

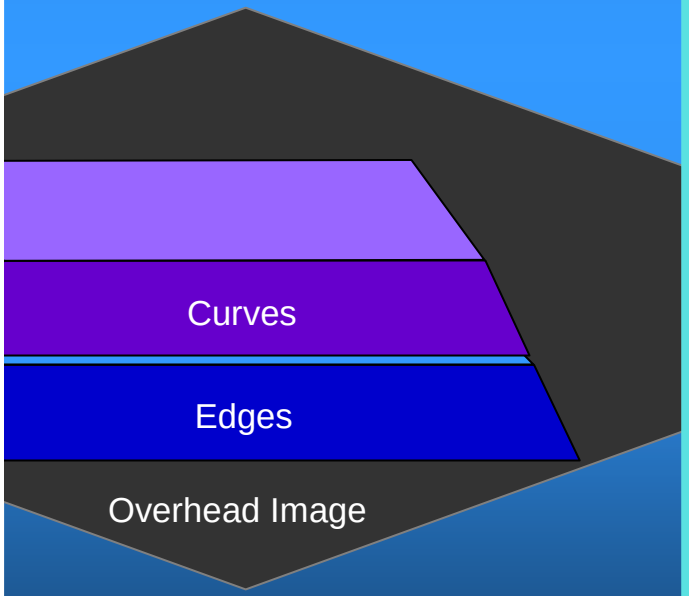


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

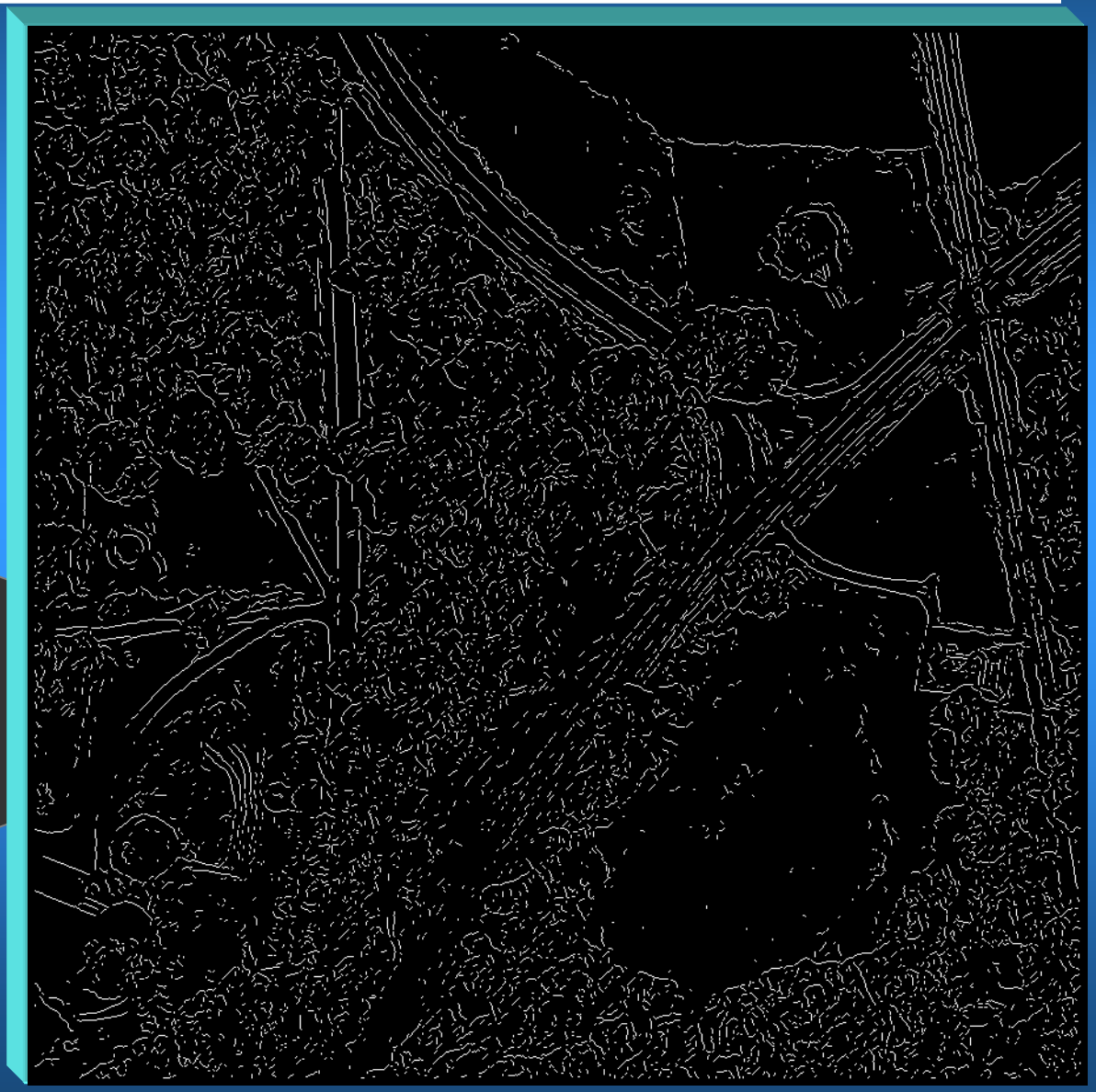
$36^\circ \le \theta \le 54^\circ$ & $-144^\circ \le \theta \le -126^\circ$





$numChannels = 20,$

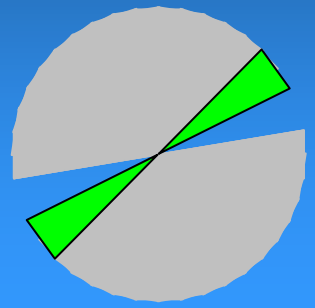
$C_{channel} = 12.0,\ L_{channel} = 2$

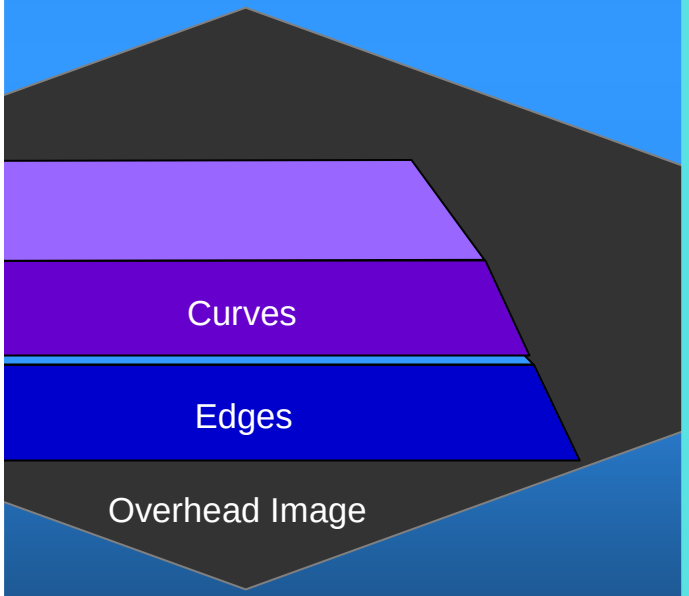


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

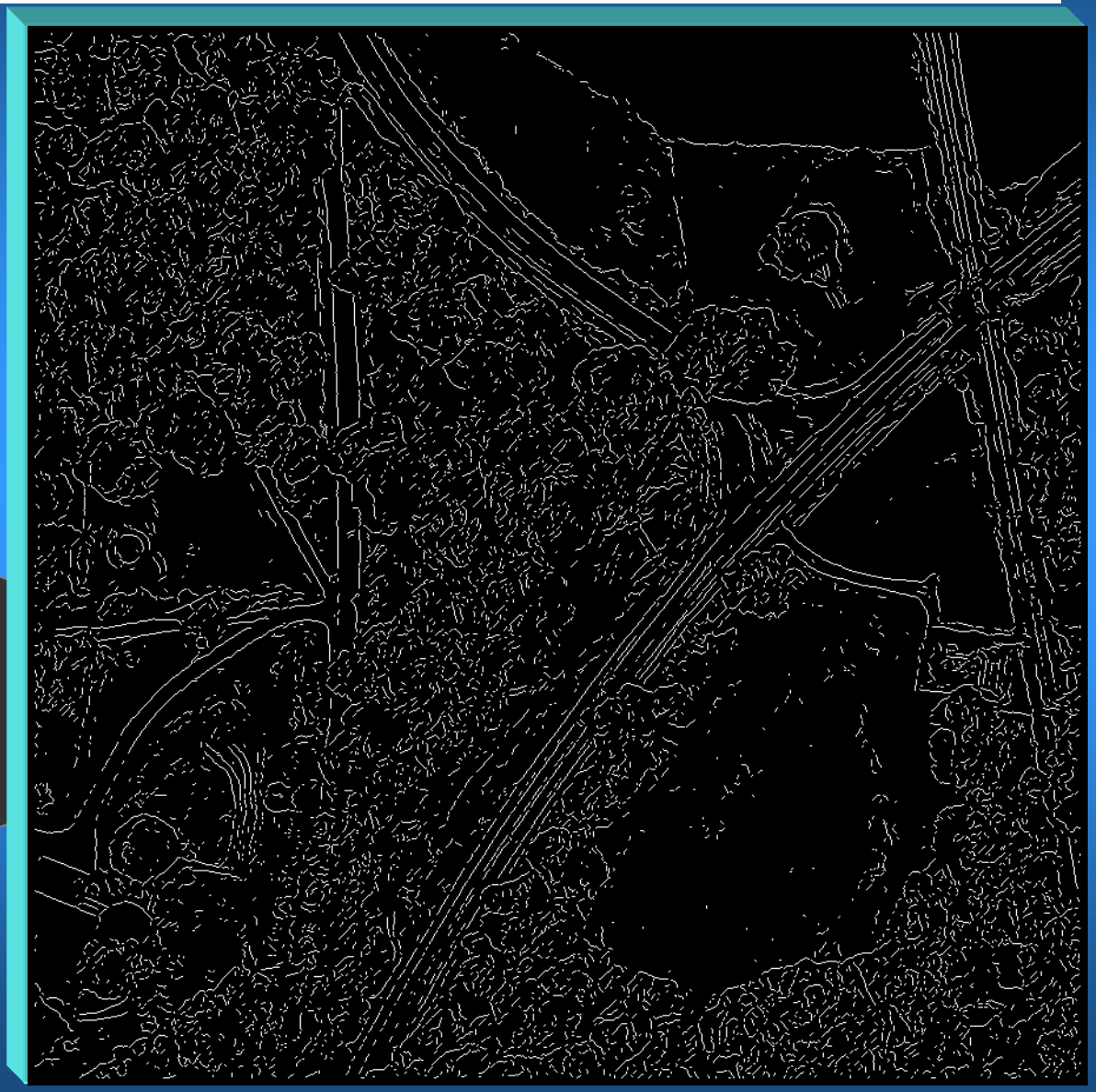
$27^\circ \le \theta \le 45^\circ$ & $-153^\circ \le \theta \le -135^\circ$





