Probability Divergences and Generative Models

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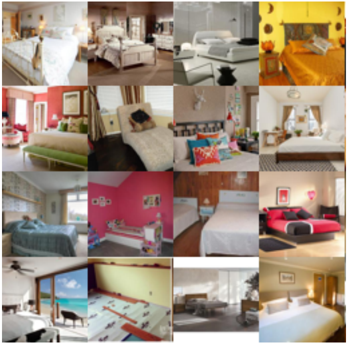
Training generative models

- Have: One collection of samples X from unknown distribution P.
- Goal: generate samples Q that look like P

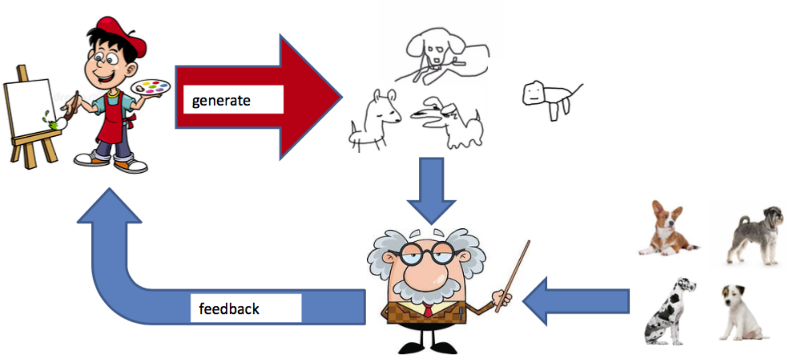


LSUN bedroom samples P

Generated Q, MMD GAN

Role of divergence $D(P, Q)$?

Reminder: generative adversarial network



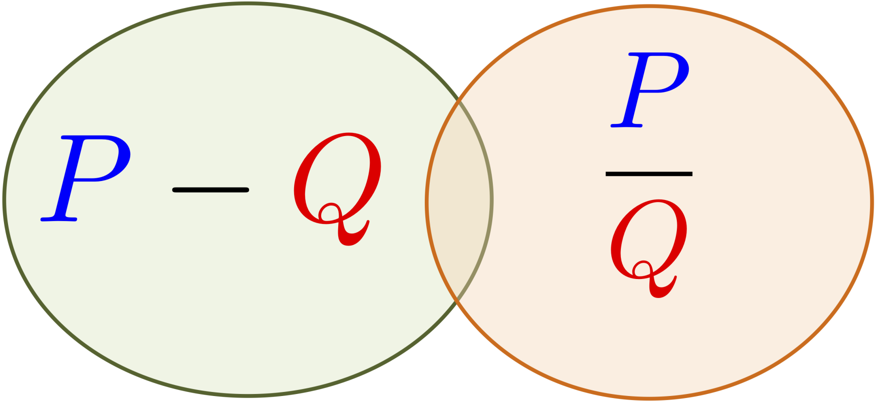
Outline

- Integral probability metrics (MMD, Wasserstein)
- ϕ-divergences (f-divergences) and a variational lower bound (KL)
- Generalized energy-based models
  - "Like a GAN" but incorporating critic into sample generation
  - Performs better than using generator alone

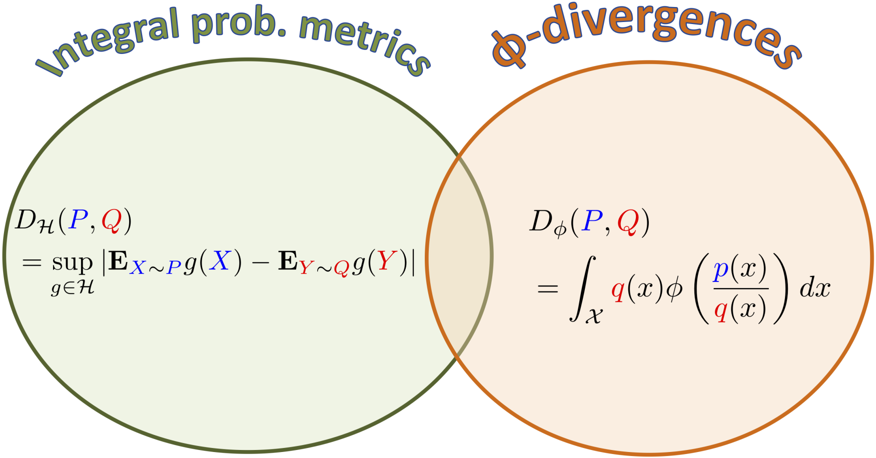
Arbel, Zhou, G., Generalized Energy Based Models (ICLR 2021)

Divergence measures (critics)

Divergences



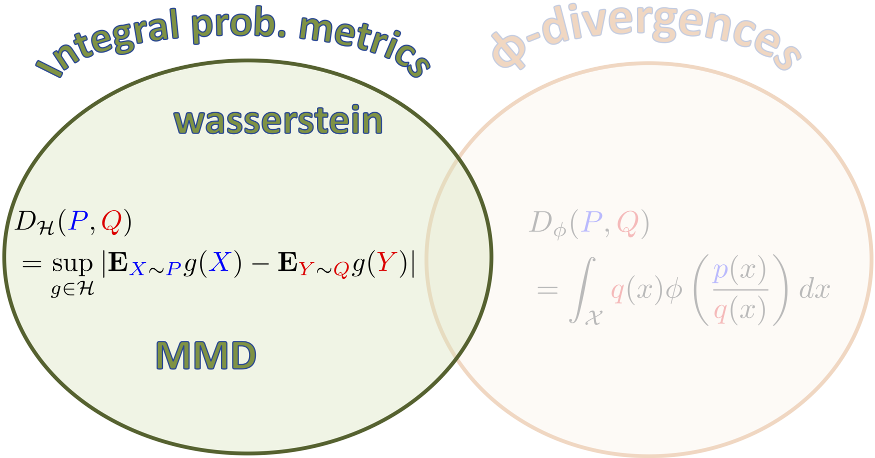
Divergences



$$D_{\mathcal{H}}(P, Q) = \sup_{g \in \mathcal{H}} \left| \mathbf{E}_{X \sim P}\, g(X) - \mathbf{E}_{Y \sim Q}\, g(Y) \right|$$

$$D_{\phi}(P, Q) = \int_{\mathcal{X}} q(x) \phi\left(\frac{p(x)}{q(x)} \right) dx$$

