Collaborative Whiteboard/Drawing Tool

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* Performance vs Quality
* Collaboration vs Consistency
* Scalability Considerations

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Clarify the Problem and Requirements

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Problem Understanding

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Design a collaborative whiteboard/drawing application that enables multiple users to create, edit, and share visual content in real-time, similar to Miro, Figma, or Microsoft Whiteboard. The system must support various drawing tools, shapes, text annotations, and multimedia content while maintaining smooth real-time synchronization across all participants.

Functional Requirements

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- **Drawing Tools**: Pen, pencil, brush, eraser with pressure sensitivity and customizable properties

- **Shape Tools**: Rectangle, circle, line, arrow, polygon, bezier curves
- **Text & Annotations**: Text boxes, sticky notes, callouts, comments with formatting
- **Media Support**: Image import, video embedding, audio notes, file attachments
- **Real-time Collaboration**: Multi-user editing with live cursors and presence indicators
- **Layer Management**: Multiple layers, layer ordering, visibility controls
- **Selection & Transformation**: Multi-select, move, rotate, scale, group/ungroup objects
- **Templates & Frameworks**: Pre-built templates, wireframe kits, diagramming tools

Non-Functional Requirements

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- **Performance**: <16ms drawing latency, 60fps smooth animations, <100ms collaboration sync
- **Scalability**: Support 100+ concurrent users per board, unlimited canvas size
- **Availability**: 99.9% uptime with offline drawing capabilities
- **Cross-platform**: Web browsers, tablet apps with touch/stylus support
- **Responsiveness**: Adaptive UI for different screen sizes and input methods
- **Data Persistence**: Auto-save, version history, real-time backup
- **Memory Efficiency**: Handle large canvases without performance degradation

Key Assumptions

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- Typical board complexity: 1000-10000 objects per canvas
- Peak concurrent users per board: 20-100 participants
- Average session duration: 30-180 minutes
- Drawing operation frequency: 10-100 operations per second during active use
- Canvas size: Support for infinite canvas with viewport-based rendering
- Device types: Desktop browsers, tablets, smartphones with varying input capabilities
- Network conditions: Support for mobile networks to high-speed connections

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High-Level Design (HLD)

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System Architecture Overview

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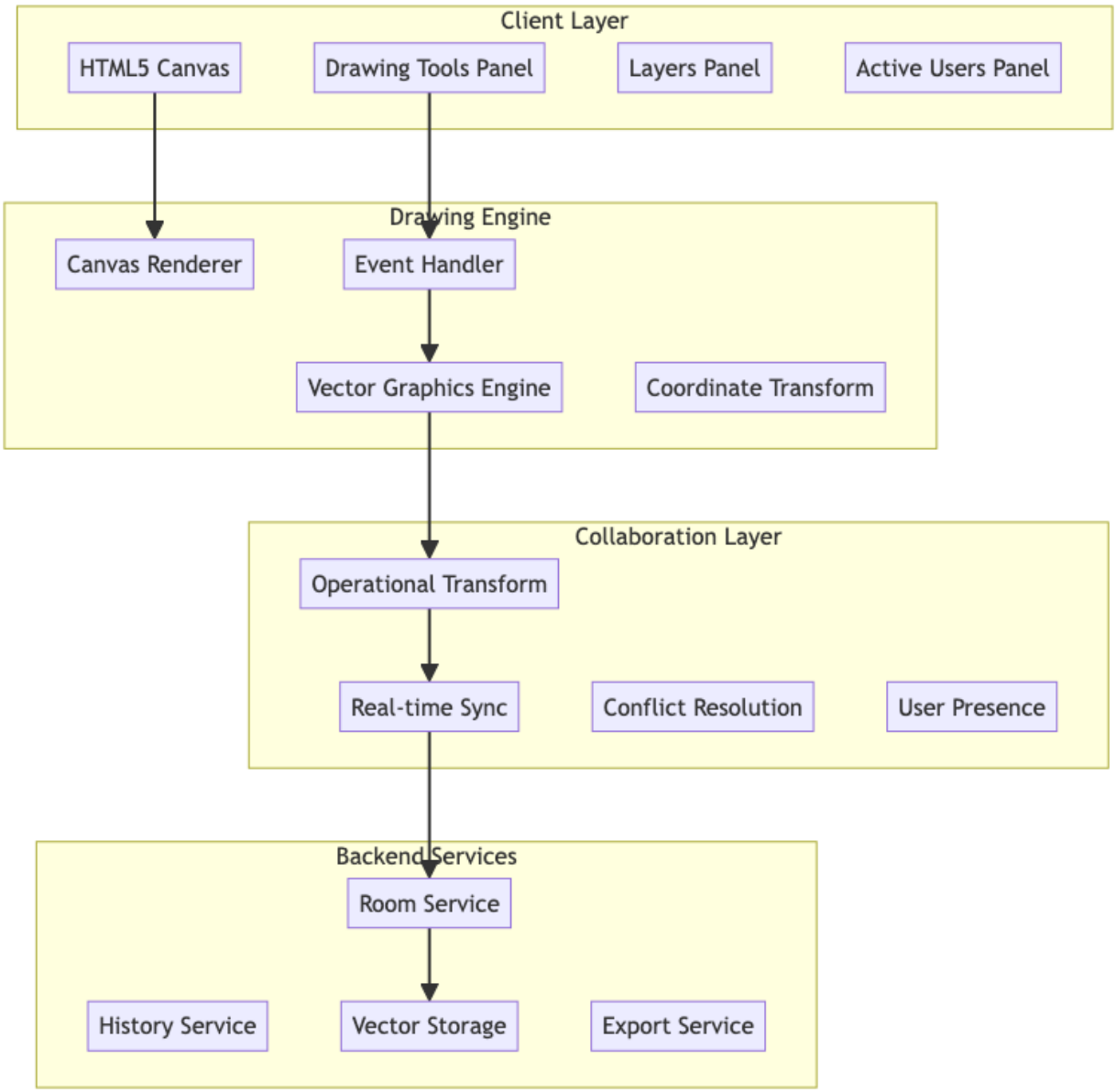