$numChannels = 20,$

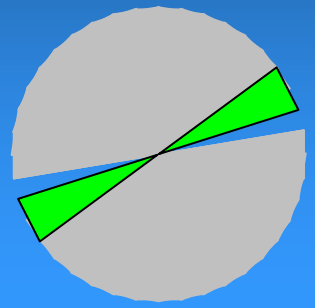
$C_{channel} = 12.0,\ L_{channel} = 2$

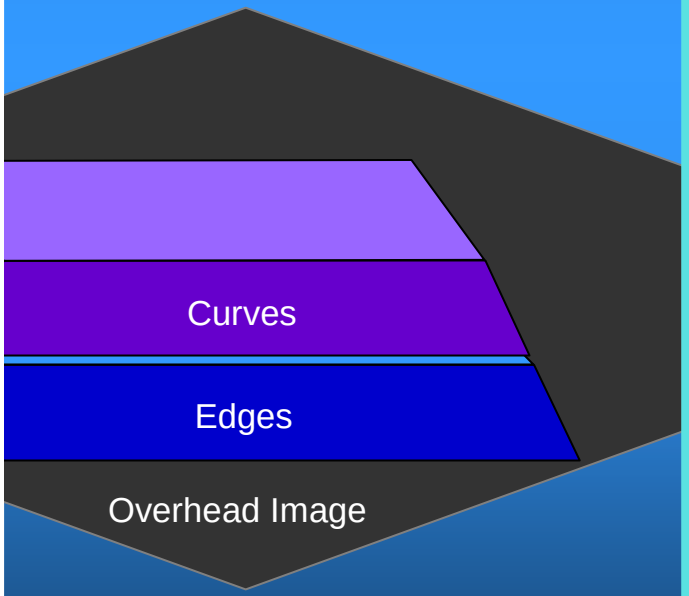


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

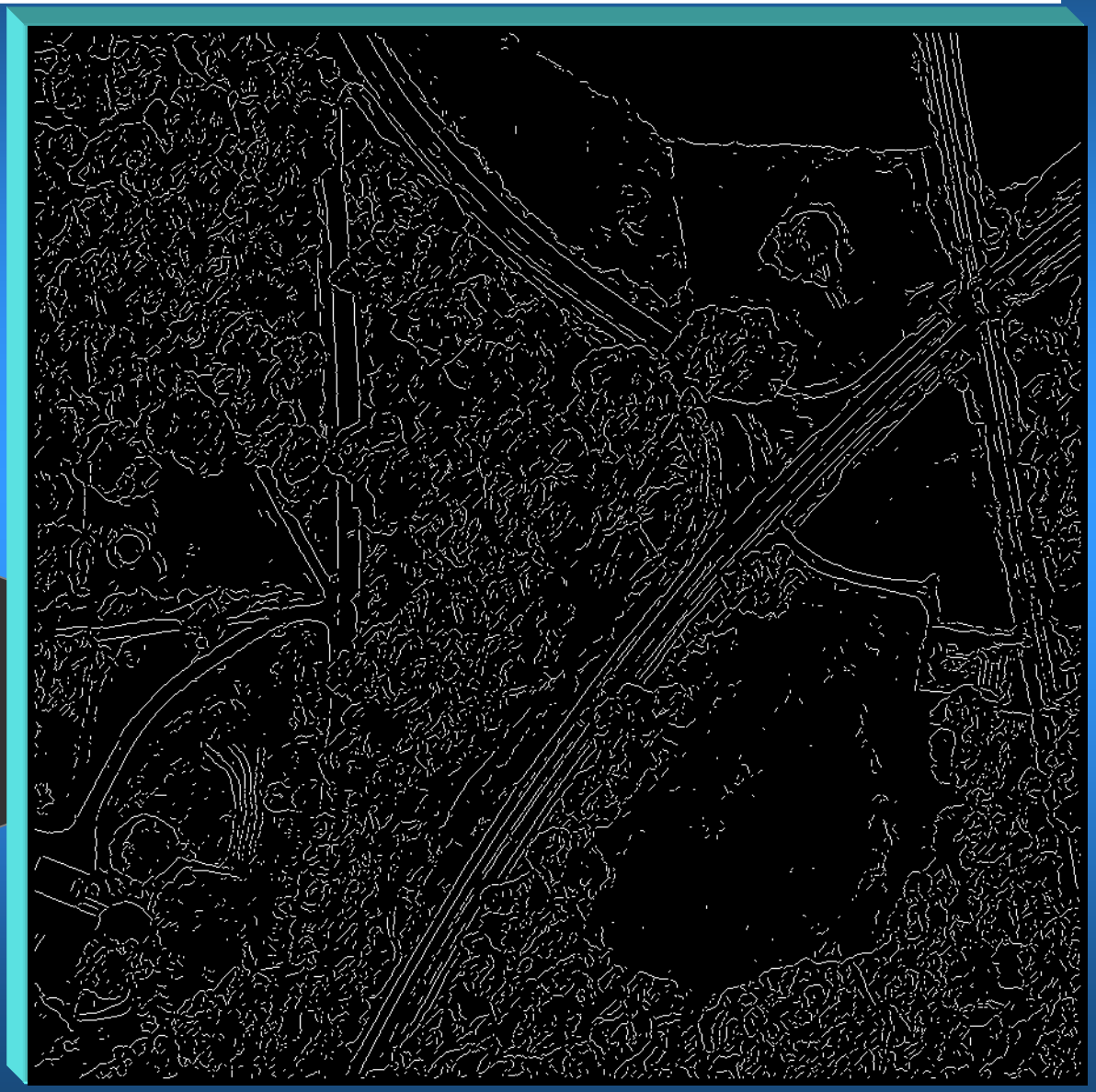
Orientation channel added:

$18^\circ \le \theta \le 36^\circ$ & $-162^\circ \le \theta \le -144^\circ$





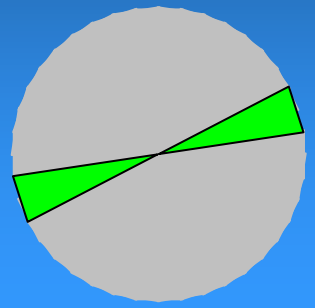
$$numChannels = 20,$$
$$C_{channel} = 12.0,\ L_{channel} = 2$$

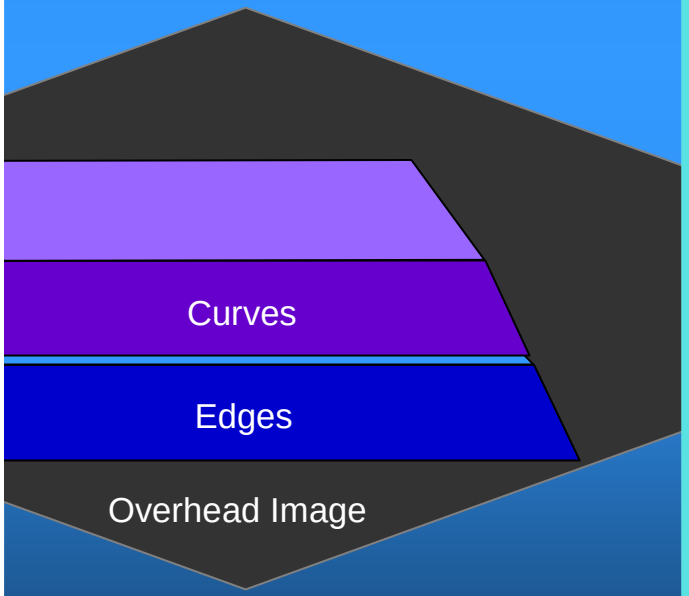


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

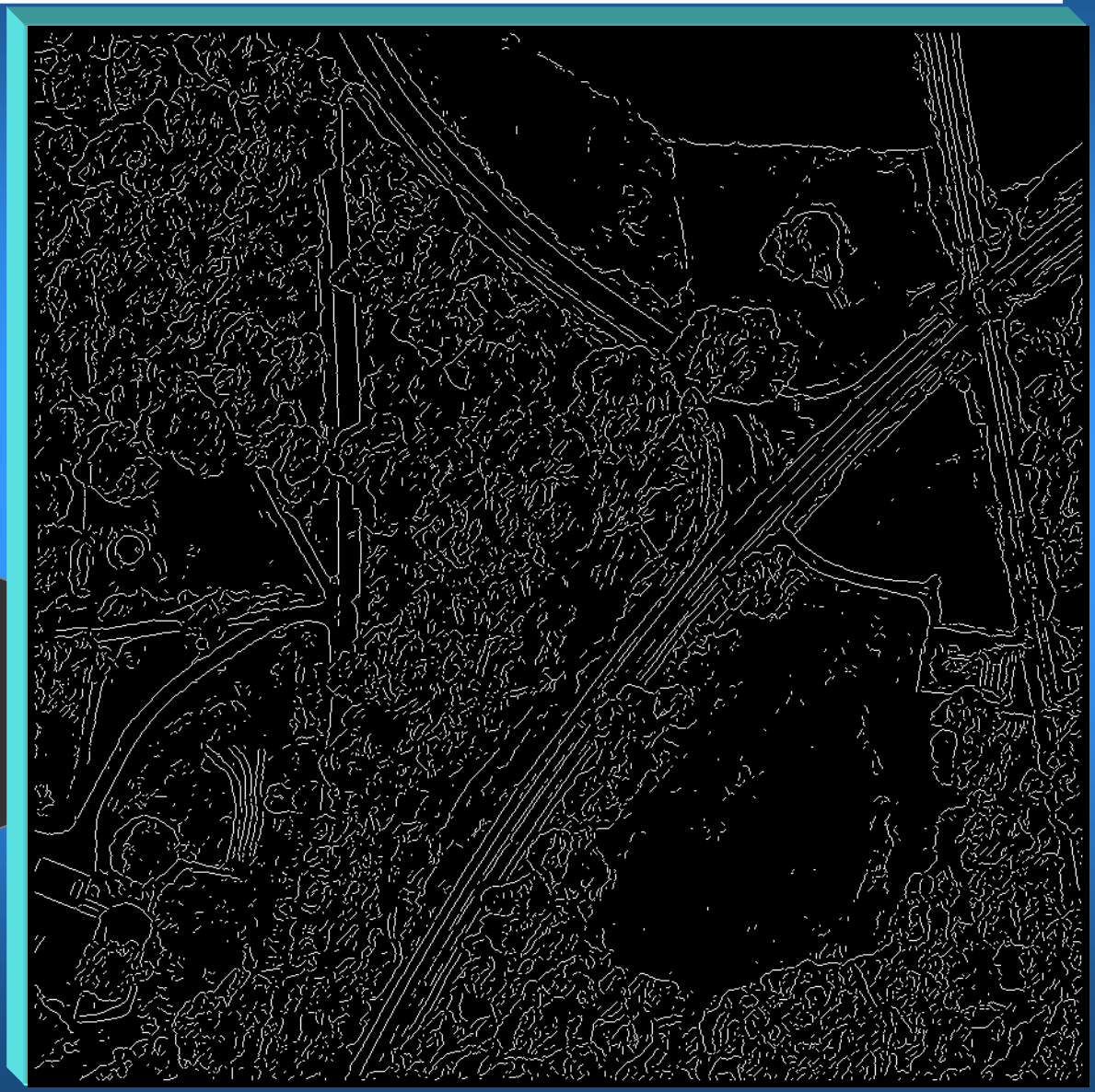
$9^\circ \le \theta \le 27^\circ$ & $-171^\circ \le \theta \le -153^\circ$