The Integral Probability Metrics



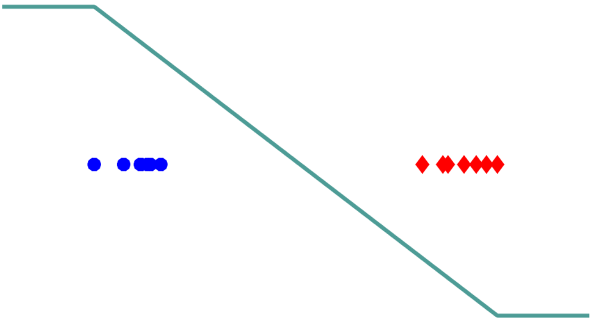
Wasserstein distance

A helpful critic:

$$W_1(P, Q) = \sup_{\|f\|_L \leq 1} E_P f(X) - E_Q f(Y).$$

$$\|f\|_L := \sup_{x \neq y} |f(x) - f(y)| / \|x - y\|$$

$$W_1 = 0.88$$



Santambrogio, Optimal Transport for Applied Mathematicians (2015, Section 5.4)
G Peyré, M Cuturi, Computational Optimal Transport (2019)
M. Cuturi, J. Solomon, NeurIPS tutorial (2017)

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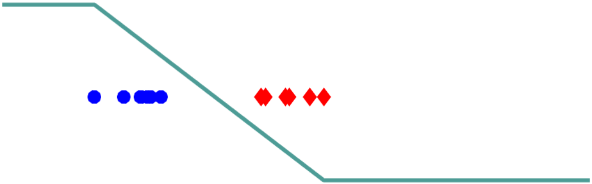
$$W_1 = 0.65$$



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The Maximum Mean Discrepancy

Maximum mean discrepancy: smooth function for P vs Q

$$MMD(P, Q; F) := \sup_{\|f\| \leq 1} \left[\mathrm{E}_P f(X) - \mathrm{E}_Q f(Y) \right]$$

$$(F = \text{unit ball in RKHS } \mathcal{F})$$

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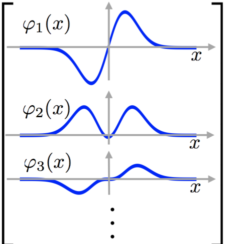
Functions are linear combinations of features:

$$f(x) = \langle f, \varphi(x) \rangle_{\mathcal{F}} = \sum_{\ell=1}^{\infty} f_\ell \varphi_\ell(x) = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \end{bmatrix}^\top$$



$$\|f\|_{\mathcal{F}}^2 := \sum_{i=1}^{\infty} f_i^2 \leq 1$$

Infinitely many features using kernels

Kernels: dot products of features

Feature map $\varphi(x) \in \mathcal{F}$,

$$\varphi(x) = [\dots \varphi_i(x) \dots] \in \ell_2$$

For positive definite k,

$$k(x, x') = \langle \varphi(x), \varphi(x') \rangle_{\mathcal{F}}$$

Infinitely many features $\varphi(x)$, dot product in closed form!

Infinitely many features using kernels

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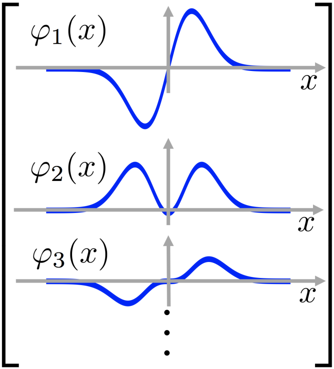
Infinitely many features $\varphi(x)$, dot product in closed form!

Exponentiated quadratic kernel

$$k(x, x') = \exp\left(-\gamma \left\| x - x' \right\|^2\right)$$

$$\varphi(x) =$$



Features: Gaussian Processes for Machine learning, Rasmussen and Williams, Ch. 4.

The MMD: an integral probability metric

Maximum mean discrepancy: smooth function for P vs Q

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$$(F = \text{unit ball in RKHS } \mathcal{F})$$

For characteristic RKHS $\mathcal{F}$, $MMD(P, Q; F) = 0$ iff $P = Q$

- Energy distance is a special case [Sejdinovic, Sriperumbudur, G. Fukumizu, 2013]

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Expectations of functions are linear combinations of expected features

$$\mathrm{E}_P(f(X)) = \langle f, \mathrm{E}_P \varphi(X) \rangle_{\mathcal{F}} = \langle f, \mu_P \rangle_{\mathcal{F}}$$

(always true if kernel is bounded)

Integral prob. metric vs feature mean difference

The MMD:

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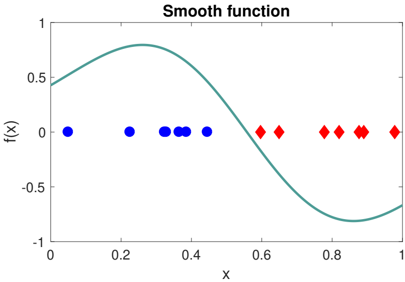

Integral prob. metric vs feature mean difference

The MMD:

use

$$
\begin{aligned}
&MMD(P, Q; F) \\
&= \sup_{\|f\|\leq 1} \left[\mathrm{E}_P f(X) - \mathrm{E}_Q f(Y) \right] \\
&= \sup_{\|f\|\leq 1} \langle f, \mu_P - \mu_Q \rangle_{\mathcal{F}}
\end{aligned}
$$

$$\mathrm{E}_P f(X) = \langle \mu_P, f \rangle_{\mathcal{F}}$$

Integral prob. metric vs feature mean difference

The MMD:

$$MMD(P, Q; F)$$
$$= \sup_{\|f\| \leq 1} \left[\mathrm{E}_P f(X) - \mathrm{E}_Q f(Y) \right]$$
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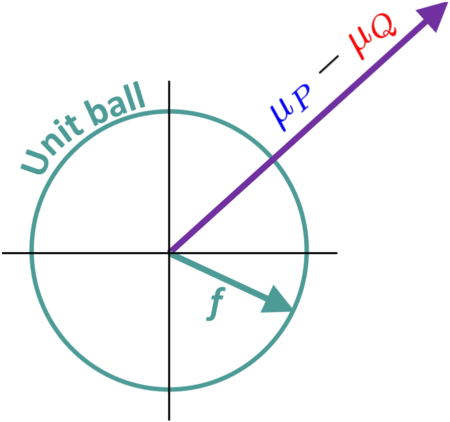