Drawing Object Model

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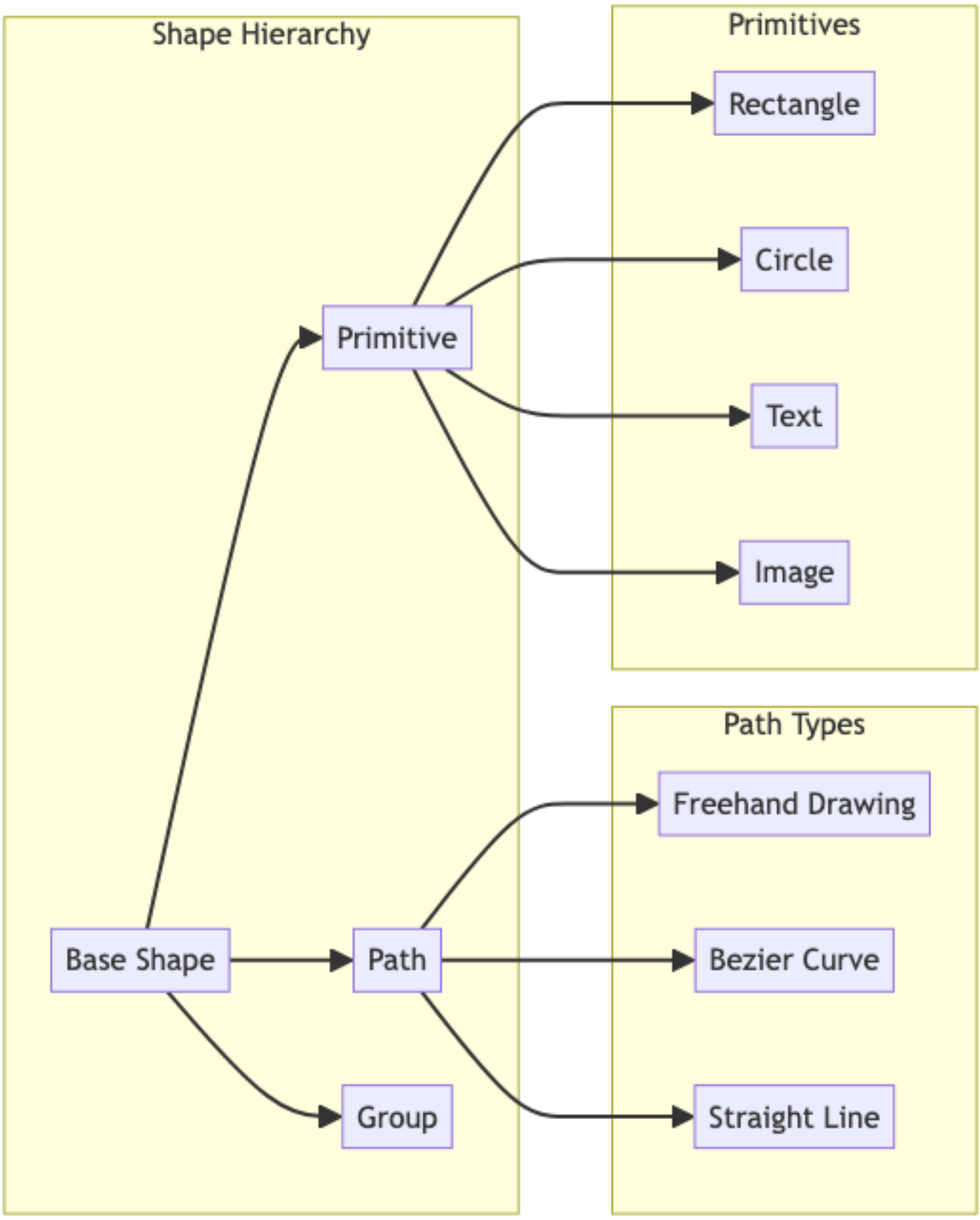

Low-Level Design (LLD)

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Real-time Drawing Synchronization

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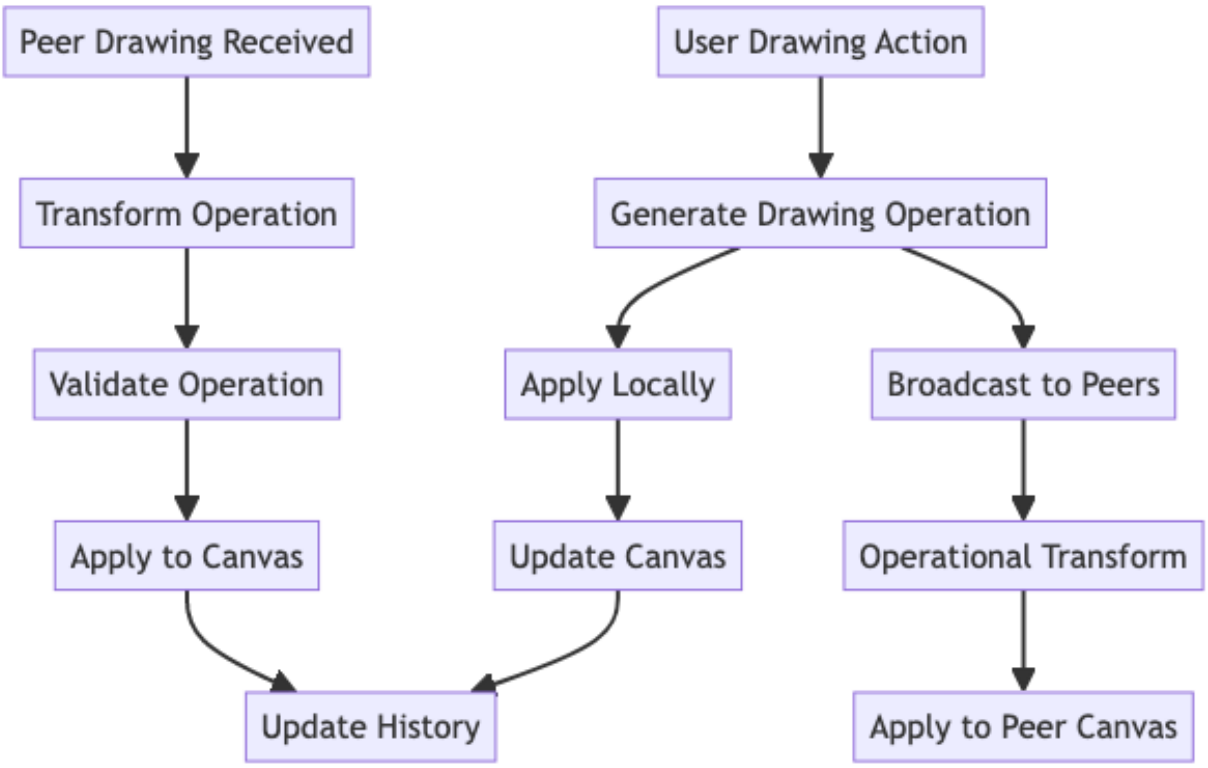

Canvas Rendering Pipeline

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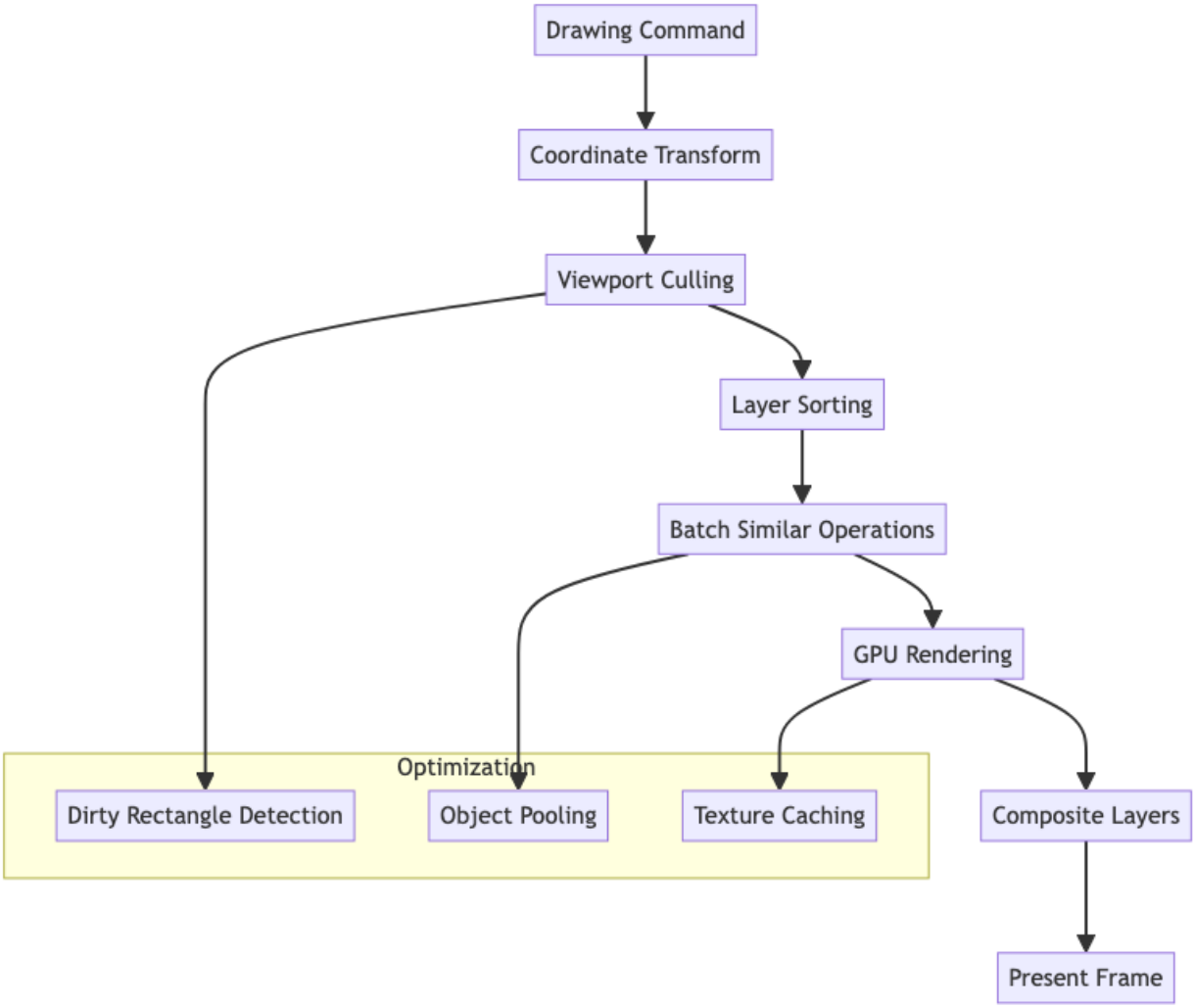