$numChannels = 20,$

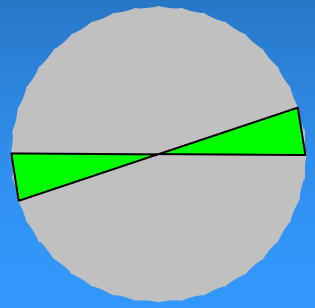
$C_{channel} = 12.0,\ L_{channel} = 2$

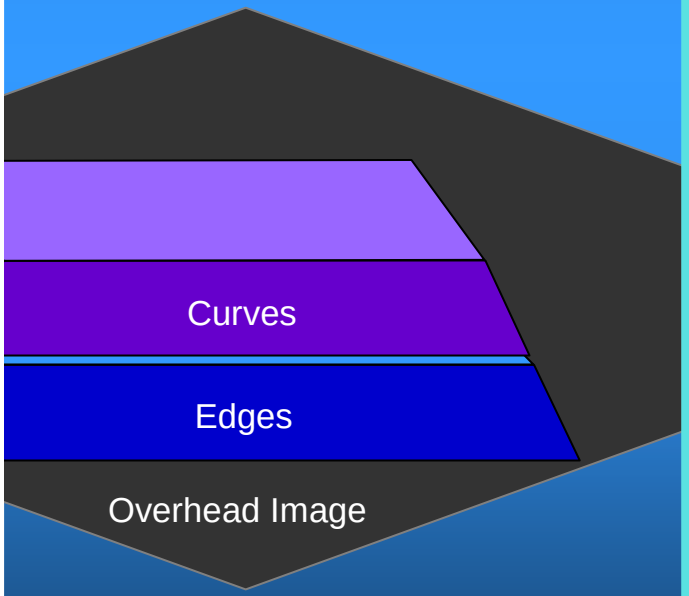


Evolving Curve Map as Surviving Curves from Separate Orientation Channels Are Added

Orientation channel added:

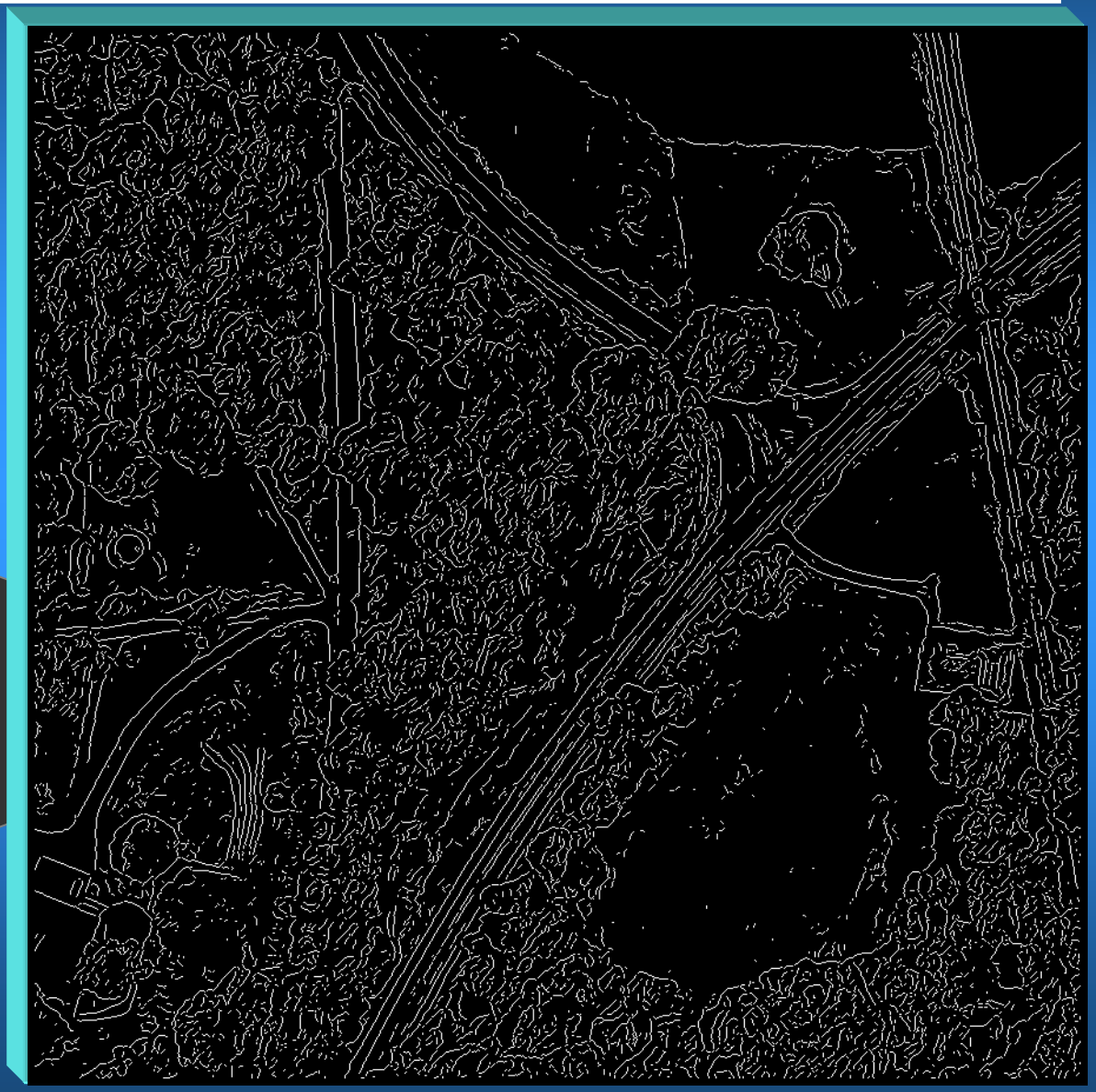
$0^\circ \le \theta \le 18^\circ$ & $-180^\circ \le \theta \le -162^\circ$