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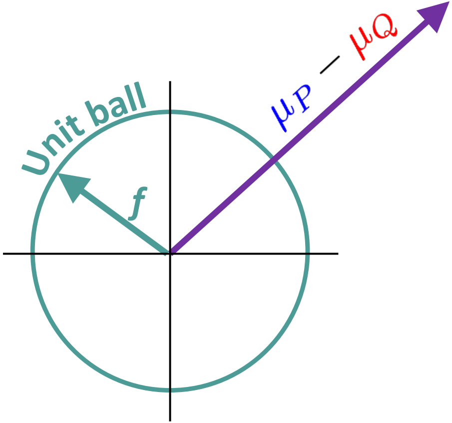

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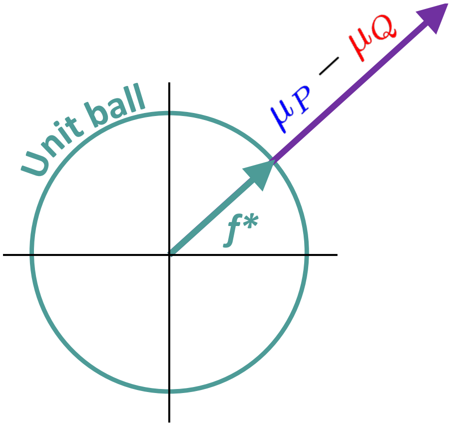


$$f^* = \frac{\mu_P - \mu_Q}{\|\mu_P - \mu_Q\|}$$

Integral prob. metric vs feature mean difference

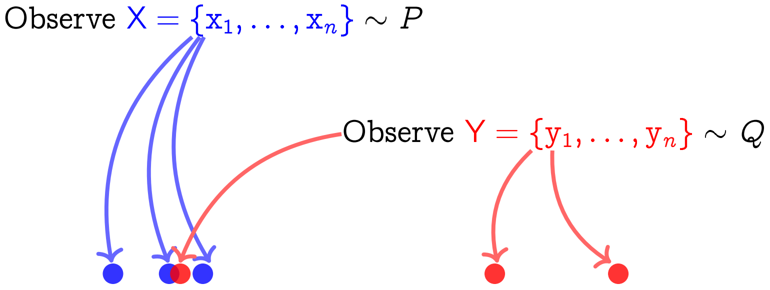
The MMD:

$$
\begin{aligned}
&MMD(P, Q; F) \\
&= \sup_{\|f\| \leq 1} \left[\mathrm{E}_P f(X) - \mathrm{E}_Q f(Y) \right] \\
&= \sup_{\|f\| \leq 1} \langle f, \mu_P - \mu_Q \rangle_{\mathcal{F}} \\
&= \|\mu_P - \mu_Q\|
\end{aligned}
$$

IPM view equivalent to feature mean difference (kernel case only)

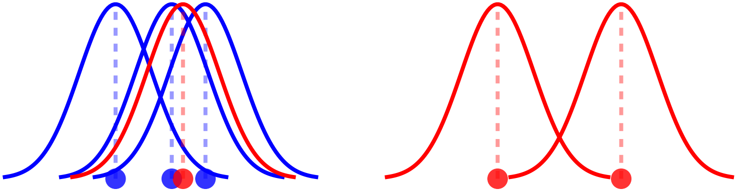
Construction of MMD witness

Construction of empirical witness function (proof: next slide!)



Construction of MMD witness

Construction of empirical witness function (proof: next slide!)



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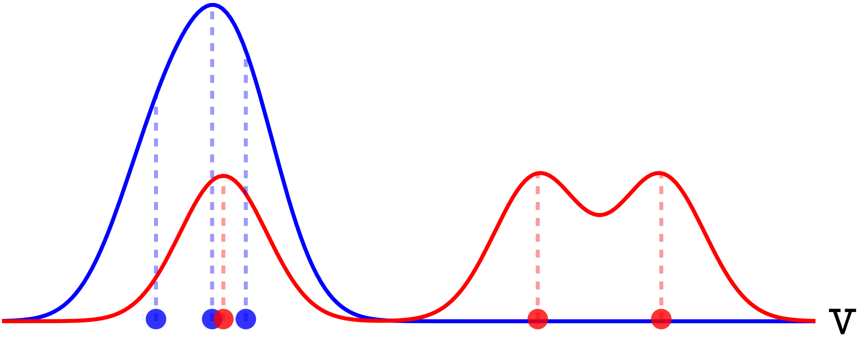

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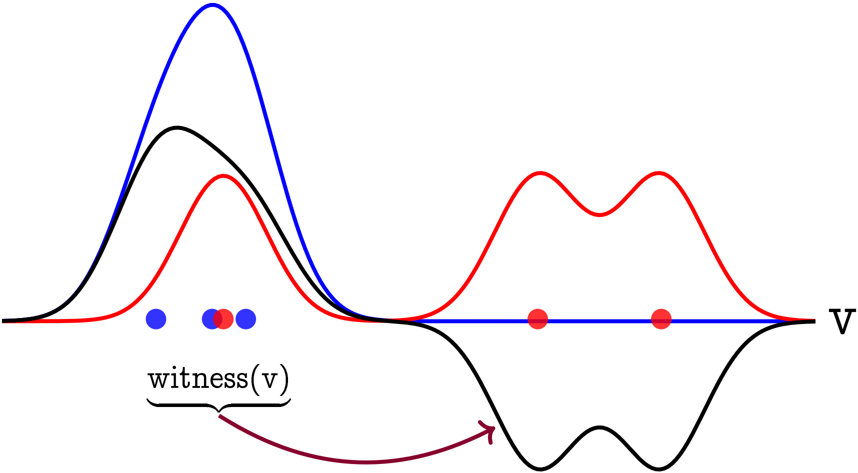

Derivation of empirical witness function

Recall the witness function expression

$$f^* \propto \mu_P - \mu_Q$$

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The empirical feature mean for P

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Recall the witness function expression

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The empirical witness function at v

$$\begin{aligned} f^*(v) &= \langle f^*, \varphi(v)\rangle_{\mathcal{F}} \\ &\propto \langle \widehat{\mu}_P - \widehat{\mu}_Q, \varphi(v)\rangle_{\mathcal{F}} \\ &= \frac{1}{n}\sum_{i=1}^{n} k(x_i, v) - \frac{1}{n}\sum_{i=1}^{n} k(\mathrm{y}_i, v) \end{aligned}$$