Collaborative Drawing State Machine

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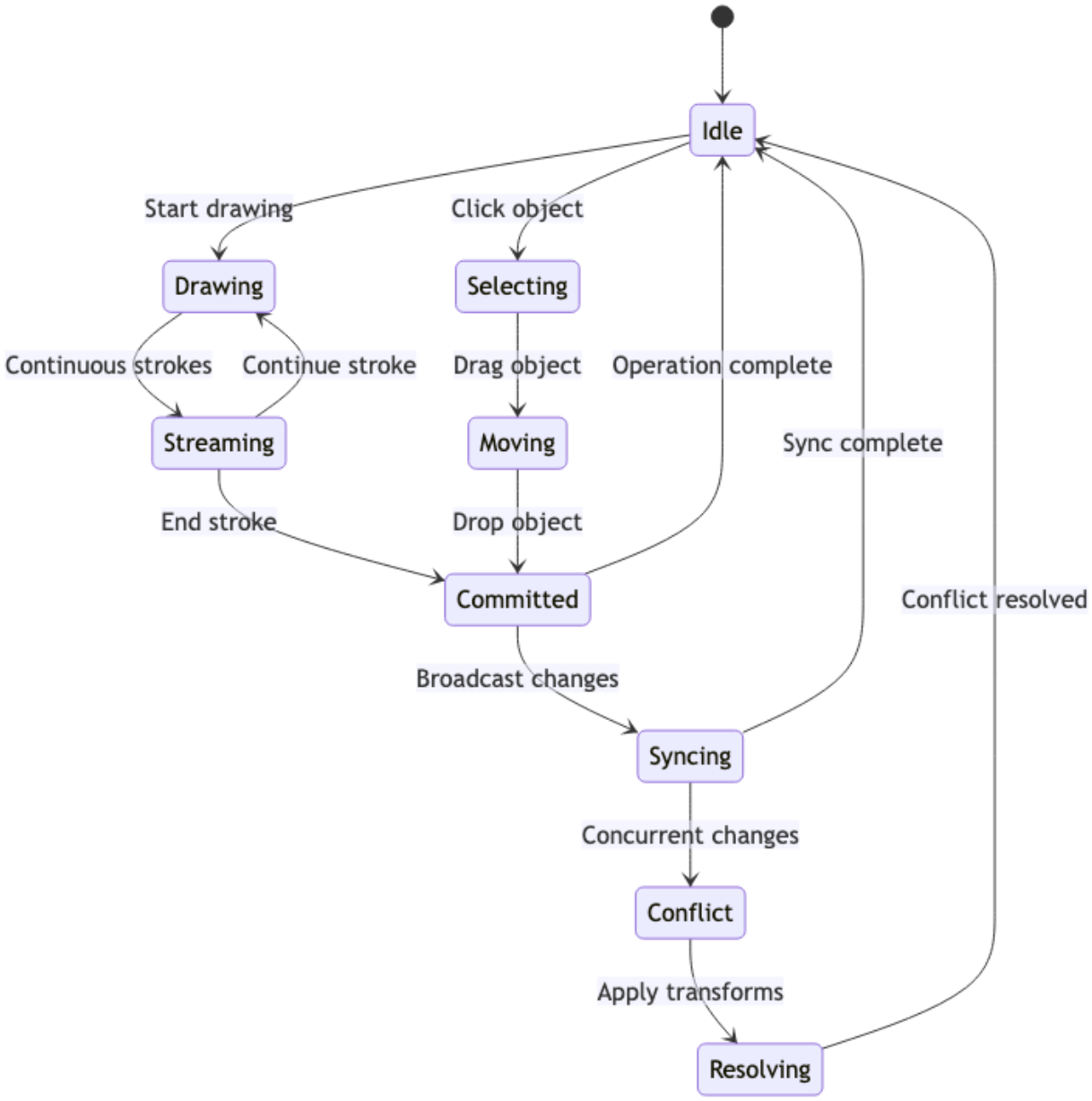

Core Algorithms

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1. Operational Transform for Drawing Operations

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Drawing Operation Types:

```
DrawOperation = {
  type: 'create' | 'modify' | 'delete' | 'move',
  objectId: string,
  data: ShapeData,
  timestamp: number,
  userId: string
}
```

Transform Algorithm:

```
For concurrent operations A and B:
1. Check operation dependencies
2. Transform spatial coordinates
3. Handle object lifecycle conflicts
4. Preserve drawing intent
5. Maintain visual consistency
```

Conflict Resolution Strategies: - **Create-Create**: Generate unique IDs, allow both - **Modify-Modify**: Merge properties, last-writer-wins for conflicts - **Delete-Modify**: Delete takes precedence - **Move-Move**: Apply vector addition for position

2. Vector Path Smoothing Algorithm

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Ramer-Douglas-Peucker Simplification:

```
function simplifyPath(points, tolerance):
  if points.length <= 2:
    return points

  maxDistance = 0
  maxIndex = 0

  for i in range(1, points.length - 1):
    distance = perpendicularDistance(points[i], line(points[0], points[-1]))
    if distance > maxDistance:
      maxDistance = distance
      maxIndex = i

  if maxDistance > tolerance:
    left = simplifyPath(points[0:maxIndex+1], tolerance)
    right = simplifyPath(points[maxIndex:], tolerance)
    return left[:-1] + right
```

```
  else:
    return [points[0], points[-1]]
```

Bezier Curve Fitting: - Calculate control points using least squares - Maintain C1 continuity between segments - Optimize for minimal point count - Preserve original drawing intention

3. Spatial Indexing for Hit Testing

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R-Tree Implementation:

```
RTreeNode = {
  bounds: Rectangle,
  children: RTreeNode[] | Shape[],
  isLeaf: boolean
}
```

Hit Testing Algorithm: 1. Traverse R-tree from root 2. Check bounding box intersections 3. Perform precise hit testing on leaf shapes 4. Return shapes in depth order 5. Handle overlapping objects

Insertion Strategy: - Choose leaf with minimal area enlargement - Split nodes when capacity exceeded - Rebalance tree periodically - Update bounds propagation

4. Multi-layer Rendering System

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Layer Management:

```
Layer = {
  id: string,
  zIndex: number,
  visible: boolean,
  locked: boolean,
  opacity: number,
  shapes: Shape[]
}
```

Composite Rendering Process: 1. Sort layers by z-index 2. Render each layer to separate canvas 3. Apply layer-specific effects (opacity, blend modes) 4. Composite layers using GPU acceleration 5. Handle layer visibility changes efficiently

