Conditional GANs
Outline

• Introduction
• Generation conditioned on class
  • Self-attention GAN
  • BigGAN
• Generation conditioned on image
  • Paired image-to-image translation: pix2pix
  • Unpaired image-to-image translation: CycleGAN
• Recent trends
Conditional generation

- Suppose we want to condition the generation of samples on discrete side information (label) $y$
  - How do we add $y$ to the basic GAN framework?
Conditional generation

• Suppose we want to condition the generation of samples on discrete side information (label) $y$
  • How do we add $y$ to the basic GAN framework?

\[
\begin{align*}
G & \quad y \quad G(z, y) \\
\quad z \quad & \quad D \\
D(G(z, y), y) & \quad y
\end{align*}
\]
Conditional generation

• Example: simple network for generating 28 x 28 MNIST digits

Conditional generation

- Example: simple network for generating 28 x 28 MNIST digits

Conditional generation

- Example: simple network for generating 28 x 28 MNIST digits

Conditional generation

- Another example: text-to-image synthesis

S. Reed, Z. Akata, X. Yan, L. Logeswaran, B. Schiele, H. Lee, Generative adversarial text to image synthesis, ICML 2016
Conditional generation

• Another example: text-to-image synthesis

Outline

• Introduction

• Generation conditioned on class
  • Self-attention GAN
  • BigGAN
Self-attention GAN

- Adaptive receptive fields to capture non-local structure

Self-attention GAN

• Adaptive receptive fields to capture non-local structure (based on Wang et al., 2018)
Self-attention GAN: Implementation details

- Hinge loss formulation:

\[ L_D = -E_{(x,y) \sim p_{data}} \left[ \min(0, D(x, y) - 1) \right] - E_{z \sim p_z, y \sim p_{data}} \left[ \min(0, -D(G(z, y), y) - 1) \right] \]

\[ L_G = -E_{z \sim p_z, y \sim p_{data}} D(G(z, y), y) \]
Self-attention GAN: Implementation details

- Hinge loss formulation
- Conditioning the discriminator: projection (Miyato & Koyama, 2018)
- Conditioning the generator: conditional batch norm
Self-attention GAN: Implementation details

- Hinge loss formulation
- Conditioning the discriminator: *projection* (Miyato & Koyama, 2018)
- Conditioning the generator: *conditional batch norm*
- *Spectral normalization* for generator and discriminator (Miyato et al., 2018) – divide weight matrices by largest singular value (estimated)
- Different learning rates for generator and discriminator (TTUR – Heusel et al., 2017)
Self-attention GAN: Results

- 128 x 128 ImageNet

goldfish

indigo bunting

redshank

Saint Bernard
Self-attention GAN: Results

- Attention map visualization
BigGAN

- Scale up SA-GAN to generate ImageNet images up to 512 x 512 resolution

A. Brock, J. Donahue, K. Simonyan, Large scale GAN training for high fidelity natural image synthesis, ICLR 2019
BigGAN: Implementation details

- 8x larger batch size, 50% more channels (2x more parameters) than baseline SA-GAN
- Hierarchical latent space: feed (transformations of) $z$ vector into multiple layers of the generator
BigGAN: Implementation details

- 8x larger batch size, 50% more channels (2x more parameters) than baseline SA-GAN
- Hierarchical latent space: feed (transformations of) \( z \) vector into multiple layers of the generator
- Truncation trick: at test time, resample the values of the \( z \) vector with magnitude above a chosen threshold
- Trade off diversity for image quality

“The effects of increasing truncation. From left to right, the threshold is set to 2, 1, 0.5, 0.04.”
BigGAN: Implementation details

- 8x larger batch size, 50% more channels (2x more parameters) than baseline SA-GAN
- Hierarchical latent space: feed (transformations of) $z$ vector into multiple layers of the generator
- Truncation trick: at test time, resample the values of the $z$ vector with magnitude above a chosen threshold
- Lots of other tricks (initialization, training, etc.)
- Training observed to be unstable, but good results are achieved “just before collapse”
- Evidence that discriminator memorizes the training data, but the generator doesn’t
BigGAN: Implementation details

https://xkcd.com/1838/
BigGAN: Results

- Samples at 256 x 256 resolution:
BigGAN: Results

• Samples at 512 x 512 resolution:
BigGAN: Results

- Interpolation between $c, z$ pairs:
BigGAN: Results

- Interpolation between $c$ with $z$ held constant:
BigGAN: Results

- Difficult classes:
Announcements and reminders

• Assignment 3 deadline extended until the end of tomorrow, November 4

• Assignment 4 is out, due November 20 (right before Thanksgiving break)
  • Two parts – one on GANs, one on RNNs
  • Get started on the GAN part now!