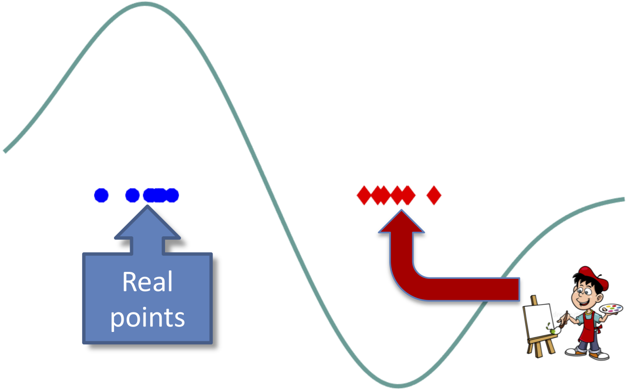
Don't need explicit feature coefficients $f^* := \left[\begin{array}{ccc} f_1^* & f_2^* & \dots \end{array}\right]$

Maximum mean discrepancy

A helpful critic:

$MMD(P, Q) = \sup_{\|f\|_{\mathcal{F}} \leq 1} E_P f(X) - E_Q f(Y).$

MMD=1.8



Maximum mean discrepancy

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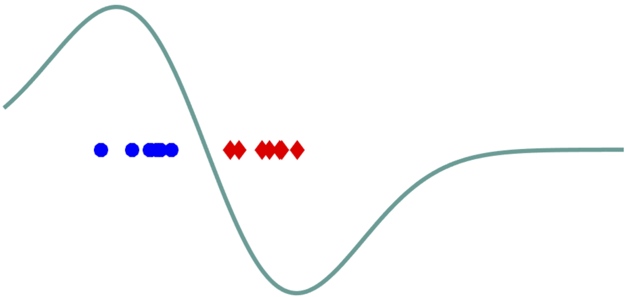
$$MMD(P, Q) = \sup_{\|f\|_{\mathcal{F}} \leq 1} E_P f(X) - E_Q f(Y)$$

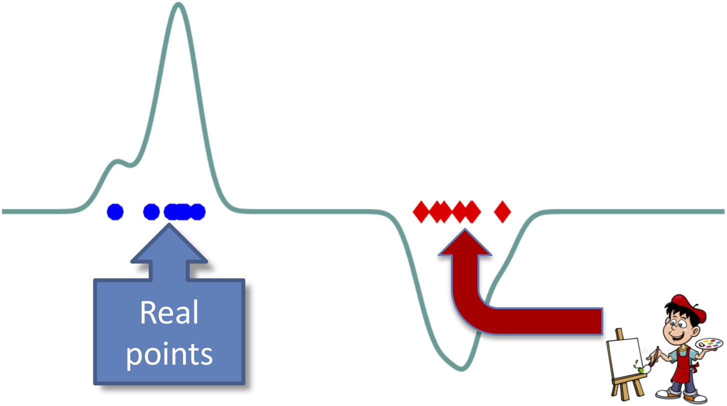
MMD=1.1



Maximum mean discrepancy

An unhelpful critic:
$MMD(P, Q)$ with a narrow kernel.

MMD=0.64



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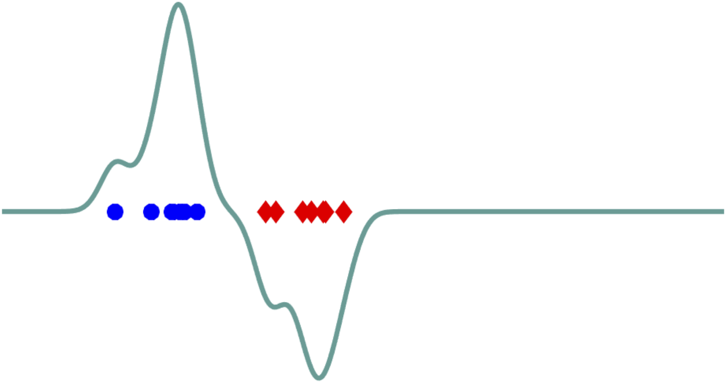
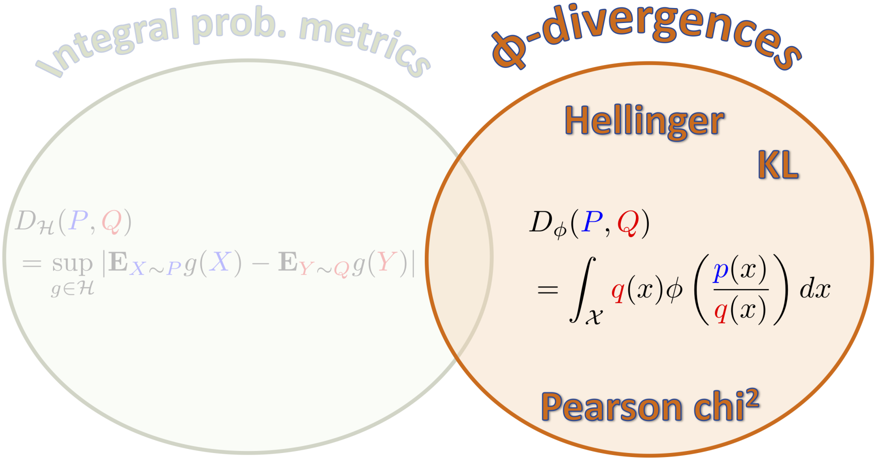


The ϕ-divergences



The ϕ-divergences

Define the ϕ-divergence(f-divergence):

$$D_\phi(P, Q) = \int \phi\left(\frac{p(z)}{q(z)}\right) q(z)dz$$

where ϕ is convex, lower-semicontinuous, $\phi(1) = 0$.

- Example: $\phi(u) = u\log(u)$ gives KL divergence,

$$\begin{aligned} D_{KL}(P, Q) &= \int \log\left(\frac{p(z)}{q(z)}\right) p(z)dz \\ &= \int \left(\frac{p(z)}{q(z)}\right) \log\left(\frac{p(z)}{q(z)}\right) q(z)dz \end{aligned}$$

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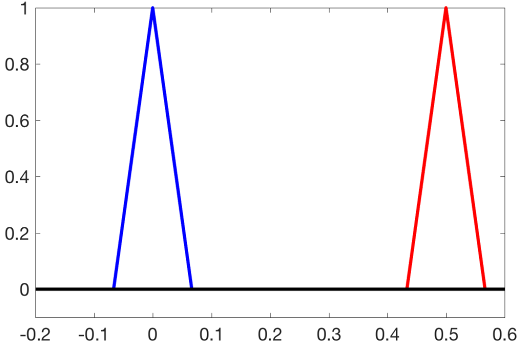
Are ϕ-divergences good critics?

Simple example: disjoint support.