5. Pressure-Sensitive Drawing Algorithm

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Pressure Interpolation:

```
function interpolatePressure(points):
  for i in range(1, points.length):
    startPressure = points[i-1].pressure
    endPressure = points[i].pressure
    distance = calculateDistance(points[i-1], points[i])
    segments = Math.max(1, Math.floor(distance / 2))

    for j in range(segments):
      t = j / segments
      pressure = lerp(startPressure, endPressure, t)
      interpolatedPoints.push({
        x: lerp(points[i-1].x, points[i].x, t),
        y: lerp(points[i-1].y, points[i].y, t),
        pressure: pressure
      })
```

Brush Dynamics: - Map pressure to stroke width - Adjust opacity based on velocity - Implement tilt sensitivity for stylus - Apply texture mapping for natural brush effects

Component Architecture

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Drawing Tool Components

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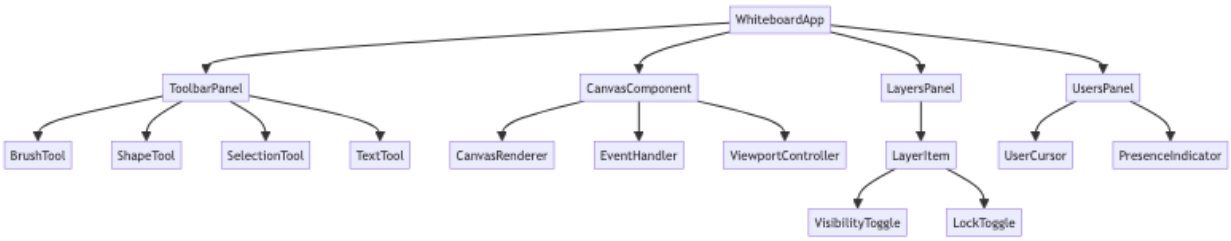

State Management Architecture

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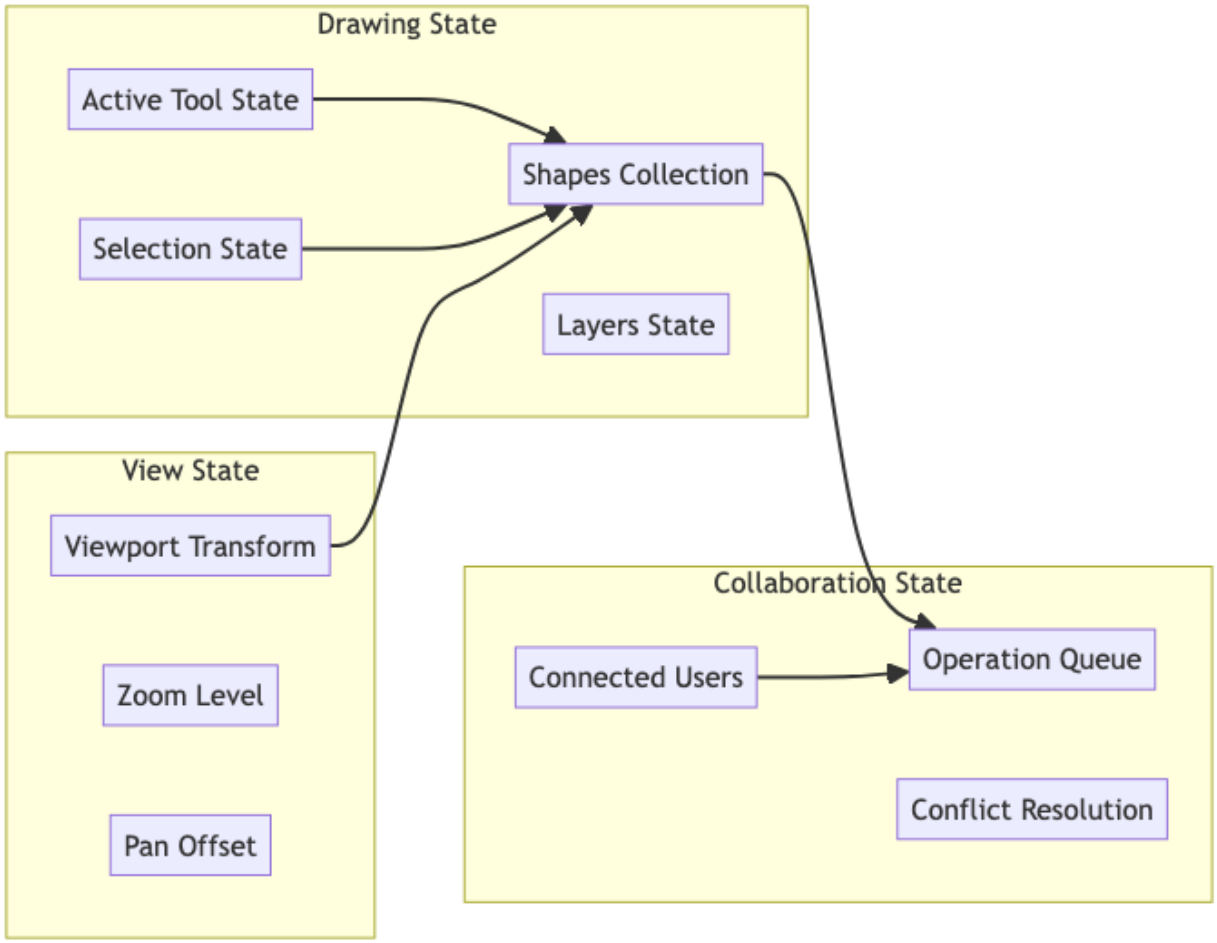