• Project progress reports due Monday, November 16
  • Target length ~3 pages
Conditional GANs: Outline

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  - BigGAN
- Generation conditioned on image
  - Paired image-to-image translation: pix2pix
  - Unpaired image-to-image translation: CycleGAN
Image-to-image translation

Image-to-image translation

- Produce modified image $y$ conditioned on input image $x$ (note change of notation)
  - Generator receives $x$ as input
  - Discriminator receives an $x, y$ pair and has to decide whether it is real or fake
Image-to-image translation

- Generator architecture: U-Net

- Note: no $z$ used as input, transformation is basically deterministic
Image-to-image translation

- Generator architecture: U-Net

Encode: convolution → BatchNorm → ReLU
Decode: transposed convolution → BatchNorm → ReLU
Image-to-image translation

- Generator architecture: U-Net

Effect of adding skip connections to the generator
Image-to-image translation

- Generator loss: GAN loss plus L1 reconstruction penalty

\[ G^* = \arg \min_G \max_D \mathcal{L}_{GAN}(G, D) + \lambda \sum_i \|y_i - G(x_i)\|_1 \]

Generated output $G(x_i)$ should be close to ground truth target $y_i$
Image-to-image translation

• Generator loss: GAN loss plus L1 reconstruction penalty

\[
G^* = \arg \min_G \max_D \mathcal{L}_{GAN}(G, D) + \lambda \sum_i \| y_i - G(x_i) \|_1
\]
Image-to-image translation

• Discriminator: PatchGAN
  
• Given input image $x$ and second image $y$, decide whether $y$ is a ground truth target or produced by the generator
Image-to-image translation

- **Discriminator: PatchGAN**
  - Given input image \( x \) and second image \( y \), decide whether \( y \) is a ground truth target or produced by the generator
  - Output is a 30 x 30 map where each value (0 to 1) represents the quality of the corresponding section of the output image, these values are averaged to obtain final discriminator loss
  - Fully convolutional network, effective patch size can be increased by increasing the depth

Figure source
Image-to-image translation

- **Discriminator:** PatchGAN
  - Given input image \( x \) and second image \( y \), decide whether \( y \) is a ground truth target or produced by the generator.
  - Output is a 30 x 30 map where each value (0 to 1) represents the quality of the corresponding section of the output image; these values are averaged to obtain the final discriminator loss.
  - Fully convolutional network, effective patch size can be increased by increasing the depth.

Effect of discriminator patch size on generator output
Image-to-image translation: Results

- Translating between maps and aerial photos
Image-to-image translation: Results

- Translating between maps and aerial photos
- Human study:

<table>
<thead>
<tr>
<th>Loss</th>
<th>Photo → Map % Turkers labeled real</th>
<th>Map → Photo % Turkers labeled real</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>2.8% ± 1.0%</td>
<td>0.8% ± 0.3%</td>
</tr>
<tr>
<td>L1+cGAN</td>
<td>6.1% ± 1.3%</td>
<td>18.9% ± 2.5%</td>
</tr>
</tbody>
</table>
Image-to-image translation: Results

- Semantic labels to scenes
Image-to-image translation: Results

- Semantic labels to scenes
- Evaluation: FCN score
  - The higher the quality of the output, the better the FCN should do at recovering the original semantic labels

<table>
<thead>
<tr>
<th>Loss</th>
<th>Per-pixel acc.</th>
<th>Per-class acc.</th>
<th>Class IOU</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.42</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>GAN</td>
<td>0.22</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>cGAN</td>
<td>0.57</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>L1+GAN</td>
<td>0.64</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>L1+cGAN</td>
<td><strong>0.66</strong></td>
<td><strong>0.23</strong></td>
<td><strong>0.17</strong></td>
</tr>
<tr>
<td>Ground truth</td>
<td>0.80</td>
<td>0.26</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Image-to-image translation: Results