Goodfellow et al. (NeurIPS 2014), Arjovsky and Bottou [ICLR 2017]

$$D_{KL}(P, Q) = \infty \qquad D_{JS}(P, Q) = \log 2$$



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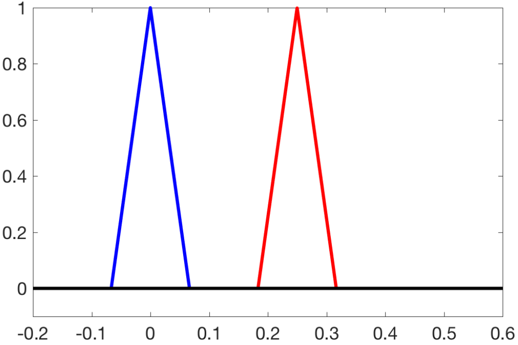
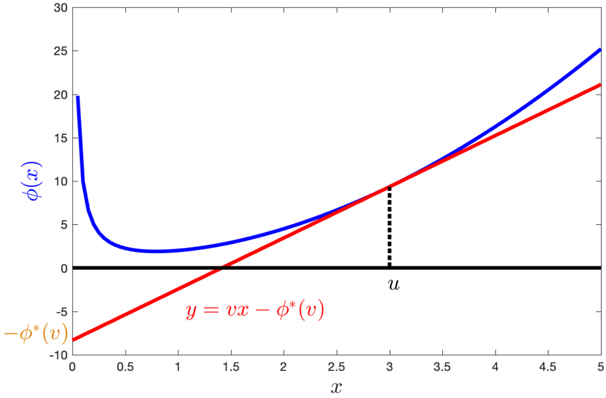


ϕ-divergences in practice

Background: the conjugate (Fenchel) dual

$$\phi^*(v) = \sup_{u \in \mathbb{R}} \{uv - \phi(u)\}.$$



- $\phi^*(v)$ is negative intercept of tangent to ϕ with slope v

ϕ-divergences in practice

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- For a convex l.s.c. ϕ we have

$$\phi^{**}(x) = \phi(x) = \sup_{v \in \mathbb{R}} \{xv - \phi^*(v)\}$$

ϕ-divergences in practice

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- KL divergence:

$$\phi(x) = x \log(x) \qquad \phi^*(v) = \exp(v - 1)$$

A variational lower bound

A lower-bound ϕ-divergence approximation:

$$D_\phi(P, Q) = \int q(z)\phi\left(\frac{p(z)}{q(z)}\right) dz$$

Nguyen, Wainwright, Jordan, IEEE Transactions on Information Theory (2010);
Nowozin, Cseke, Tomioka, NeurIPS (2016)

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$\phi^*(v)$ is dual of $\phi(v)$.

A variational lower bound

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$$D_\phi(P, Q) = \int q(z)\phi\left(\frac{p(z)}{q(z)}\right) dz$$
$$= \int q(z) \sup_{f_z} \left(\frac{p(z)}{q(z)} f_z - \phi^*(f_z)\right)$$
$$\geq \sup_{f \in \mathcal{H}} \mathrm{E}_P f(X) - \mathrm{E}_Q \phi^*(f(Y))$$

(restrict the function class)

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$$\geq \sup_{f \in \mathcal{H}} \mathrm{E}_P f(X) - \mathrm{E}_Q \phi^*\left(f(Y)\right)$$

(restrict the function class)

Bound tight when:

$$f^\diamond(z) = \partial\phi\left(\frac{p(z)}{q(z)}\right)$$

if ratio defined.

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Case of the KL

$$D_{KL}(P, Q) = \int \log\left(\frac{p(z)}{q(z)}\right) p(z)\, dz$$

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Case of the KL

$$D_{KL}(P, Q) = \int \log\left(\frac{p(z)}{q(z)}\right) p(z)\,dz$$

$$\geq \sup_{f\in\mathcal{H}} -\mathrm{E}_P f(X) + 1 - \mathrm{E}_Q \underbrace{\exp\left(-f(Y)\right)}_{\phi^*(-f(Y)+1)}$$

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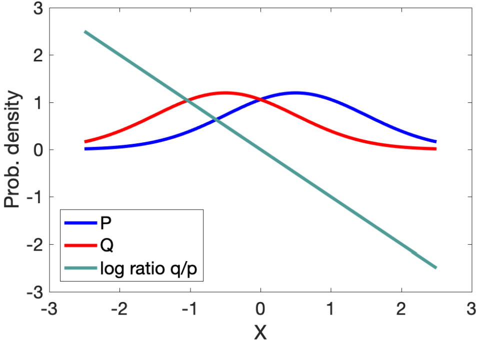

Bound tight when:

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Case of the KL

$$D_{KL}(P, Q) = \int \log\left(\frac{p(z)}{q(z)}\right) p(z)\,dz$$

$$\geq \sup_{f\in\mathcal{H}} -\mathrm{E}_P f(X) + 1 - \mathrm{E}_Q \exp\left(-f(Y)\right)$$

$$\approx \sup_{f\in\mathcal{H}} \left[-\frac{1}{n}\sum_{j=1}^{n} f(x_i) - \frac{1}{n}\sum_{i=1}^{n} \exp(-f(y_i))\right] + 1$$

$$x_i \overset{\text{i.i.d.}}{\sim} P$$

$$y_i \overset{\text{i.i.d.}}{\sim} Q$$

Nguyen, Wainwright, Jordan, IEEE Transactions on Information Theory (2010); Nowozin, Cseke, Tomioka, NeurIPS (2016)

Case of the KL

$$D_{KL}(P, Q) = \int \log\left(\frac{p(z)}{q(z)}\right) p(z)\,dz$$

$$\geq \sup_{f \in \mathcal{H}} -\mathrm{E}_P f(X) + 1 - \mathrm{E}_Q \exp(-f(Y))$$

$$\approx \sup_{f \in \mathcal{H}} \left[-\frac{1}{n}\sum_{j=1}^{n} f(x_i) - \frac{1}{n}\sum_{i=1}^{n} \exp(-f(y_i)) \right] + 1$$

This is a

KL

Approximate

Lower-bound

Estimator.