React Component Implementation

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WhiteboardApp.jsx

```
import React, { useState, useCallback, useRef, useEffect } from 'react';
import { WhiteboardProvider } from './WhiteboardContext';
import ToolbarPanel from './ToolbarPanel';
import CanvasComponent from './CanvasComponent';
import LayersPanel from './LayersPanel';
import UsersPanel from './UsersPanel';
import { useWebSocket } from './hooks/useWebSocket';

const WhiteboardApp = ({ roomId, userId }) => {
```

```
const [shapes, setShapes] = useState([]);
const [layers, setLayers] = useState([{ id: 'layer1', name: 'Layer 1', visible: true,
const [activeTool, setActiveTool] = useState('brush');
const [selectedShapes, setSelectedShapes] = useState([]);
const [viewport, setViewport] = useState({ x: 0, y: 0, zoom: 1 });
const [users, setUsers] = useState([]);
const [isDrawing, setIsDrawing] = useState(false);

const canvasRef = useRef(null);
const { socket, isConnected } = useWebSocket(`/whiteboard/${roomId}`);

useEffect(() => {
  if (socket) {
    socket.on('shape:added', handleRemoteShapeAdded);
    socket.on('shape:updated', handleRemoteShapeUpdated);
    socket.on('shape:deleted', handleRemoteShapeDeleted);
    socket.on('user:joined', handleUserJoined);
    socket.on('user:left', handleUserLeft);
    socket.on('cursor:moved', handleCursorMoved);

    return () => {
      socket.off('shape:added');
      socket.off('shape:updated');
      socket.off('shape:deleted');
      socket.off('user:joined');
      socket.off('user:left');
      socket.off('cursor:moved');
    };
  }
}, [socket]);

const addShape = useCallback((shapeData) => {
  const newShape = {
    id: generateId(),
    ...shapeData,
    userId,
    timestamp: Date.now()
  };

  setShapes(prev => [...prev, newShape]);
  socket?.emit('shape:add', newShape);
}, [userId, socket]);

const updateShape = useCallback((shapeId, updates) => {
  setShapes(prev => prev.map(shape =>
```

```
    shape.id === shapeId ? { ...shape, ...updates } : shape
  ));

  socket?.emit('shape:update', { shapeId, updates });
}, [socket]);

const deleteShape = useCallback((shapeId) => {
  setShapes(prev => prev.filter(shape => shape.id !== shapeId));
  socket?.emit('shape:delete', { shapeId });
}, [socket]);

const handleCanvasMouseDown = useCallback((e) => {
  if (activeTool === 'select') {
    handleSelectionStart(e);
  } else {
    handleDrawingStart(e);
  }
}, [activeTool]);

const handleDrawingStart = useCallback((e) => {
  setIsDrawing(true);
  const point = getCanvasPoint(e);

  const shapeData = {
    type: activeTool,
    points: [point],
    style: getCurrentStyle(),
    layerId: getCurrentLayerId()
  };

  addShape(shapeData);
}, [activeTool, addShape]);

const handleCanvasMouseMove = useCallback((e) => {
  const point = getCanvasPoint(e);

  // Broadcast cursor position
  socket?.emit('cursor:move', { userId, position: point });

  if (isDrawing && shapes.length > 0) {
    const lastShape = shapes[shapes.length - 1];
    if (lastShape.userId === userId) {
      updateShape(lastShape.id, {
        points: [...lastShape.points, point]
      });
```

```
    }
  }
}, [isDrawing, shapes, userId, socket, updateShape]);

const handleCanvasMouseUp = useCallback(() => {
  setIsDrawing(false);
}, []);

const getCanvasPoint = (e) => {
  const rect = canvasRef.current.getBoundingClientRect();
  return {
    x: (e.clientX - rect.left - viewport.x) / viewport.zoom,
    y: (e.clientY - rect.top - viewport.y) / viewport.zoom
  };
};

const getCurrentStyle = () => ({
  strokeColor: '#000000',
  strokeWidth: 2,
  fillColor: 'transparent'
});

const getCurrentLayerId = () => layers.find(l => l.visible && !l.locked)?.id || layers

const handleRemoteShapeAdded = useCallback((shape) => {
  if (shape.userId !== userId) {
    setShapes(prev => [...prev, shape]);
  }
}, [userId]);

const handleRemoteShapeUpdated = useCallback((data) => {
  setShapes(prev => prev.map(shape =>
    shape.id === data.shapeId ? { ...shape, ...data.updates } : shape
  ));
}, []);

const handleRemoteShapeDeleted = useCallback((data) => {
  setShapes(prev => prev.filter(shape => shape.id !== data.shapeId));
}, []);

const handleUserJoined = useCallback((user) => {
  setUsers(prev => [...prev, user]);
}, []);

const handleUserLeft = useCallback((data) => {
```

```
  setUsers(prev => prev.filter(user => user.id !== data.userId));
}, []);

const handleCursorMoved = useCallback((data) => {
  setUsers(prev => prev.map(user =>
    user.id === data.userId
      ? { ...user, cursor: data.position }
      : user
  ));
}, []);

const generateId = () => Date.now().toString(36) + Math.random().toString(36).substr(2

return (
  <WhiteboardProvider value={{
    shapes,
    layers,
    activeTool,
    selectedShapes,
    viewport,
    users,
    isConnected,
    setActiveTool,
    setSelectedShapes,
    setViewport,
    addShape,
    updateShape,
    deleteShape
  }}>
    <div className="whiteboard-app">
      <ToolbarPanel />

      <div className="whiteboard-main">
        <CanvasComponent
          ref={canvasRef}
          onMouseDown={handleCanvasMouseDown}
          onMouseMove={handleCanvasMouseMove}
          onMouseUp={handleCanvasMouseUp}
        />

        <div className="side-panels">
          <LayersPanel />
          <UsersPanel />
        </div>
      </div>
```

```
      </div>
    </WhiteboardProvider>
  );
};

export default WhiteboardApp;
```

CanvasComponent.jsx

```
import React, { useContext, useRef, useEffect, forwardRef } from 'react';
import { WhiteboardContext } from './WhiteboardContext';
import ShapeRenderer from './ShapeRenderer';
import UserCursors from './UserCursors';

const CanvasComponent = forwardRef(({ onMouseDown, onMouseMove, onMouseUp }, ref) => {
  const { shapes, layers, viewport, selectedShapes, users } = useContext(WhiteboardConte
  const canvasRef = useRef(null);
  const overlayRef = useRef(null);

  useEffect(() => {
    if (ref) {
      ref.current = canvasRef.current;
    }
  }, [ref]);

  useEffect(() => {
    drawCanvas();
  }, [shapes, layers, viewport]);

  const drawCanvas = () => {
    const canvas = canvasRef.current;
    const ctx = canvas.getContext('2d');

    // Clear canvas
    ctx.clearRect(0, 0, canvas.width, canvas.height);

    // Apply viewport transform
    ctx.save();
    ctx.translate(viewport.x, viewport.y);
    ctx.scale(viewport.zoom, viewport.zoom);

    // Draw shapes by layer
    layers.forEach(layer => {
      if (layer.visible) {
        const layerShapes = shapes.filter(shape => shape.layerId === layer.id);
        layerShapes.forEach(shape => {
```

```
        drawShape(ctx, shape);
      });
    }
  });

  // Draw selection highlights
  selectedShapes.forEach(shapeId => {
    const shape = shapes.find(s => s.id === shapeId);
    if (shape) {
      drawSelectionHighlight(ctx, shape);
    }
  });

  ctx.restore();
};

const drawShape = (ctx, shape) => {
  ctx.save();

  // Apply shape style
  ctx.strokeStyle = shape.style.strokeColor;
  ctx.lineWidth = shape.style.strokeWidth;
  ctx.fillStyle = shape.style.fillColor;

  switch (shape.type) {
    case 'brush':
      drawBrushStroke(ctx, shape);
      break;
    case 'rectangle':
      drawRectangle(ctx, shape);
      break;
    case 'circle':
      drawCircle(ctx, shape);
      break;
    case 'line':
      drawLine(ctx, shape);
      break;
    case 'text':
      drawText(ctx, shape);
      break;
  }

  ctx.restore();
};
```

```
const drawBrushStroke = (ctx, shape) => {
  if (shape.points.length < 2) return;

  ctx.beginPath();
  ctx.moveTo(shape.points[0].x, shape.points[0].y);

  for (let i = 1; i < shape.points.length; i++) {
    ctx.lineTo(shape.points[i].x, shape.points[i].y);
  }

  ctx.stroke();
};

const drawRectangle = (ctx, shape) => {
  if (shape.points.length < 2) return;

  const [start, end] = shape.points;
  const width = end.x - start.x;
  const height = end.y - start.y;

  ctx.beginPath();
  ctx.rect(start.x, start.y, width, height);
  ctx.stroke();

  if (shape.style.fillColor !== 'transparent') {
    ctx.fill();
  }
};

const drawCircle = (ctx, shape) => {
  if (shape.points.length < 2) return;

  const [center, edge] = shape.points;
  const radius = Math.sqrt(
    Math.pow(edge.x - center.x, 2) + Math.pow(edge.y - center.y, 2)
  );

  ctx.beginPath();
  ctx.arc(center.x, center.y, radius, 0, 2 * Math.PI);
  ctx.stroke();

  if (shape.style.fillColor !== 'transparent') {
    ctx.fill();
  }
};
```

```
const drawLine = (ctx, shape) => {
  if (shape.points.length < 2) return;

  const [start, end] = shape.points;
  ctx.beginPath();
  ctx.moveTo(start.x, start.y);
  ctx.lineTo(end.x, end.y);
  ctx.stroke();
};

const drawText = (ctx, shape) => {
  if (!shape.text || shape.points.length < 1) return;

  ctx.font = `${shape.style.fontSize || 16}px ${shape.style.fontFamily || 'Arial'}`;
  ctx.fillStyle = shape.style.strokeColor;
  ctx.fillText(shape.text, shape.points[0].x, shape.points[0].y);
};

const drawSelectionHighlight = (ctx, shape) => {
  ctx.save();
  ctx.strokeStyle = '#0066ff';
  ctx.lineWidth = 2;
  ctx.setLineDash([5, 5]);

  // Draw bounding box
  const bounds = getShapeBounds(shape);
  ctx.strokeRect(bounds.x, bounds.y, bounds.width, bounds.height);

  ctx.restore();
};

const getShapeBounds = (shape) => {
  if (!shape.points.length) return { x: 0, y: 0, width: 0, height: 0 };

  const xs = shape.points.map(p => p.x);
  const ys = shape.points.map(p => p.y);

  return {
    x: Math.min(...xs),
    y: Math.min(...ys),
    width: Math.max(...xs) - Math.min(...xs),
    height: Math.max(...ys) - Math.min(...ys)
  };
};
```

```
  return (
    <div className="canvas-container">
      <canvas
        ref={canvasRef}
        width={1920}
        height={1080}
        className="drawing-canvas"
        onMouseDown={onMouseDown}
        onMouseMove={onMouseMove}
        onMouseUp={onMouseUp}
      />

      <div ref={overlayRef} className="canvas-overlay">
        <UserCursors users={users} viewport={viewport} />
      </div>
    </div>
  );
});

export default CanvasComponent;
```