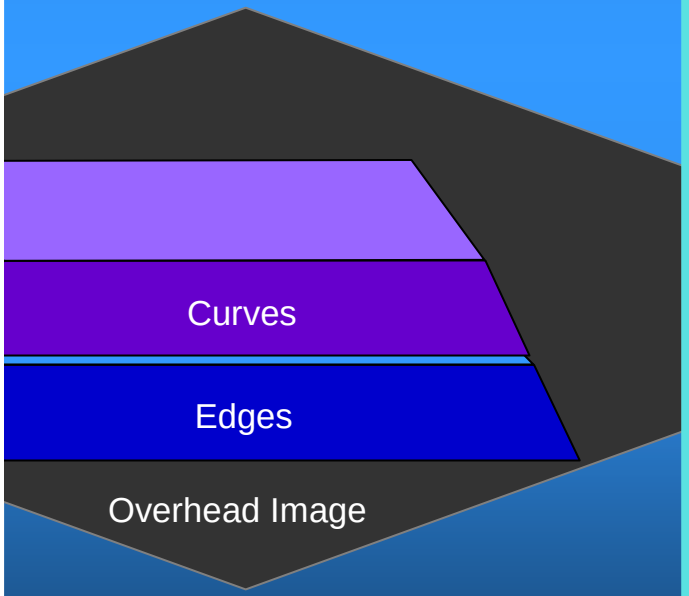


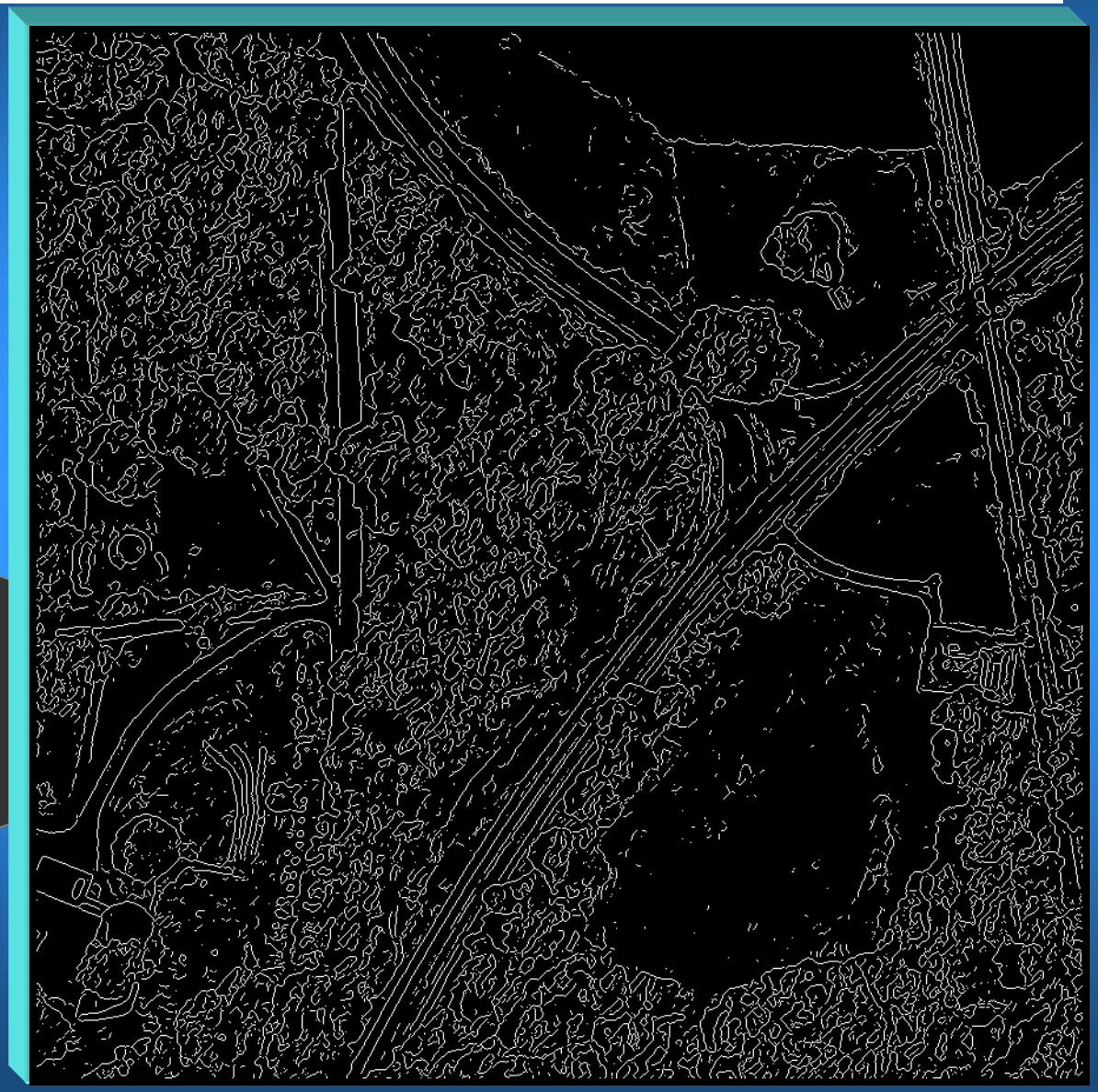
$numChannels = 20,$

$C_{channel} = 12.0,\ L_{channel} = 2$

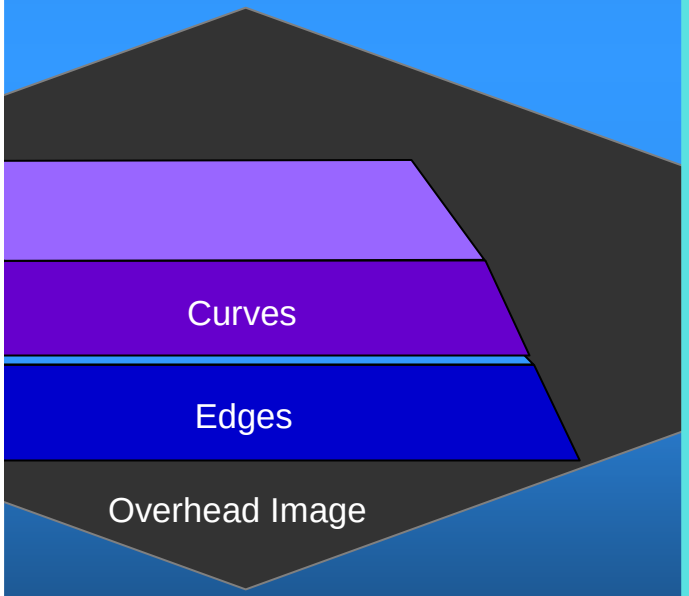


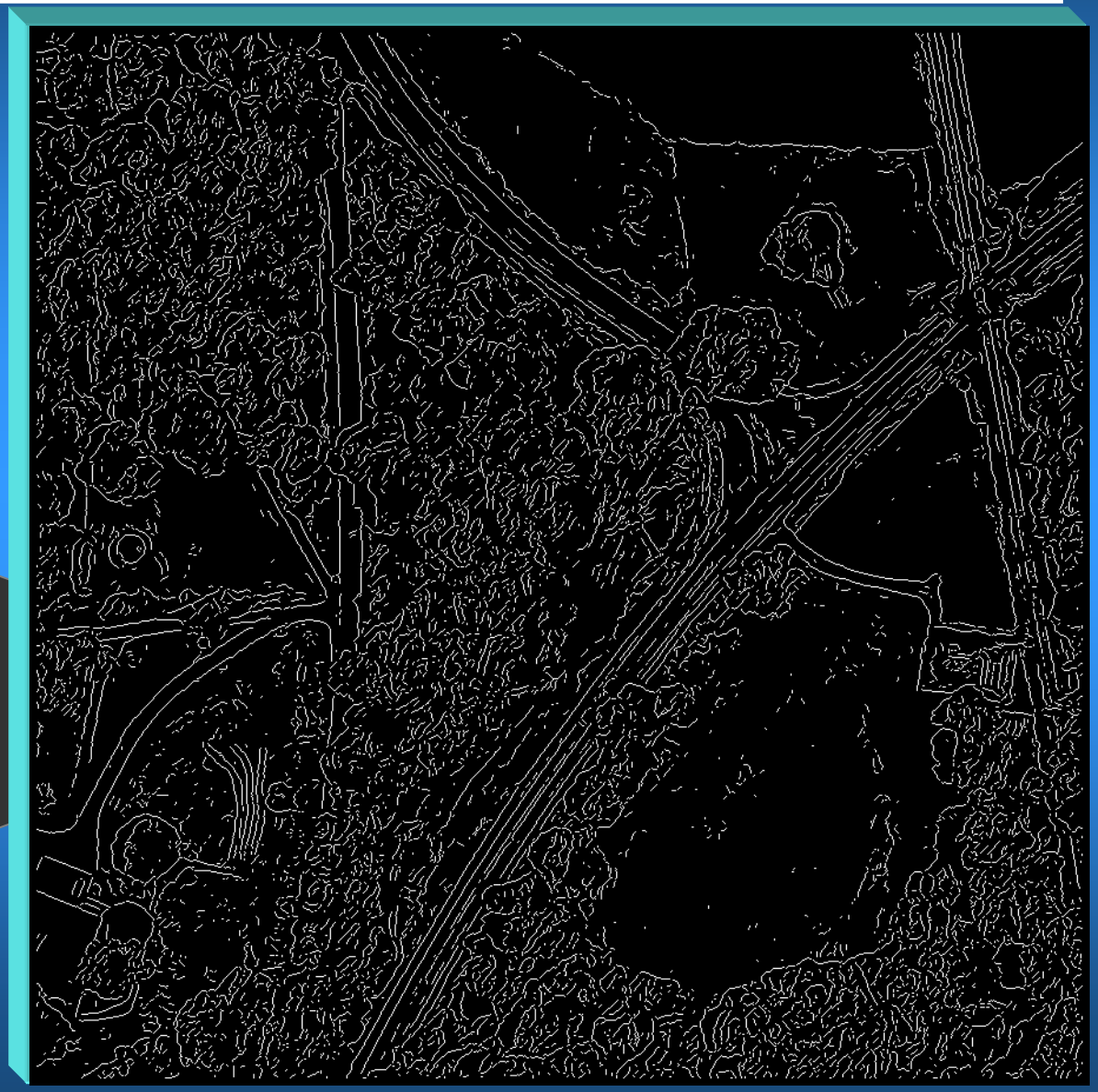
Edges Before Channel De-Cluttering



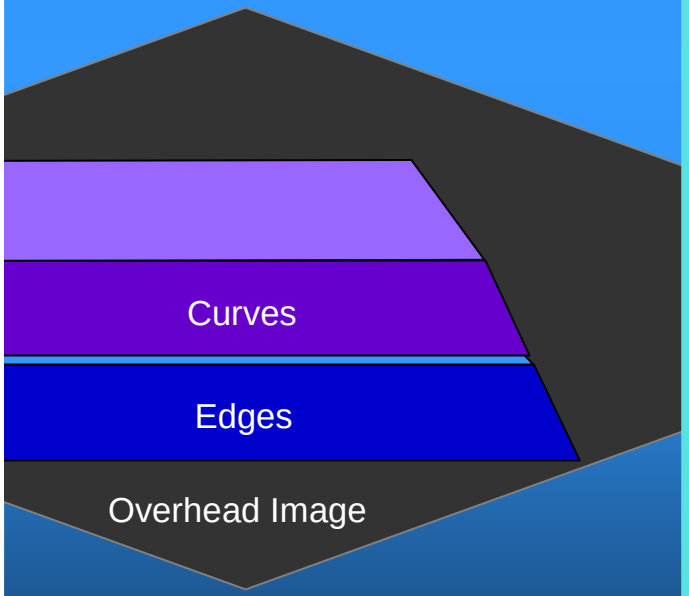


Curves After Channel De-Cluttering



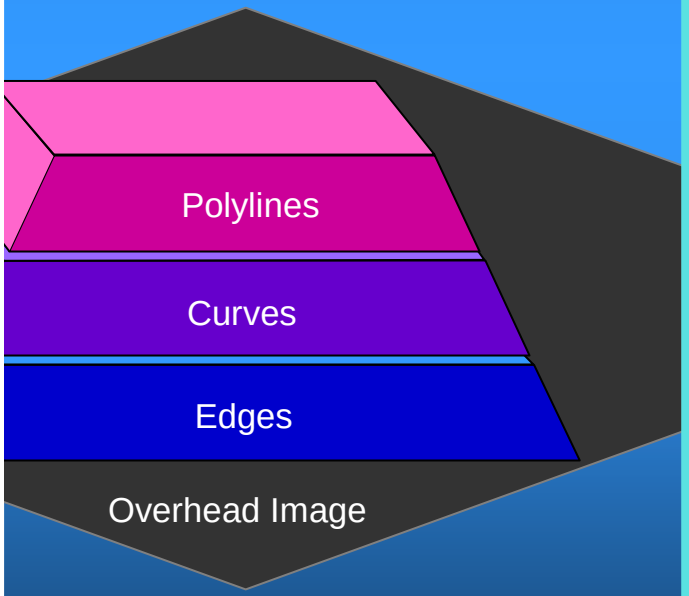


Final Curve Map After Composite De-Cluttering

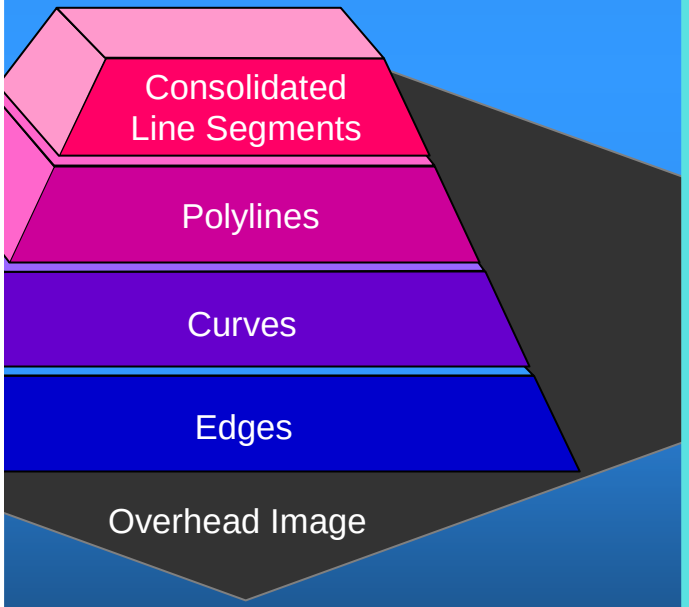


$ct_{composite} = 32.0,\ L_{composite} = 20$

Linearizing Curves Using Polylines

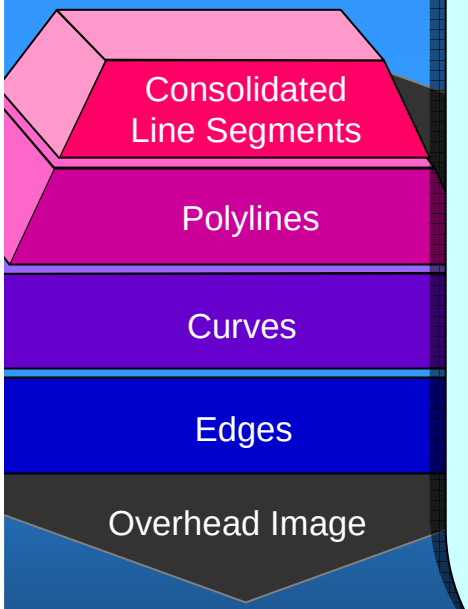


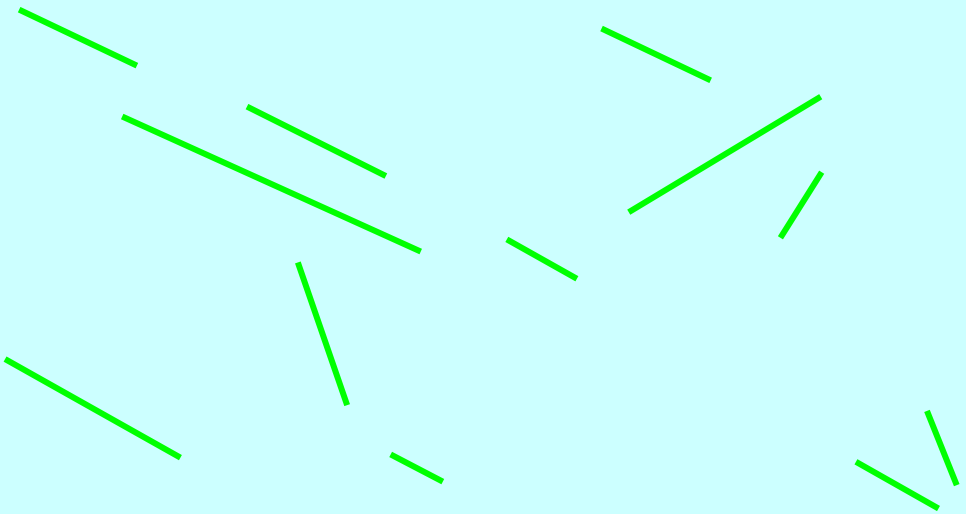
Consolidating Parallel Line Segments



Consolidating Parallel Line Segments

- Starting with the longest remaining line segment as the seed,





Consolidating Parallel Line Segments

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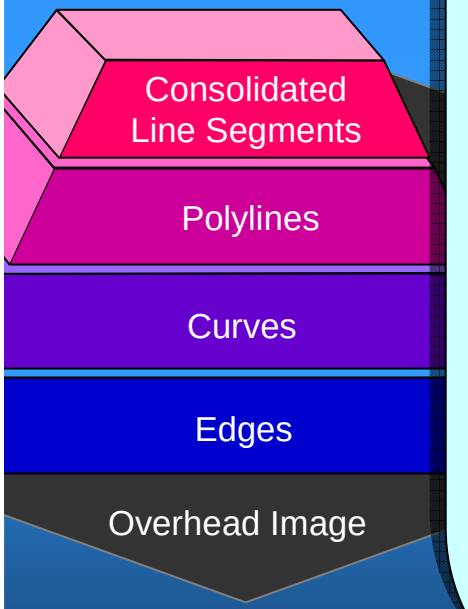