- Scenes to semantic labels

<table>
<thead>
<tr>
<th>Input</th>
<th>Ground truth</th>
<th>L1</th>
<th>cGAN</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Input Image" /></td>
<td><img src="image2.png" alt="Ground Truth" /></td>
<td><img src="image3.png" alt="L1 Result" /></td>
<td><img src="image4.png" alt="cGAN Result" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="Input Image" /></td>
<td><img src="image6.png" alt="Ground Truth" /></td>
<td><img src="image7.png" alt="L1 Result" /></td>
<td><img src="image8.png" alt="cGAN Result" /></td>
</tr>
<tr>
<td><img src="image9.png" alt="Input Image" /></td>
<td><img src="image10.png" alt="Ground Truth" /></td>
<td><img src="image11.png" alt="L1 Result" /></td>
<td><img src="image12.png" alt="cGAN Result" /></td>
</tr>
<tr>
<td><img src="image13.png" alt="Input Image" /></td>
<td><img src="image14.png" alt="Ground Truth" /></td>
<td><img src="image15.png" alt="L1 Result" /></td>
<td><img src="image16.png" alt="cGAN Result" /></td>
</tr>
</tbody>
</table>
Image-to-image translation: Results

- Scenes to semantic labels
- Accuracy is worse than that of regular FCNs or generator with L1 loss

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<th>Loss</th>
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<th>Class IOU</th>
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</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.86</td>
<td>0.42</td>
<td>0.35</td>
</tr>
<tr>
<td>cGAN</td>
<td>0.74</td>
<td>0.28</td>
<td>0.22</td>
</tr>
<tr>
<td>L1+cGAN</td>
<td>0.83</td>
<td>0.36</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Image-to-image translation: Results

- Semantic labels to facades
Image-to-image translation: Results

- Day to night
Image-to-image translation: Results

• Edges to photos
Image-to-image translation: Results

- pix2pix demo
Image-to-image translation: Limitations

- Visual quality could be improved
- Requires $x, y$ pairs for training
- Does not model conditional distribution $P(y|x)$, returns a single mode instead
Unpaired image-to-image translation

- Given two unordered image collections $X$ and $Y$, learn to “translate” an image from one into the other and vice versa.

Unpaired image-to-image translation

- Given two unordered image collections $X$ and $Y$, learn to “translate” an image from one into the other and vice versa.

CycleGAN

- Given: domains $X$ and $Y$
- Train two generators $F$ and $G$ and two discriminators $D_X$ and $D_Y$
  - $G$ translates from $X$ to $Y$, $F$ translates from $Y$ to $X$
  - $D_X$ recognizes images from $X$, $D_Y$ from $Y$
  - Cycle consistency: we want $F(G(x)) \approx x$ and $G(F(y)) \approx y$
CycleGAN: Architecture

- Generators (based on Johnson et al., 2016):

- Discriminators: PatchGAN on 70 x 70 patches
CycleGAN: Loss

- Requirements:
  - $G$ translates from $X$ to $Y$, $F$ translates from $Y$ to $X$
  - $D_X$ recognizes images from $X$, $D_Y$ from $Y$
  - We want $F(G(x)) \approx x$ and $G(F(y)) \approx y$

- CycleGAN discriminator loss: LSGAN

\[
\mathcal{L}_{GAN}(D_Y) = \mathbb{E}_{y \sim p_{data}(y)}[(D_Y(y) - 1)^2] + \mathbb{E}_{x \sim p_{data}(x)}[D_Y(G(x))^2]
\]
\[
\mathcal{L}_{GAN}(D_X) = \mathbb{E}_{x \sim p_{data}(x)}[(D_X(x) - 1)^2] + \mathbb{E}_{y \sim p_{data}(y)}[D_X(F(y))^2]
\]