ToolbarPanel.jsx

```
import React, { useContext } from 'react';
import { WhiteboardContext } from './WhiteboardContext';

const ToolbarPanel = () => {
  const { activeTool, setActiveTool } = useContext(WhiteboardContext);

  const tools = [
    { id: 'select', name: 'Select', icon: ' ' },
    { id: 'brush', name: 'Brush', icon: ' ' },
    { id: 'rectangle', name: 'Rectangle', icon: ' ' },
    { id: 'circle', name: 'Circle', icon: ' ' },
    { id: 'line', name: 'Line', icon: ' ' },
    { id: 'text', name: 'Text', icon: 'T' }
  ];

  return (
    <div className="toolbar-panel">
      <div className="tool-group">
        {tools.map(tool => (
          <button
            key={tool.id}
            className={`tool-button ${activeTool === tool.id ? 'active' : ''}`}
```

```
            onClick={() => setActiveTool(tool.id)}
            title={tool.name}
          >
            {tool.icon}
          </button>
        ))}
      </div>

      <div className="tool-group">
        <input type="color" className="color-picker" defaultValue="#000000" />
        <input type="range" min="1" max="20" defaultValue="2" className="brush-size" />
      </div>
    </div>
  );
};

export default ToolbarPanel;
```

Real-time Collaboration

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WebSocket Protocol Design

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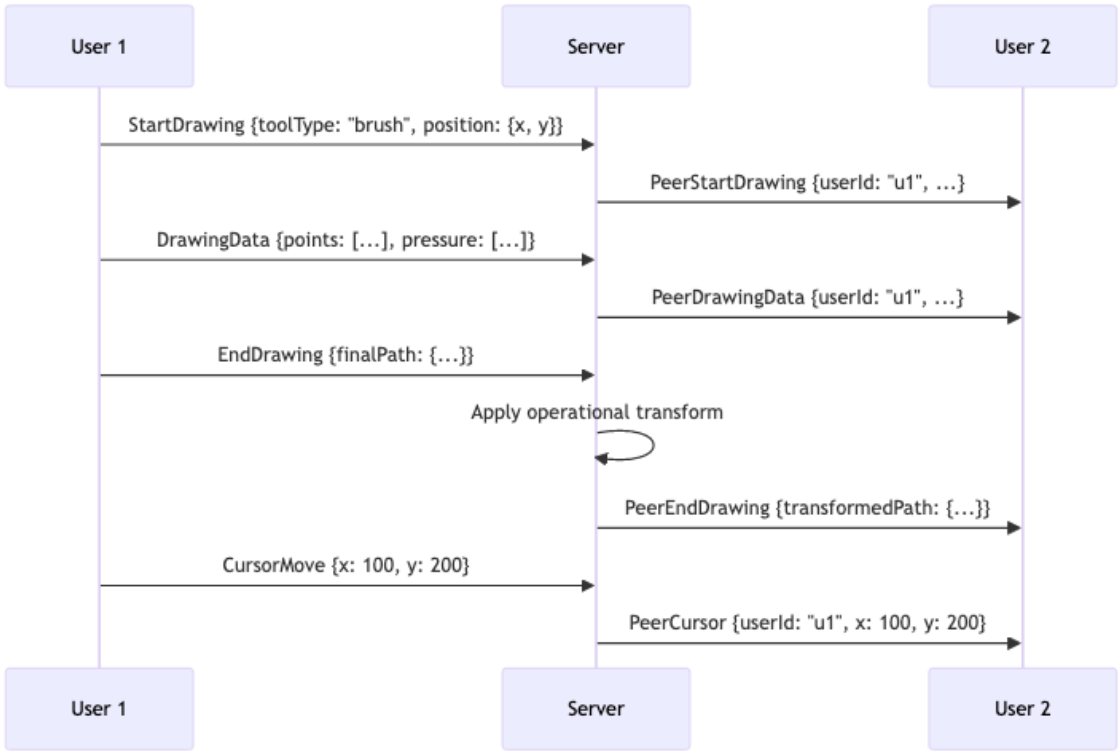

Presence System

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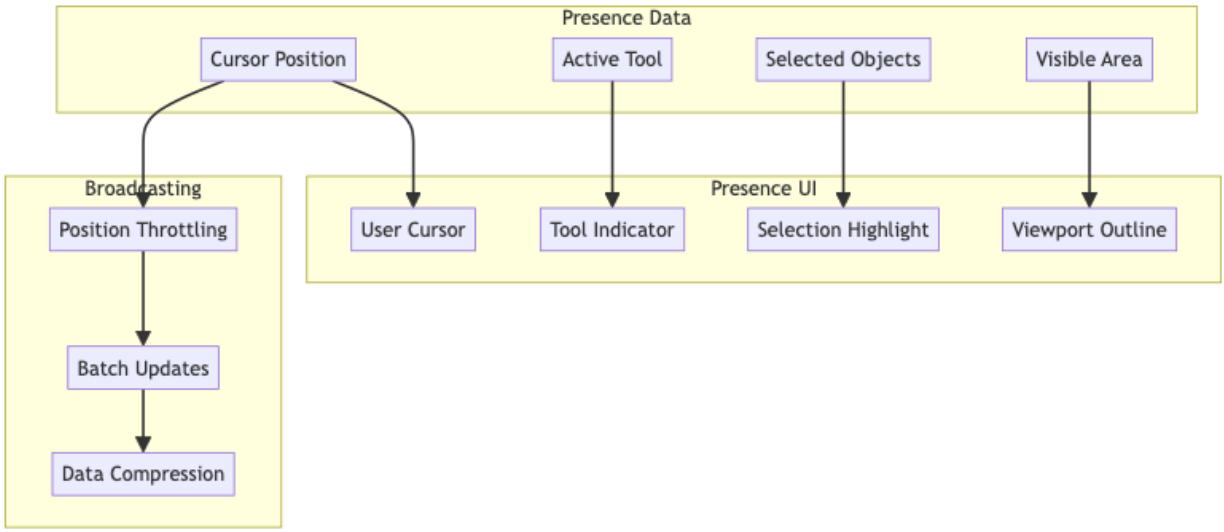

TypeScript Interfaces & Component Props

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Core Data Interfaces

```typescript
interface WhiteboardObject {
  id: string;
  type: 'shape' | 'text' | 'image' | 'line' | 'freehand';
  position: Point;
  dimensions: Dimensions;
  style: ObjectStyle;
  layerIndex: number;
  authorId: string;
  timestamp: Date;
  locked: boolean;
}

interface DrawingPath {
  id: string;
  points: Point[];
  pressure?: number[];
  tool: DrawingTool;
  style: StrokeStyle;
  smooth: boolean;
  closed: boolean;
}

interface WhiteboardUser {
  id: string;
  name: string;
  avatar?: string;
  color: string;
  cursor: Point;
  tool: DrawingTool;
  isActive: boolean;
  permissions: UserPermissions;
}

interface ObjectStyle {
  strokeColor: string;
  strokeWidth: number;
  fillColor: string;
  opacity: number;
  lineDash?: number[];
  fontSize?: number;
  fontFamily?: string;
```

```
}

interface WhiteboardState {
  id: string;
  objects: WhiteboardObject[];
  layers: Layer[];
  viewport: Viewport;
  collaborators: WhiteboardUser[];
  version: number;
  lastModified: Date;
}
```