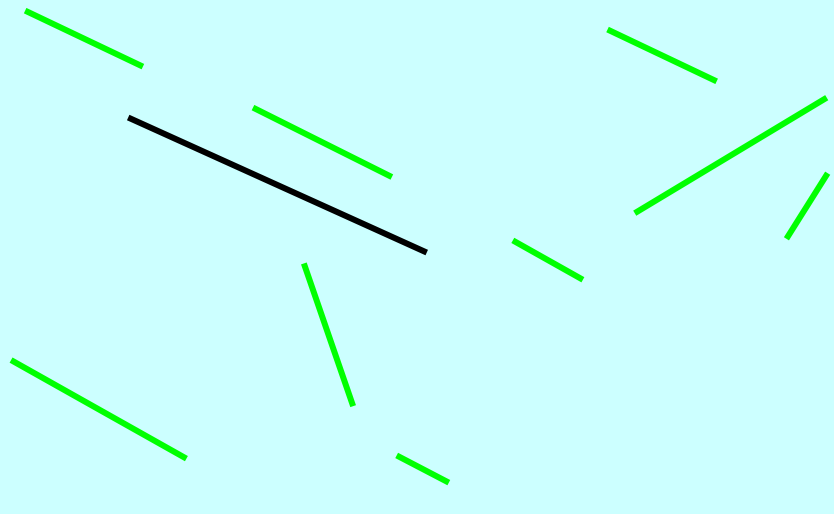
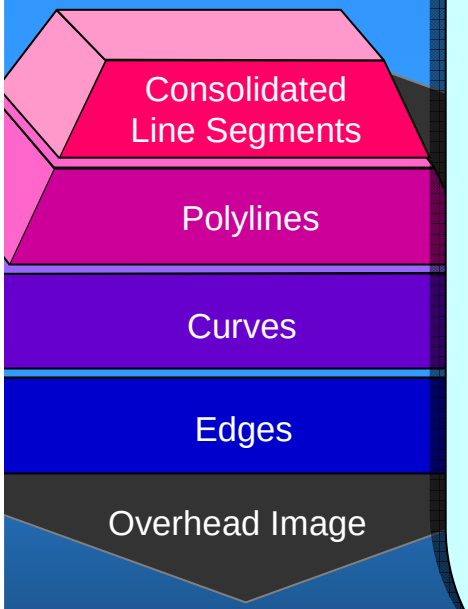


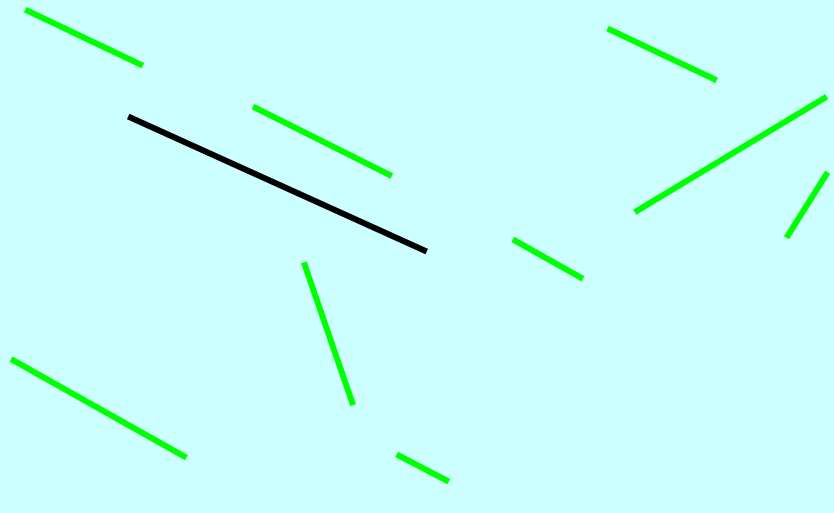


Consolidating Parallel Line Segments

•Starting with the longest remaining line segment as the seed, line segments that are:

1. Nearly parallel





Consolidating Parallel Line Segments

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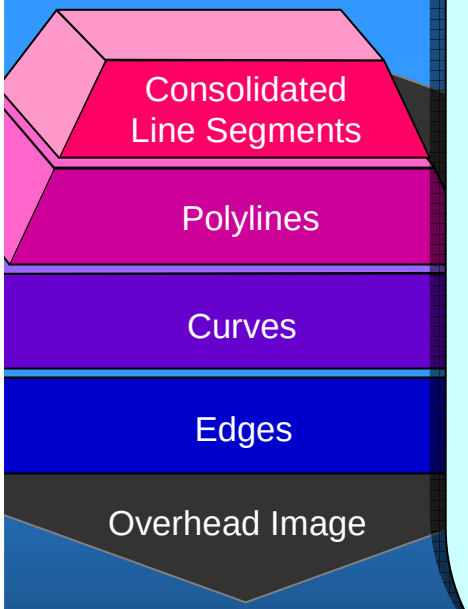
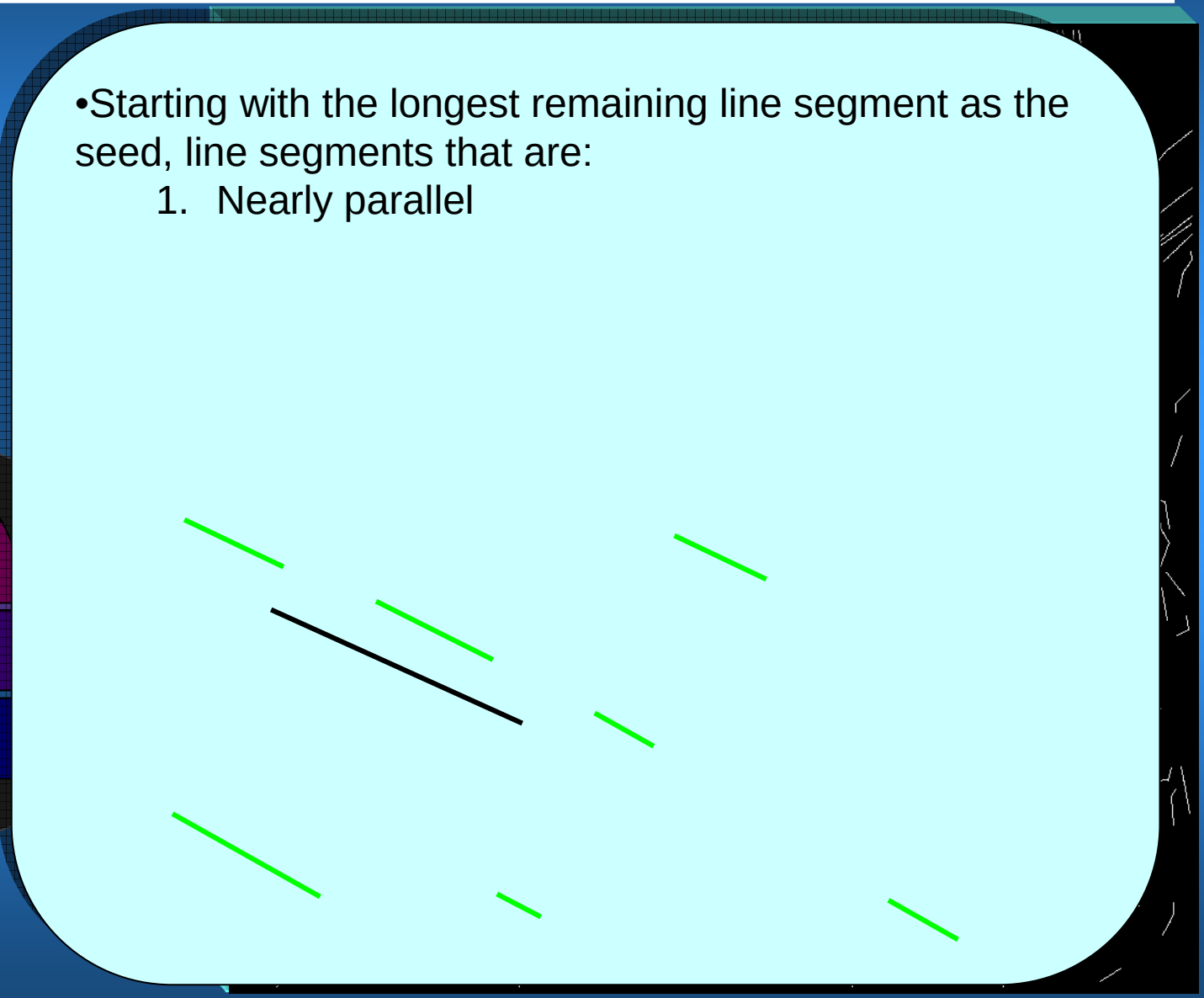
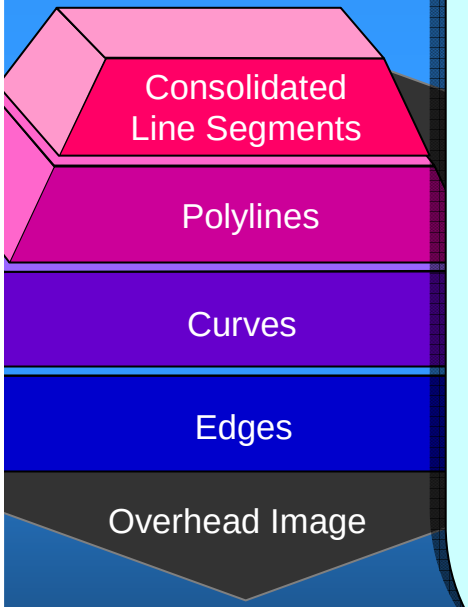


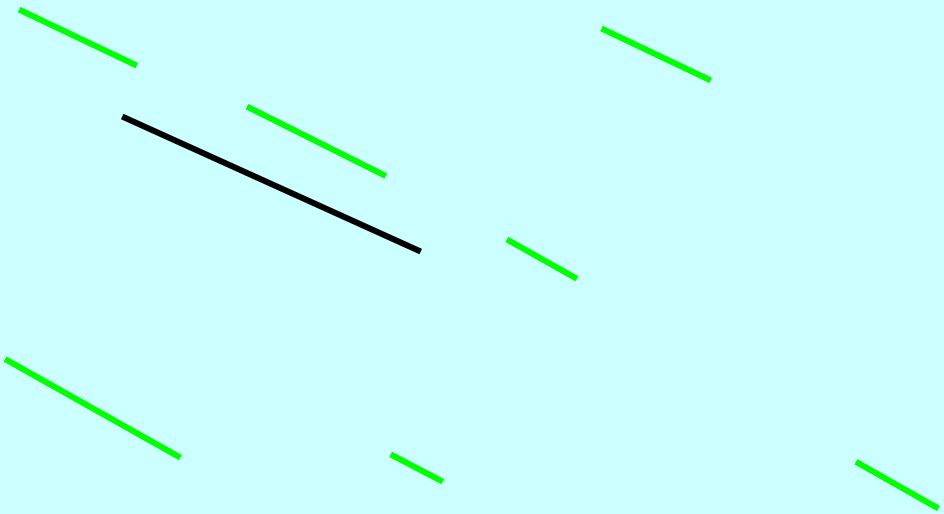


Consolidating Parallel Line Segments

•Starting with the longest remaining line segment as the seed, line segments that are:

1. Nearly parallel
2. Transversally nearby





Consolidating Parallel Line Segments

•Starting with the longest remaining line segment as the seed, line segments that are:

1. Nearly parallel
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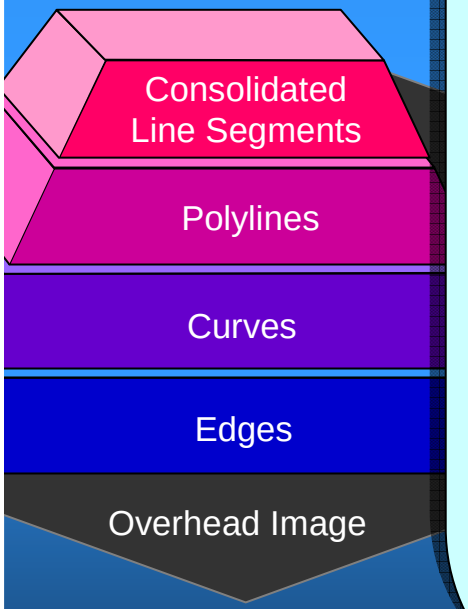
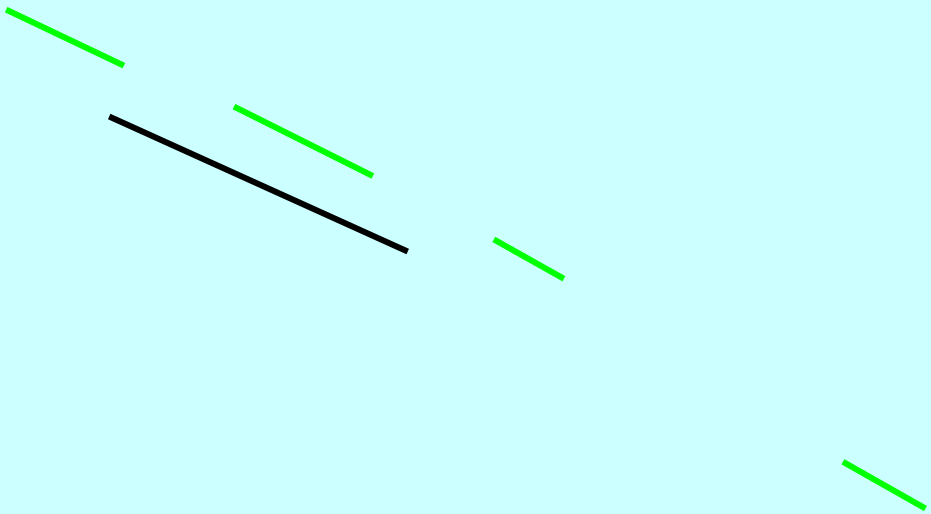
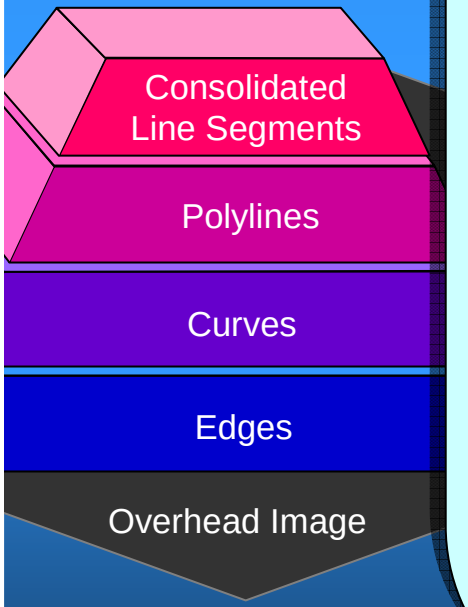


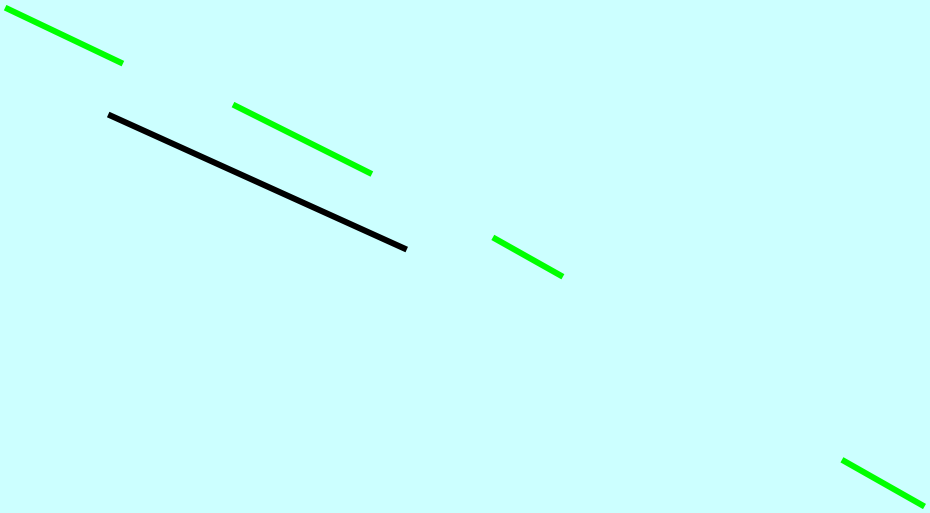


Consolidating Parallel Line Segments

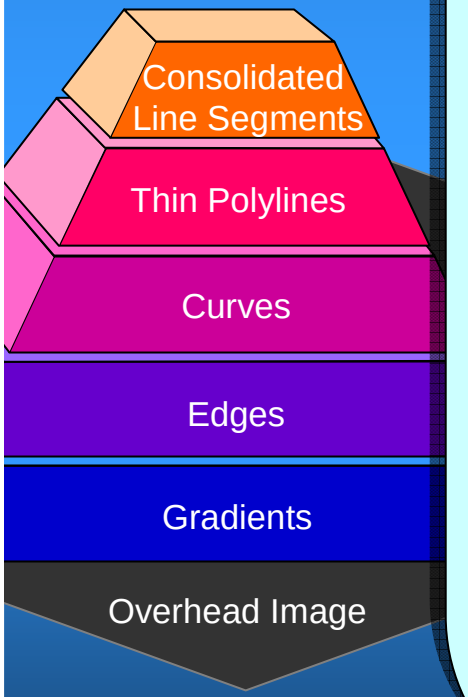
•Starting with the longest remaining line segment as the seed, line segments that are:

1. Nearly parallel
2. Transversally nearby
3. Longitudinally close



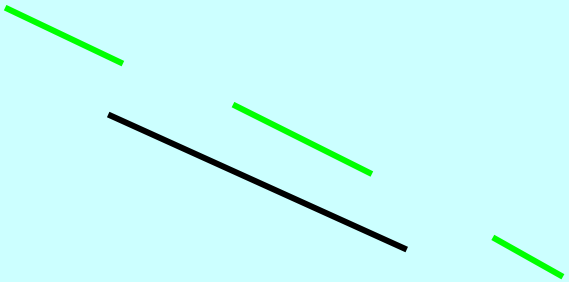


Consolidating Parallel Line Segments



•Starting with the longest remaining line segment as the seed, line segments that are:

1. Nearly parallel
2. Transversally nearby
3. Longitudinally close

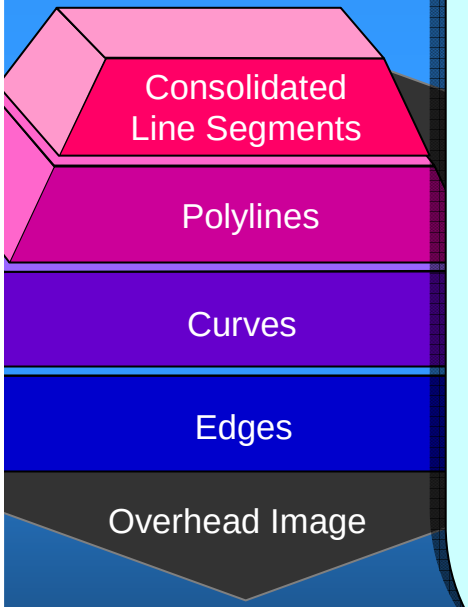


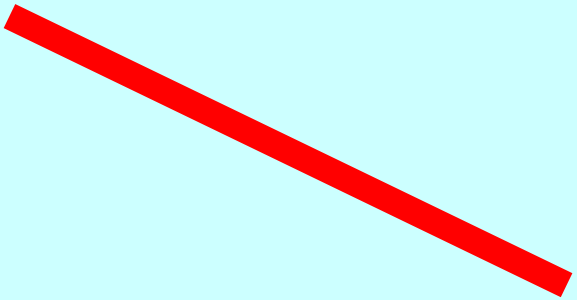
Consolidating Parallel Line Segments

•Starting with the longest remaining line segment as the seed, line segments that are:

1. Nearly parallel
2. Transversally nearby
3. Longitudinally close

are consolidated into a single thick line segment.





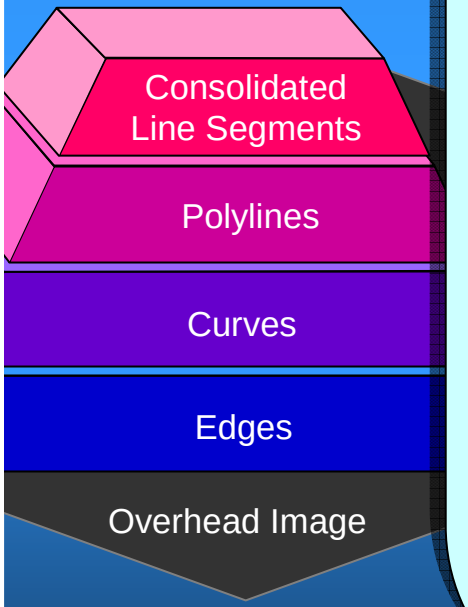
Consolidating Parallel Line Segments

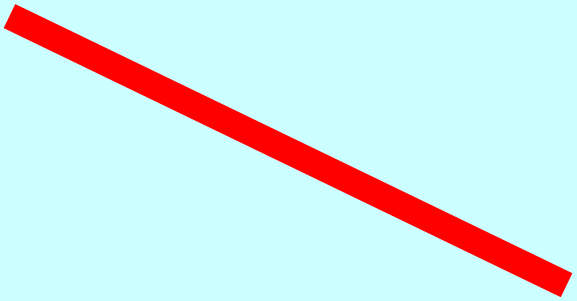
•Starting with the longest remaining line segment as the seed, line segments that are:

1. Nearly parallel
2. Transversally nearby
3. Longitudinally close

are consolidated into a single thick line segment.