- CycleGAN generator loss:

\[
\mathcal{L}_{cyc}(G, F) = \mathbb{E}_{x \sim p_{data}(x)}[D_Y(G(x) - 1)^2] + \mathbb{E}_{y \sim p_{data}(y)}[D_X(F(y) - 1)^2]
\]
\[
+ \mathbb{E}_{x \sim p_{data}(x)}[\|F(G(x)) - x\|_1] + \mathbb{E}_{y \sim p_{data}(y)}[\|G(F(y)) - y\|_1]
\]
CycleGAN

- Illustration of cycle consistency:
CycleGAN: Results

- Translation between maps and aerial photos
CycleGAN: Results

- Other pix2pix tasks
CycleGAN: Results

- Scene to labels and labels to scene
  - Worse performance than pix2pix due to lack of paired training data

<table>
<thead>
<tr>
<th>Method</th>
<th>Per-pixel acc.</th>
<th>Per-class acc.</th>
<th>Class IOU</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoGAN [32]</td>
<td>0.40</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>BiGAN/ALI [9, 7]</td>
<td>0.19</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>SimGAN [46]</td>
<td>0.20</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>Feature loss + GAN</td>
<td>0.06</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>CycleGAN (ours)</td>
<td><strong>0.52</strong></td>
<td><strong>0.17</strong></td>
<td><strong>0.11</strong></td>
</tr>
<tr>
<td>pix2pix [22]</td>
<td>0.71</td>
<td>0.25</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 2: FCN-scores for different methods, evaluated on Cityscapes labels→photo.

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<tr>
<td>CoGAN [32]</td>
<td>0.45</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>BiGAN/ALI [9, 7]</td>
<td>0.41</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>SimGAN [46]</td>
<td>0.47</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>Feature loss + GAN</td>
<td>0.50</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>CycleGAN (ours)</td>
<td><strong>0.58</strong></td>
<td><strong>0.22</strong></td>
<td><strong>0.16</strong></td>
</tr>
<tr>
<td>pix2pix [22]</td>
<td>0.85</td>
<td>0.40</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table 3: Classification performance of photo→labels for different methods on cityscapes.
CycleGAN: Results

- Tasks for which paired data is unavailable
CycleGAN: Results

- Style transfer
CycleGAN: Failure cases
CycleGAN: Failure cases

Input

Output

horse → zebra
CycleGAN: Limitations

- Cannot handle shape changes (e.g., dog to cat)
- Can get confused on images outside of the training domains (e.g., horse with rider)
- Cannot close the gap with paired translation methods
- Does not account for the fact that one transformation direction may be more challenging than the other
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• Some recent highlights
Multimodal image-to-image translation

High-resolution, high-quality pix2pix

T.-C. Wang et al., High-Resolution Image Synthesis and Semantic Manipulation with Conditional GANs, CVPR 2018
High-resolution, high-quality pix2pix

- Two-scale generator architecture (up to 2048 x 1024 resolution)

First train *global generator* network (G1) on lower-res images

Then append higher-res *enhancer network* (G2) blocks and train G1 and G2 jointly

T.-C. Wang et al., *High-Resolution Image Synthesis and Semantic Manipulation with Conditional GANs*, CVPR 2018
High-resolution, high-quality pix2pix

- Two-scale generator architecture (up to 2048 x 1024 resolution)
- Three-scale discriminator architecture (full res, 2x and 4x downsampled)
- Incorporate feature matching loss into discriminator
Human generation conditioned on pose

Figure 3: (Top) **Training**: Our model uses a pose detector $P$ to create pose stick figures from video frames of the target subject. We learn the mapping $G$ alongside an adversarial discriminator $D$ which attempts to distinguish between the “real” correspondences $(x_t, x_{t+1}), (y_t, y_{t+1})$ and the “fake” sequence $(x_t, x_{t+1}), (G(x_t), G(x_{t+1}))$. (Bottom) **Transfer**: We use a pose detector $P$ to obtain pose joints for the source person that are transformed by our normalization process $Norm$ into joints for the target person for which pose stick figures are created. Then we apply the trained mapping $G$.

Human generation conditioned on pose

https://carolineec.github.io/everybody_dance_now/

DeepFakes (coming up at the end of the course…)