Component Props Interfaces

```
interface WhiteboardCanvasProps {
  whiteboardId: string;
  width: number;
  height: number;
  onObjectCreate: (object: WhiteboardObject) => void;
  onObjectUpdate: (objectId: string, changes: Partial<WhiteboardObject>) => void;
  onObjectDelete: (objectId: string) => void;
  onSelectionChange: (selectedIds: string[]) => void;
  readOnly?: boolean;
  showGrid?: boolean;
}

interface DrawingToolbarProps {
  selectedTool: DrawingTool;
  onToolChange: (tool: DrawingTool) => void;
  strokeColor: string;
  strokeWidth: number;
  fillColor: string;
  onStyleChange: (style: Partial<ObjectStyle>) => void;
  disabled?: boolean;
  customTools?: ToolDefinition[];
}

interface LayerPanelProps {
  layers: Layer[];
  selectedLayerId: string;
  onLayerSelect: (layerId: string) => void;
  onLayerCreate: (name: string) => void;
  onLayerDelete: (layerId: string) => void;
  onLayerToggleVisibility: (layerId: string) => void;
  onLayerReorder: (layerId: string, newIndex: number) => void;
```

```
}

interface CollaboratorsPanelProps {
  users: WhiteboardUser[];
  currentUser: WhiteboardUser;
  onUserInvite?: (email: string) => void;
  onUserRemove?: (userId: string) => void;
  onPermissionChange?: (userId: string, permissions: UserPermissions) => void;
  showCursors?: boolean;
}
```

API Reference

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Whiteboard Management

- `GET /api/whiteboards` - List user's whiteboards with collaboration info
- `POST /api/whiteboards` - Create new whiteboard with initial configuration
- `GET /api/whiteboards/:id` - Get whiteboard content and metadata
- `PUT /api/whiteboards/:id` - Update whiteboard settings and properties
- `DELETE /api/whiteboards/:id` - Delete whiteboard and all associated data

Drawing Operations

- `POST /api/whiteboards/:id/objects` - Add new drawing object to whiteboard
- `PUT /api/whiteboards/:id/objects/:objectId` - Update existing object properties
- `DELETE /api/whiteboards/:id/objects/:objectId` - Delete object from whiteboard
- `POST /api/whiteboards/:id/paths` - Add freehand drawing path
- `POST /api/whiteboards/:id/batch` - Execute multiple operations in batch

Real-time Collaboration

- `WS /api/whiteboards/:id/collaborate` - WebSocket for real-time drawing
- `POST /api/whiteboards/:id/cursor` - Update user cursor position
- `POST /api/whiteboards/:id/selection` - Update user selection state
- `WS DRAWING_OPERATION` - Broadcast drawing operations to collaborators
- `WS USER_PRESENCE` - Handle user join/leave and cursor updates

Layer Management

- `GET /api/whiteboards/:id/layers` - Get whiteboard layer structure
- `POST /api/whiteboards/:id/layers` - Create new layer with properties

- `PUT /api/whiteboards/:id/layers/:layerId` - Update layer visibility or properties
- `DELETE /api/whiteboards/:id/layers/:layerId` - Delete layer and move objects
- `POST /api/whiteboards/:id/layers/reorder` - Reorder layers with z-index

Media & Assets

- `POST /api/whiteboards/:id/images` - Upload image to whiteboard
- `GET /api/whiteboards/:id/assets` - Get all media assets used
- `DELETE /api/assets/:assetId` - Remove unused asset from storage
- `POST /api/whiteboards/:id/export` - Export whiteboard as image or PDF
- `POST /api/whiteboards/:id/templates` - Save whiteboard as template

Sharing & Permissions

- `POST /api/whiteboards/:id/share` - Generate shareable link with permissions
- `GET /api/whiteboards/:id/collaborators` - Get whiteboard collaborators
- `PUT /api/whiteboards/:id/permissions` - Update user access permissions
- `DELETE /api/whiteboards/:id/collaborators/:userId` - Remove collaborator
- `POST /api/whiteboards/:id/invite` - Invite users via email

Version History

- `GET /api/whiteboards/:id/snapshots` - Get whiteboard version snapshots
- `POST /api/whiteboards/:id/snapshots` - Create manual snapshot
- `GET /api/whiteboards/:id/snapshots/:snapshotId` - Get specific snapshot
- `POST /api/whiteboards/:id/restore` - Restore whiteboard to snapshot
- `GET /api/whiteboards/:id/changes` - Get change history with authors

Templates & Frameworks

- `GET /api/templates` - Browse available whiteboard templates
- `POST /api/whiteboards/:id/apply-template` - Apply template to whiteboard
- `GET /api/frameworks` - Get drawing frameworks (wireframes, diagrams)
- `POST /api/whiteboards/:id/auto-layout` - Apply automatic layout algorithm
- `POST /api/templates` - Create template from existing whiteboard

Performance Optimizations

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Canvas Rendering Optimizations

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Dirty Rectangle Rendering:

```
DirtyRegion = {
  x: number,
  y: number,
  width: number,
  height: number,
  shapes: Set<Shape>
}
```

Optimization Strategies: - Track modified regions per frame - Only redraw affected canvas areas - Use multiple canvas layers for different update frequencies - Implement object culling for off-screen shapes

GPU Acceleration: - Utilize WebGL for complex operations - Implement shader-based effects - Use vertex buffers for path rendering - Leverage hardware-accelerated compositing

Memory Management

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Object Pooling Strategy:

```
ObjectPool = {
  points: Point[],
  paths: Path[],
  shapes: Shape[],
  operations: DrawOperation[]
}
```

Memory Optimization Techniques: - Reuse drawing operation objects - Implement lazy loading for large drawings - Compress historical data - Garbage collect unused resources

Network Optimization

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Data Compression: - Binary encoding for drawing operations - Delta compression for path updates - Geometric quantization for coordinates - Huffman coding for repetitive data

Bandwidth Management: - Adaptive quality based on network conditions - Progressive shape loading - Smart batching of operations - Connection multiplexing