•Repeat until all line segments have been consolidated





Line Segment Separation Measures: Angular Separation

- A line segment, L_i, can be described by:
  1. two endpoints [(c_{i0}, r_{i0}) and (c_{i1}, r_{i1})].
  2. $\alpha_i, \beta_i, \gamma_i$ parameters of the extended line containing the line segment ($\alpha_i x + \beta_i y = \gamma_i$).
  3. s_i, θ_i parameters of the extended line containing the line segment.
  4. d_i, length of line segment

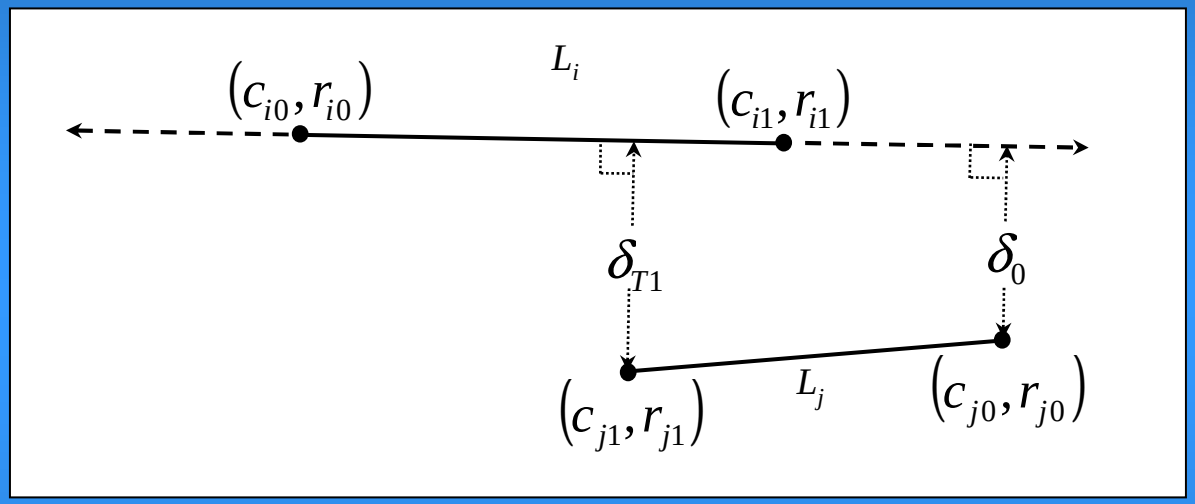
- Angular separation measures how far from parallel two line segments are.

$$\delta_\theta(\underline{L}_0, \underline{L}_1) = \min_{k=-2,-1,0,1,2} \left|\theta_0 - (\theta_1 + k\pi)\right| \in \left[0, \frac{\pi}{2}\right]$$

$$k_{\min} = \operatorname*{argmin}_{k=-2,-1,0,1,2} \left|\theta_0 - (\theta_1 + k\pi)\right| \in \left[0, \frac{\pi}{2}\right]$$

Line Segment Separation Measures: Transverse Separation

- **Transverse separation is an asymmetric measure of the distance between two nearly parallel line segments along the transverse direction.**

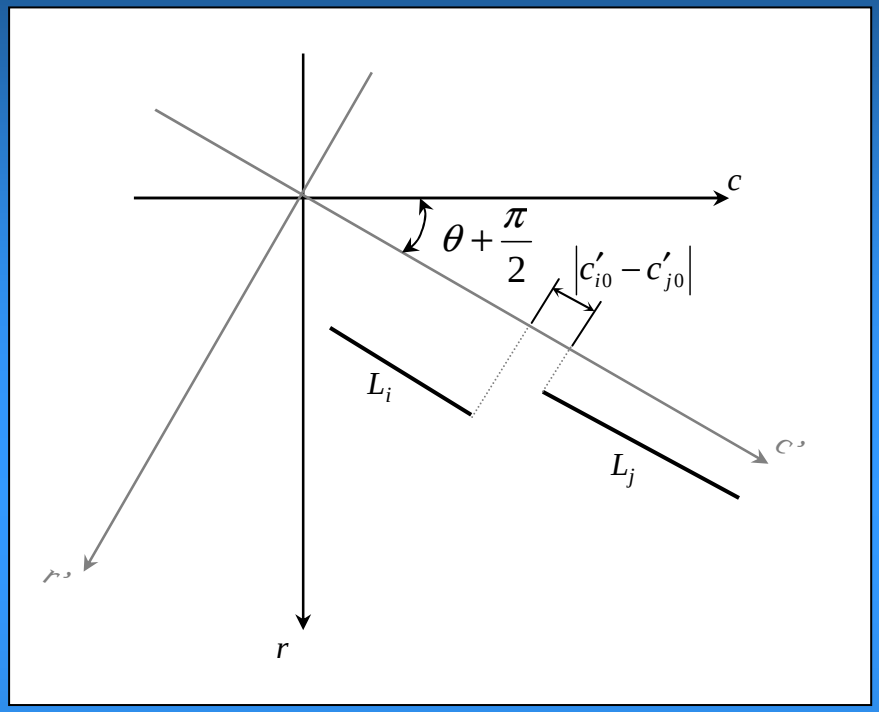


$$\delta_T\left(\underline{L}_i, \underline{L}_j\right) = \min\left(\delta_{T0}, \delta_{T1}\right)$$

$$\delta_{Tk} = \frac{\alpha_i c_{j,k} + \beta_i r_{j,k} - \gamma_i}{\sqrt{\alpha_i^2 + \beta_i^2}}$$

Line Segment Separation Measures: Longitudinal Separation

- **Longitudinal separation measures the distance between two nearly parallel line segments along the longitudinal direction normalized by their average lengths.**



$$\delta_L(\underline{L}_0, \underline{L}_1) = \begin{cases} 0, & \text{if } \left(c'_{00} \text{ or } c'_{01} \in [c'_{10}, c'_{11}]\right) \text{ or } \left(c'_{10} \text{ or } c'_{11} \in [c'_{00}, c'_{01}]\right) \\ \dfrac{\min\left[|c'_{00} - c'_{10}|, |c'_{00} - c'_{11}|, |c'_{01} - c'_{10}|, |c'_{01} - c'_{11}|\right]}{(d_0 + d_1)/2}, & \text{otherwise} \end{cases}$$

Line Segment Consolidation Set Properties

- **Contributing line segments in a consolidation set grown from a seed line segment satisfy the following requirements:**
  1. **Nearly parallel**

$$\delta_\theta\left(\underline{L}_{seed}, \underline{L}_i\right) \leq \delta_\theta \ \forall \text{ contributors } i$$

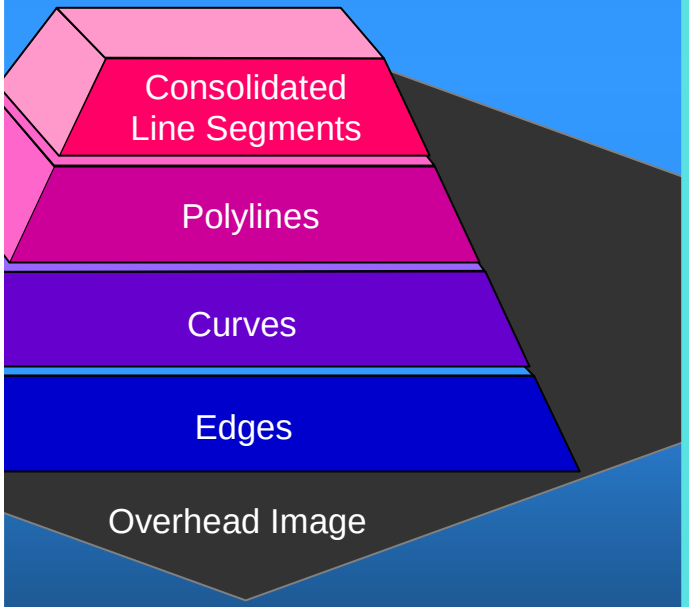
  2. **Transversally near**

$$\delta_T\left(\underline{L}_{seed}, \underline{L}_i\right) \leq \delta_T \ \forall \text{ contributors } i$$

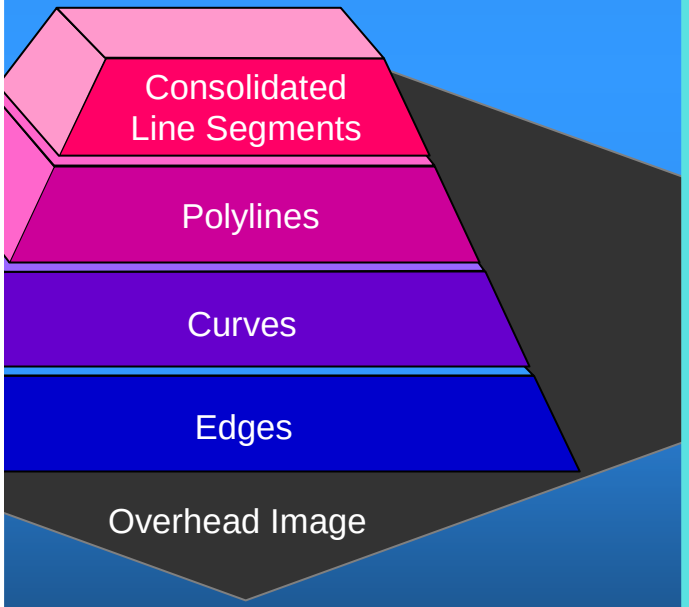
  3. **Longitudinally close**

$$\delta_L\left(\underline{L}_i, \underline{L}_j\right) \leq \delta_L \ \forall \text{ contributors } i \ \exists \text{ contributor } j$$