Nguyen, Wainwright, Jordan, IEEE Transactions on Information Theory (2010); Nowozin, Cseke, Tomioka, NeurIPS (2016)

Case of the KL

$$D_{KL}(P, Q) = \int \log\left(\frac{p(z)}{q(z)}\right) p(z)\, dz$$

$$\geq \sup_{f \in \mathcal{H}} -\mathrm{E}_P f(X) + 1 - \mathrm{E}_Q \exp(-f(Y))$$

$$\approx \sup_{f \in \mathcal{H}} \left[-\frac{1}{n} \sum_{j=1}^{n} f(x_i) - \frac{1}{n} \sum_{i=1}^{n} \exp(-f(y_i)) \right] + 1$$

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The KALE divergence

Nguyen, Wainwright, Jordan, IEEE Transactions on Information Theory (2010); Nowozin, Cseke, Tomioka, NeurIPS (2016)

Topological properties of KALE (1)

Key requirements on $\mathcal{H}$ and $\mathcal{X}$:

- Compact domain $\mathcal{X}$,
- $\mathcal{H}$ dense in the space $C(\mathcal{X})$ of continuous functions on $\mathcal{X}$ wrt $\|\cdot\|_\infty$.
- If $f \in \mathcal{H}$ then $-f \in \mathcal{H}$ and $cf \in \mathcal{H}$ for $0 \leq c \leq C_{\max}$.

Theorem: $KALE(P, Q; \mathcal{H}) \geq 0$ and $KALE(P, Q; \mathcal{H}) = 0$ iff $P = Q$.

Zhang, Liu, Zhou, Xu, and He. "On the Discrimination-Generalization Tradeoff in GANs"

(ICLR 2018, Corollary 2.4; Theorem B.1)
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$\mathcal{H}$ dense in $C(\mathcal{X})$ for $\mathcal{X} \subset \mathbb{R}^d$ when:

$$\mathcal{H} = \text{span}\{\sigma(w \top x + b) : [w, b] \in \Theta\}$$

$\sigma(u) = \max\{u, 0\}^\alpha$, $\alpha \in \mathbb{N}$, and $\{\lambda\theta : \lambda \geq 0, \theta \in \Theta\} = \mathbb{R}^{d+1}$.

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Additional requirement: all functions in $\mathcal{H}$ Lipschitz in their inputs with constant L

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Partial proof idea:

$$\begin{aligned} KALE(P, Q; \mathcal{H}) &= -\int f \, dP - \int \exp(-f) \, dQ + 1 \\ &= \int f(x) \, dQ(x) - f(x') \, dP(x') \\ &\quad - \int \underbrace{(\exp(-f) + f - 1)}_{\geq 0} \, dQ \\ &\leq \int f(x) \, dQ(x) - f(x') \, dP(x') \leq L W_1(P, Q) \end{aligned}$$

Liu, Bousquet, Chaudhuri. "Approximation and Convergence Properties of Generative Adversarial Learning" (NeurIPS 2017); Arbel, Liang, G. (ICLR 2021, Proposition 1)

Empirical properties of KALE

$$KALE(P, Q; \mathcal{H}) = \sup_{f \in \mathcal{H}} -E_P f(X) - E_Q \exp(-f(Y)) + 1$$

$$f = \langle w, \phi(x) \rangle_{\mathcal{H}} \qquad \mathcal{H} \text{ an RKHS}$$

$$\|w\|^2_{\mathcal{H}} \quad \text{penalized :}$$

Glaser, Arbel, G. "KALE Flow: A Relaxed KL Gradient Flow for Probabilities with Disjoint Support," (arXiv, 2021, Section 2)

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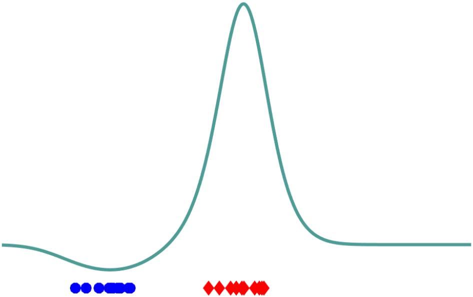
$\|w\|^2_{\mathcal{H}}$ penalized : KALE smoothie

$$KALE(Q, P; \mathcal{H}) = 0.18$$



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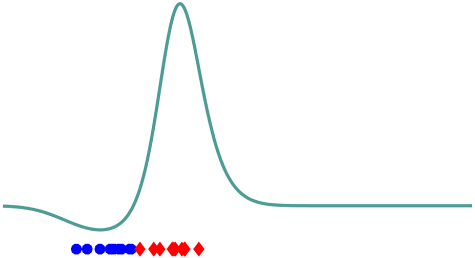
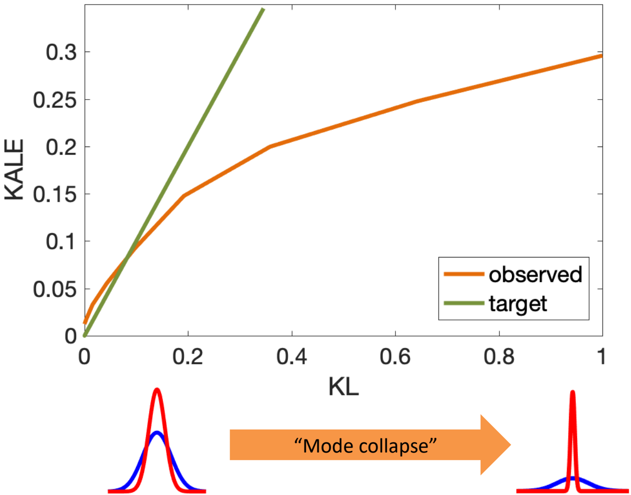
$$KALE(Q, P; \mathcal{H}) = 0.12$$



Glaser, Arbel, G. "KALE Flow: A Relaxed KL Gradient Flow for Probabilities with Disjoint Support," (arXiv, 2021, Section 2)

The KALE smoothie and "mode collapse"

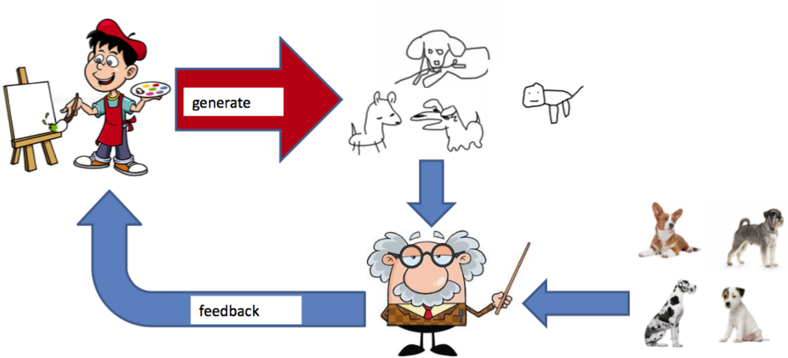
- Two Gaussians with same means, different variance