Security Considerations

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Input Validation

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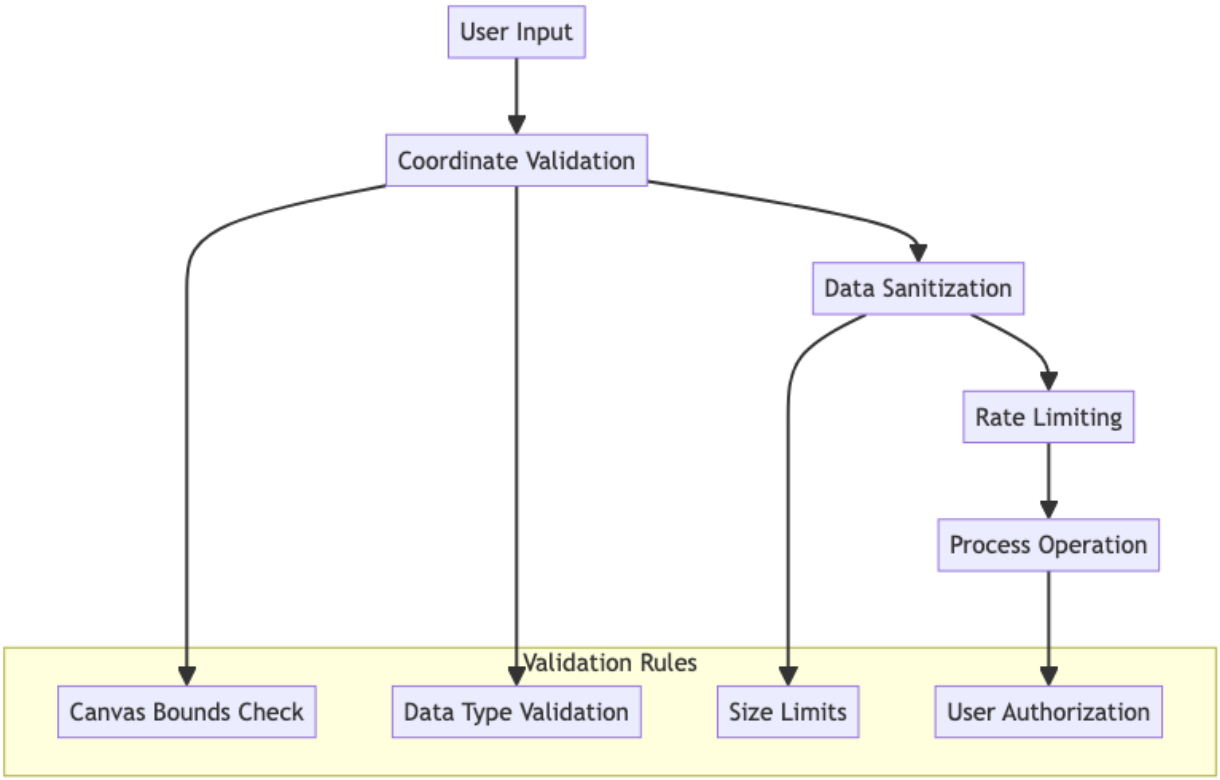

Content Security

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Drawing Content Filtering: - Image upload restrictions - Text content moderation - Shape complexity limits - File size constraints

Permission Model: - Room-based access control - Draw/view/admin permissions - Shape ownership tracking - Version control and rollback

Testing Strategy

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Unit Testing Focus Areas

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Core Algorithm Testing: - Operational transform correctness - Path simplification accuracy - Hit testing precision - Collision detection performance

Component Testing: - Tool behavior consistency - Canvas rendering output - Layer management operations - User interaction handling

Integration Testing

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Collaboration Testing: - Multi-user drawing scenarios - Conflict resolution accuracy - Real-time synchronization - Network failure recovery

Performance Testing: - Large drawing handling - High-frequency input processing - Memory usage patterns - Rendering frame rates

End-to-End Testing

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User Workflow Testing: - Complete drawing sessions - Cross-device compatibility - Touch and stylus input - Export functionality

Accessibility Implementation

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Keyboard Navigation

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Navigation Patterns: - Tab through tool panels - Arrow keys for shape manipulation - Keyboard shortcuts for common tools - Screen reader announcements

Alternative Input Methods: - Voice commands for drawing actions - Switch navigation support - High contrast mode - Magnification support

Screen Reader Support

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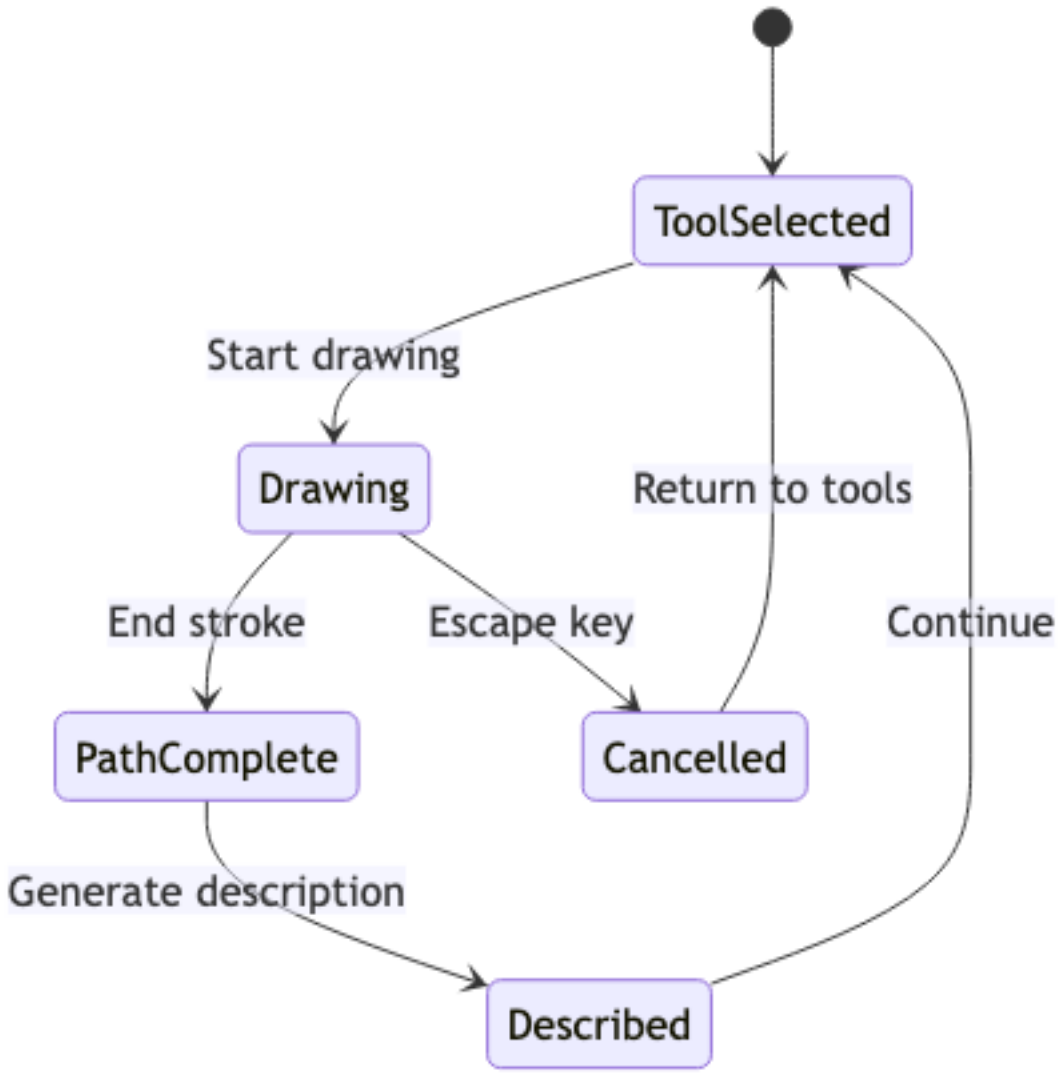

Accessibility Features: - Spatial audio feedback for drawing - Tactile feedback integration - Descriptive text for visual elements - Structured navigation landmarks

Trade-offs and Considerations

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Performance vs Quality

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- **Vector precision**: Higher precision vs memory usage
- **Real-time sync**: Immediate updates vs bandwidth consumption
- **Visual effects**: Rich rendering vs performance impact
- **History depth**: Undo capability vs storage requirements

Collaboration vs Consistency

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- **Immediate feedback**: Local updates vs global consistency
- **Conflict resolution**: Automatic merge vs user intervention
- **Presence updates**: Real-time awareness vs network overhead
- **Offline support**: Local editing vs synchronization complexity

Scalability Considerations

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- **Room size limits**: Concurrent users vs performance
- **Drawing complexity**: Shape count vs rendering speed
- **Storage optimization**: Version history vs cost
- **Network topology**: Peer-to-peer vs server-mediated

This collaborative whiteboard system provides a robust foundation for real-time drawing collaboration with advanced features like operational transforms, pressure-sensitive input, and multi-layer rendering while maintaining high performance and accessibility standards.