Consolidating Parallel Line Segments



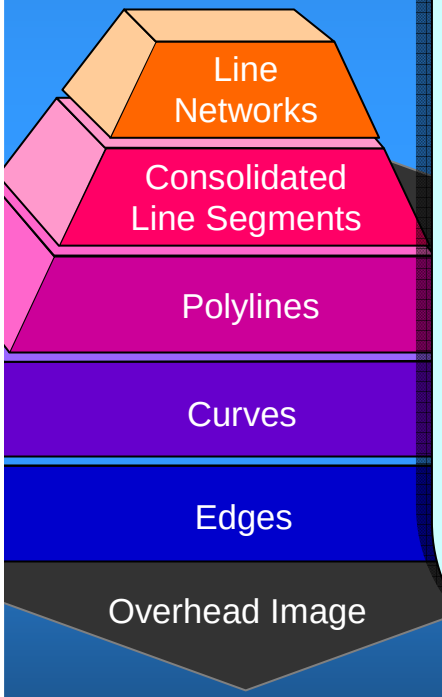
Consolidating Parallel Line Segments



$\delta_\theta = 6^\circ, \delta_T = 28, \delta_L = 1.0$

Consolidating Parallel Line Segments

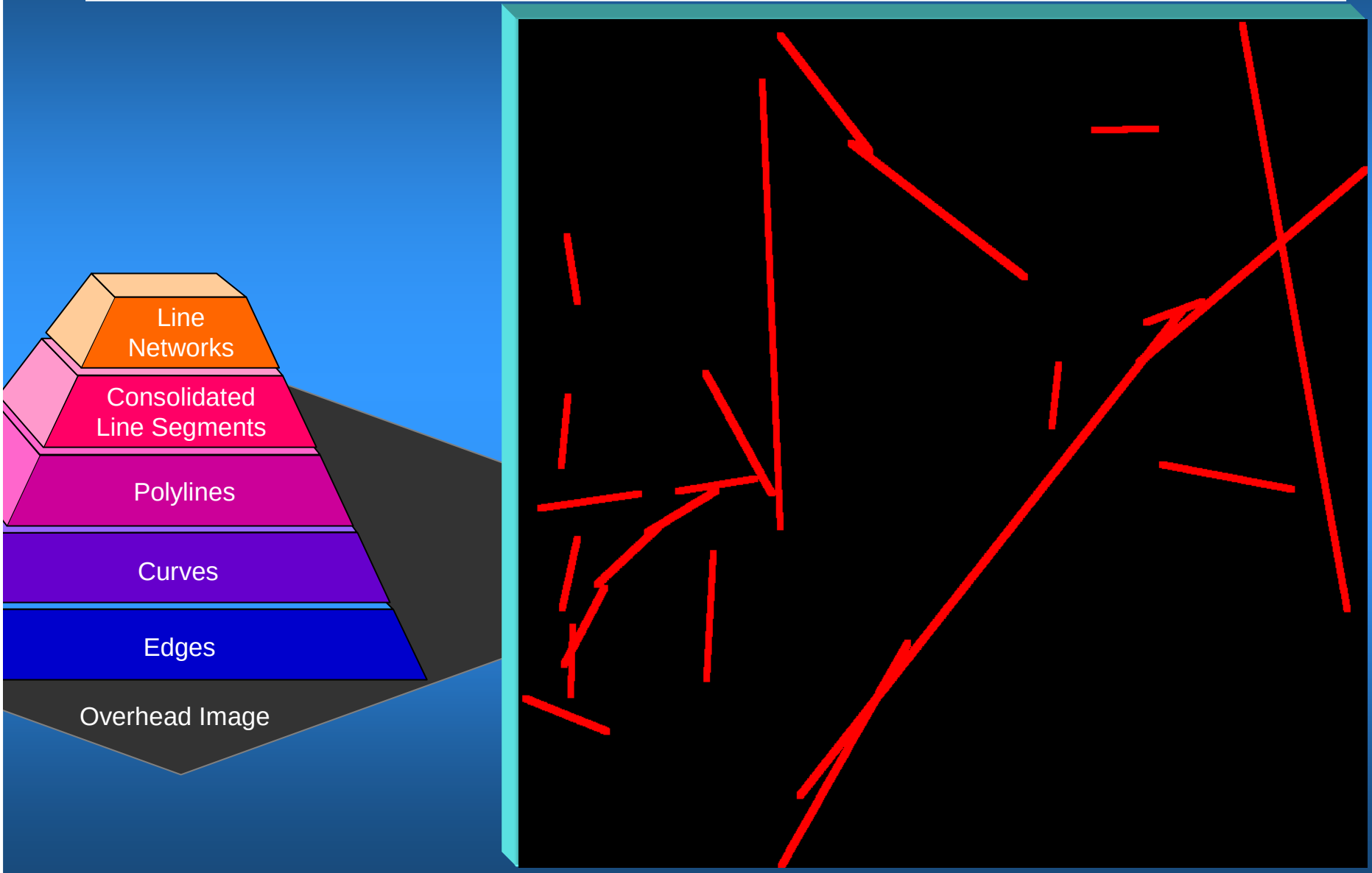
Forming Line Networks



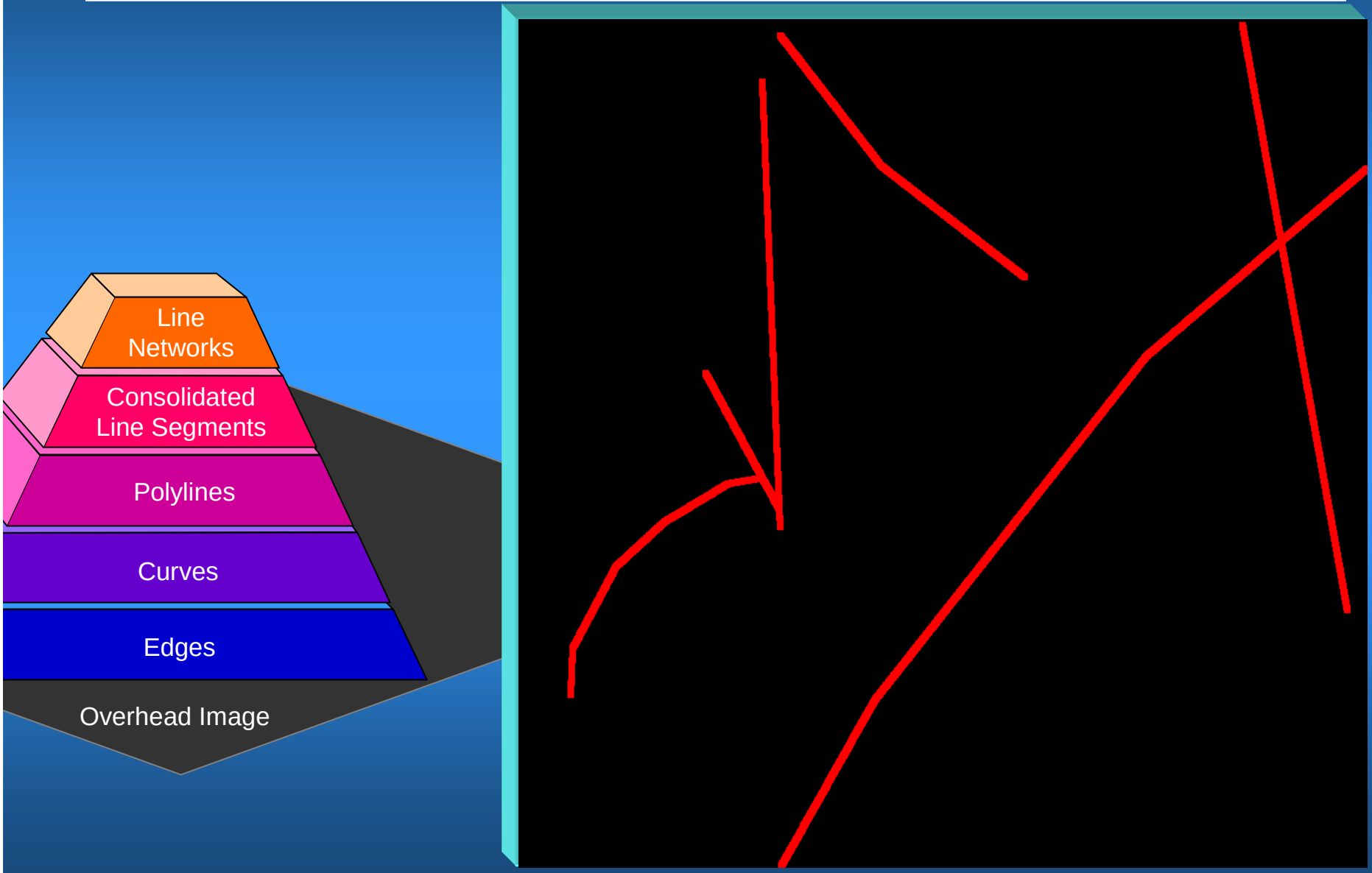
- Pairs of thick line segments are linearly extended to touch each other under two cases:
  1) both share one or more parent polyline and extension length is not too long
  2) extension length is very short

- Touching thick line segments are then linked together to form consolidated polylines.
- Finally, short consolidated polyline networks are discarded, and occluded overshoots are removed.

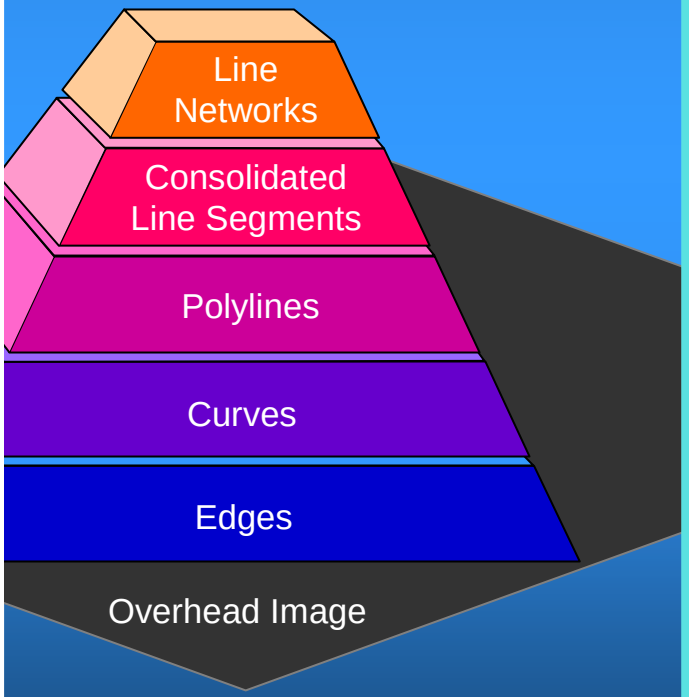
Forming Line Networks

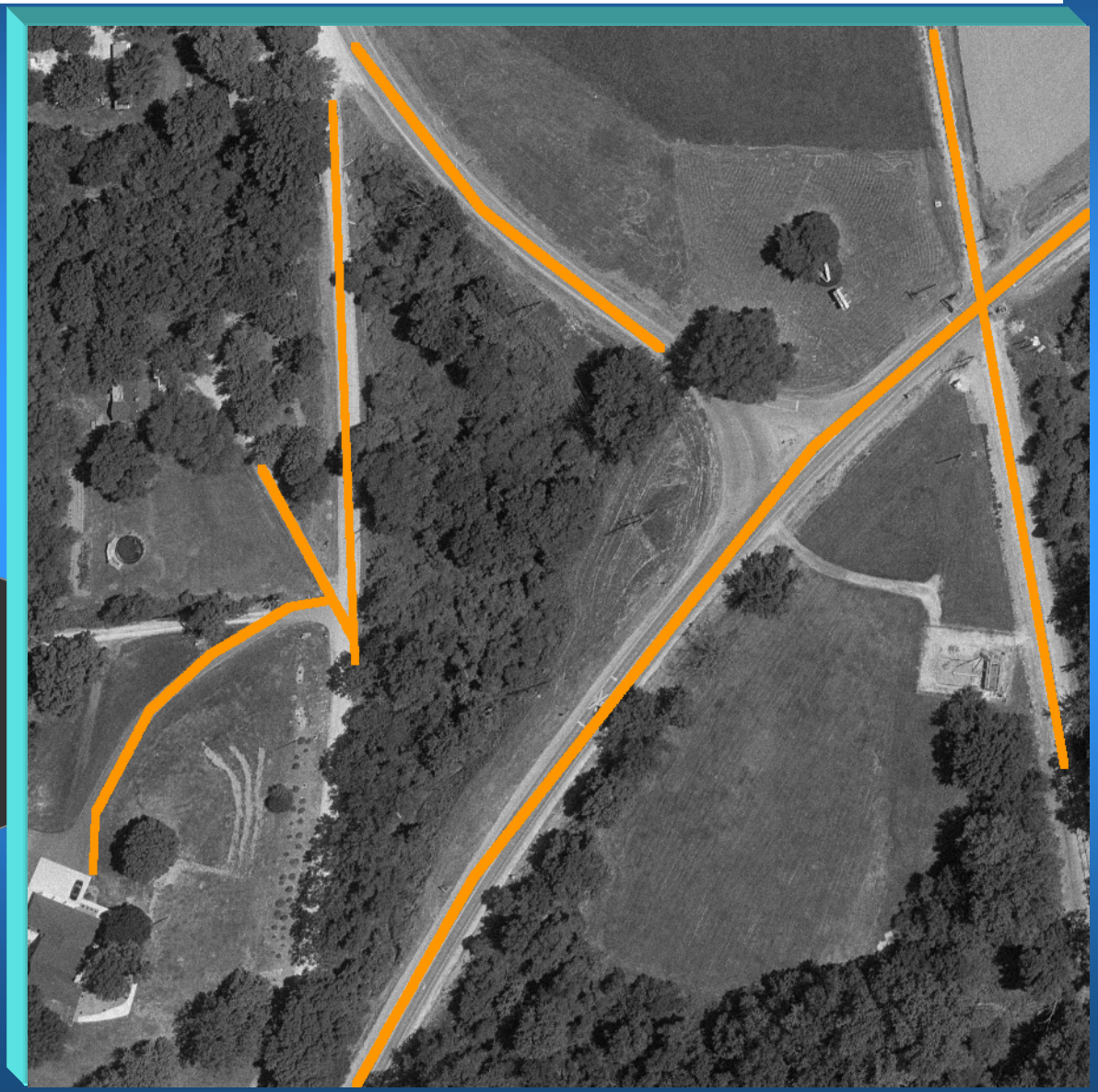


Forming Line Networks



Forming Line Networks





Urban Example: Original Overhead Image

Urban Example: Detected Line Networks

Desert: Original Overhead Image

Desert Example: Detected Line Networks

Concluding Remarks

- Our road extraction algorithm is able detect most roads in overhead images using a series of novel techniques like orientation channel de-cluttering and linear consolidation

- Successive levels in the hierarchical approach correct errors from previous levels:
  - The Curves level filters out short and curly edges
  - The Consolidated Line Segments level discards curves that are not parallel or close to other curves
  - The Line Networks level discards line segments that are not connected to large networks

- Next Steps:
  - Incorporate techniques for connecting disconnected line segments that should be connected (e.g., road segments occluded by trees)
  - Develop statistical parameter estimation methods