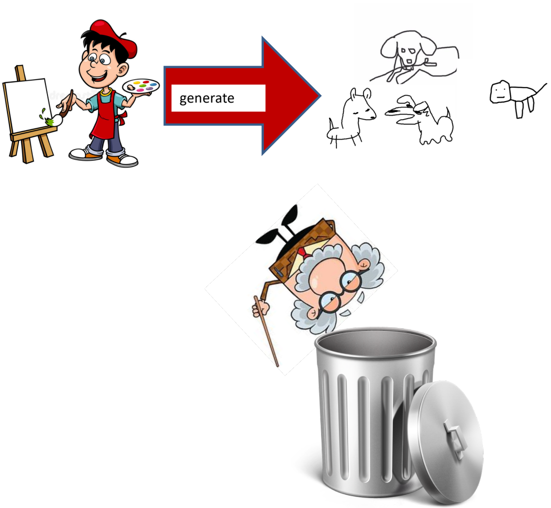
Example thanks to M. Arbel and M. Rosca

Generalized Energy-Based Models

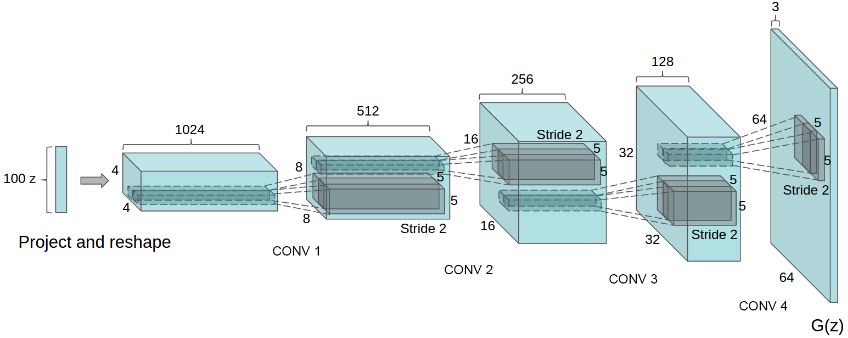
Visual notation: GAN setting



Visual notation: GAN setting



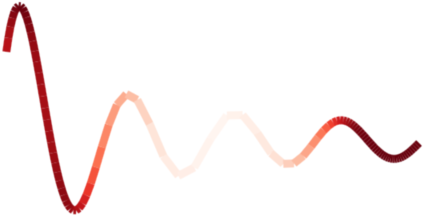
Reminder: the generator



Radford, Metz, Chintala, ICLR 2016

Generalized energy-based models: illustration

Target distribution P

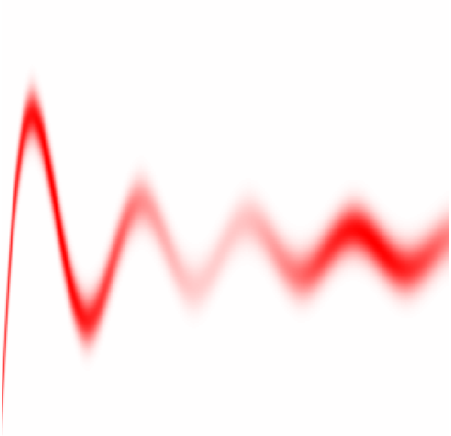


$$z \sim Unif[0,1]$$
$$\tilde{z} = \tau(z)$$
$$X = G_{\theta^\star}(\tilde{z}), \quad X_1 = \tilde{z}$$

Example thanks to M. Arbel

Generalized energy-based models: illustration

EBM approximation to target:



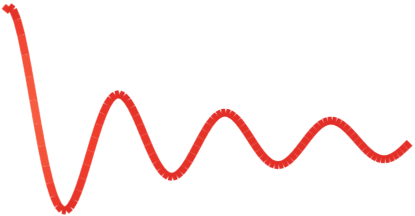
$$p(X) \propto \exp(-E(X))$$

$$E(X) = \frac{1}{2\sigma^2} \| G_\theta(X_1) - X \|^2 + A_\theta(X_1)$$

Example thanks to M. Arbel

Generalized energy-based models: illustration

GAN (generator) distribution Q_θ

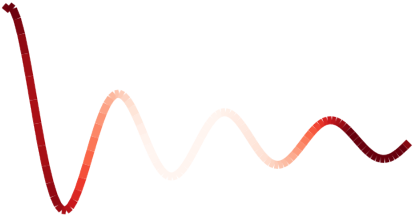


Generator	Critic
$z \sim unif[0,1]$	$MLP(X)$
$X = B_\theta(z)$	

Example thanks to M. Arbel

Generalized energy-based models: illustration

Mass of GEBM corrected by critic



Generator

$z \sim unif[0,1]$

$X = B_\theta(z)$

Re-weight using importance weights defined by energy:

$$w(x) \propto \exp(-E(x))$$

Example thanks to M. Arbel

Generalized energy-based models

Define a model $Q_{B_\theta, E}$ as follows:

- Sample from generator with parameters θ

$$X \sim Q_\theta \quad \Longleftrightarrow \quad X = B_\theta(Z), \quad Z \sim \eta$$

- Reweight the samples according to importance weights:

$$f_{Q,E}(x) = \frac{\exp(-E(x))}{Z_{Q_\theta, E}}, \qquad Z_{Q,E} = \int \exp(-E(x))\, d\,Q_\theta(x),$$

where $E \in \mathcal{E}$, the energy function class.

$f_{Q,E}(x)$ is Radon-Nikodym derivative of $Q_{B_\theta, E}$ wrt Q_θ.

- When Q_θ has density wrt Lebesgue on $\mathcal{X}$, this is a standard energy-based model.

Fitting GEBMs

Fit the model using Generalized Log-Likelihood:

$$\mathcal{L}_{P,Q}(E) := \int \log(f_{Q,E})\, dP = -\int E\, dP - \log \int \exp(-E)\, dQ_\theta$$

- When $KL(P, Q_\theta)$ well defined, above is Donsker-Varadhan lower bound on KL
  - tight when $E(z) = -\log(p(z)/q(z))$.
- However, Generalized Log-Likelihood still defined when P and Q_θ mutually singular!

KALE and the energy function

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KALE and the energy function

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From convexity of exponential,

$$-\log \int \exp(-E)\, dQ_\theta \geq -c - e^{-c} \int \exp(-E)\, dQ_\theta + 1$$

tight whenever $c = \log \int \exp(-E)\, dQ_\theta$.

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Generalized Log-Likelihood has the lower bound:

$$\mathcal{L}_{P,Q}(E) \geq -\int (E + c)\, dP - \int \exp(-E - c)\, dQ_\theta + 1$$

$$:= \mathcal{F}(P, Q_\theta; \mathcal{E} + \mathbb{R})$$

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This is the KALE with function class $\mathcal{E} + \mathbb{R}$.

KALE and the energy function

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Jointly maximizing yields the maximum likelihood energy E^* and corresponding $c^* = \log \int \exp(-E)\, dQ_\theta$.

Training the base measure (generator)

Recall the generator:

$$X = B_\theta(Z), \quad Z \sim \eta$$

Define: $\mathcal{K}(\theta) := \mathcal{F}(P, Q_\theta; \mathcal{E} + \mathbb{R})$

Training the base measure (generator)

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Theorem: $\mathcal{K}$ is lipschitz and differentiable for almost all $\theta \in \Theta$ with:

$$\nabla \mathcal{K}(\theta) = Z_{Q,E^*}^{-1} \int \nabla_x E^*(B_\theta(z)) \nabla_\theta B_\theta(z) \exp(-E^*(B_\theta(z)))\eta(z)\,dz.$$

where E^* achieves supremum in $\mathcal{F}(P, Q; \mathcal{E} + \mathbb{R})$.

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where E^* achieves supremum in $\mathcal{F}(P, Q; \mathcal{E} + \mathbb{R})$.

Assumptions:

- Functions in $\mathcal{E}$ parametrized by $\psi \in \Psi$, where Ψ compact,
  - jointly continous w.r.t. (ψ, x), L-lipschitz and L-smooth w.r.t. x.
- $(\theta, z) \mapsto B_\theta(z)$ jointly continuous wrt (θ, z), $z \mapsto B_\theta(z)$ uniformly Lipschitz w.r.t. z, lipschitz and smooth wrt θ (see paper: constants depend on z)

Sampling from the model

Consider end-to-end model $Q_{B_\theta, E}$, where recall that
$X = B_\theta(Z), \quad Z \sim \eta,$

$$f_{B,E}(x) := \frac{\exp(-E(x))}{Z_{Q,E}}$$

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$X = B_\theta(Z), \quad Z \sim \eta,$

$$f_{B,E}(x) := \frac{\exp(-E(x))}{Z_{Q,E}}$$

For a test function g,

$$\int g(x)dQ_{B,E}(x) = \int g(B(z))f_{B,E}(B(z))\eta(z)dz$$

Posterior latent distribution therefore

$$\nu_{B,E}(z) = \eta(z)f_{B,E}(B(z))$$

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Posterior latent distribution therefore

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Sample $z \sim \nu_{B,E}$ via Langevin diffusion-derived algorithms (MALA, ULA, HMC,...) to exploit gradient information.

Generate new samples in $\mathcal{X}$ via

$$X \sim Q_{B,E} \quad \iff \quad Z \sim \nu_{B,E}, \quad X = B_\theta(Z).$$

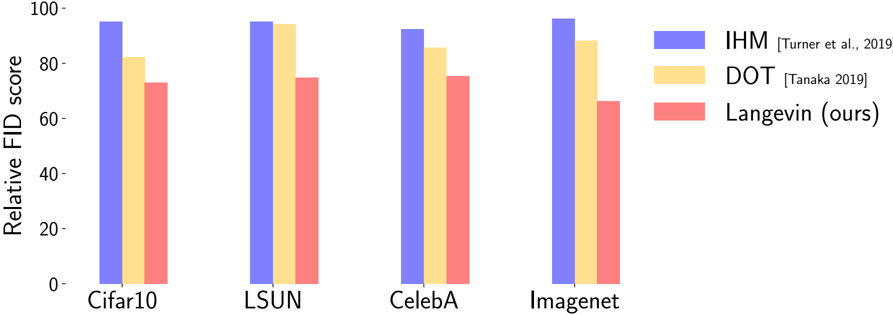
Experiments

Examples: sampling at modes

Tempered GEBM Cifar10 samples at different stages of sampling using a Kinetic Langevin Algorithm (KLA). Early samples $\rightarrow$ late samples. Model run at low temperature ($\beta = 100$) for better quality samples.

Sampling at modes: results

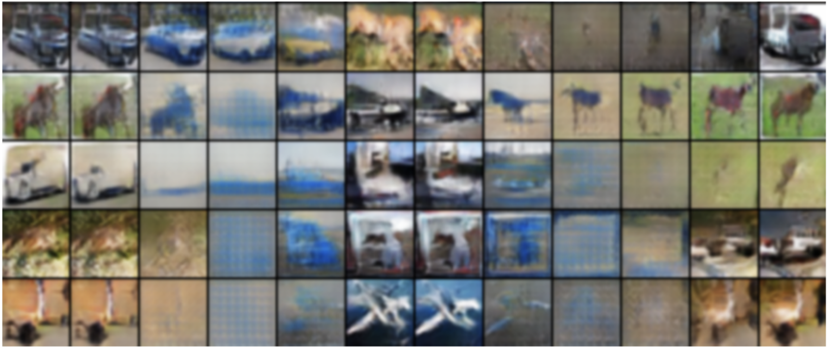
The relative FID score: $\frac{\mathrm{FID}(Q_{B_\theta,E})}{\mathrm{FID}(B_\theta)}$



For a given generator B_θ and energy E, samples always better (FID score) than generator alone.

Examples: moving between modes

Tempered GEBM Cifar10 samples at different stages of sampling using KLA. Early samples → late samples.
Model run at lower friction (but still low temperature, $\beta = 100$) for mode exploration.



Summary

- Generalized energy based model: ICLR 2021
  - End-to-end model incorporating generator and critic
  - Always better samples than generator alone.

arXiv.org > stat > arXiv:2003.05033

Statistics > Machine Learning

[Submitted on 10 Mar 2020 (v1), last revised 24 Jun 2020 (this version, v3)]

Generalized Energy Based Models

Michael Arbel, Liang Zhou, Arthur Gretton

arXiv.org > cs > arXiv:2003.06060

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[Submitted on 12 Mar 2020 (v1), last revised 24 Mar 2020 (this version, v2)]

Your GAN is Secretly an Energy-based Model and You Should use Discriminator Driven Latent Sampling

Tong Che, Ruixiang Zhang, Jascha Sohl-Dickstein, Hugo Larochelle, Liam Paull, Yuan Cao, Yoshua Bengio

https://github.com/MichaelArbel/GeneralizedEBM

Questions?


THE KERNEL
BREWERY
LONDON
BALTIC PORTER
THE KERNEL
EXPORT STOUT

Post-credit scene: MMD flow

From NeurIPS 2019:

Maximum Mean Discrepancy Gradient Flow

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Sanity check: reduction to EBM case

Base measure B_θ is real NVP with closed-form density.