Moser Flow: Divergence-based Generative Modeling on Manifolds
Supplementary

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A Proof of Moser's Theorem.

We will review here the proof of Moser Theorem 1; for more details see Moser's original paper (Moser, 1965) or Lang (2012), Chapter 18 section 2. Let $\hat{\alpha}_t = \alpha_t dV$ be the time-dependent volume form over $\mathcal{M}$ corresponding to the density interpolant α_t. Note that $\int_{\mathcal{M}} \hat{\alpha}_t = 1$. Moser's idea is to replace equation 2 with its continuous version:

$$\hat{\alpha}_0 = \Phi_t^* \hat{\alpha}_t, \quad t \in [0, 1] \tag{A1}$$

If equation A1 holds for all $t \in [0, 1]$ then plugging $t = 1$ leads to equation 2. Since equation A1 holds trivially for $t = 0$ (since Φ_0 is the identity mapping), solving it amounts to asking that $\Phi_t^* \hat{\alpha}_t$ is constant, i.e.,

$$\frac{d}{dt} \Phi_t^* \hat{\alpha}_t = 0. \tag{A2}$$

The time derivative of $\Phi_t^* \hat{\alpha}_t$ can be computed with the help of the Lie derivative (e.g., Proposition 5.2 in Lang (2012)): If Φ_t is the flow corresponding to the time dependent vector field v_t (see equation 3), and ω is a differential form then

$$\frac{d}{dt}(\Phi_t^* \omega) = \Phi_t^* (\mathfrak{L}_{v_t} \omega),$$

where $\mathfrak{L}$ denotes the Lie derivative. The Lie derivative $\mathfrak{L}_v \omega$ of a smooth vector field v and smooth differential form ω can be computed using Cartan's "magic formula" (see e.g., Theorem 14.35 in Lee (2013)):

$$\mathfrak{L}_v \omega = i_v(d\omega) + d(i_v \omega),$$

where $i_v \omega$ is the interior multiplication of a vector field and a differential form defined by $(i_v \omega)(v_2, \dots, v_n) = \omega(v, v_2, \dots, v_n)$. In case ω is an n-form (as $\hat{\alpha}_t$ in our case) we have $d\omega = 0$ so the first term in the r.h.s. above vanishes. Lastly, we will need the following "trick":

$$\frac{d}{dt}(\Phi_t^* \hat{\alpha}_t) = \frac{d}{ds}\Big|_{s=t} (\Phi_s^* \hat{\alpha}_t) + \frac{d}{ds}\Big|_{s=t} (\Phi_t^* \hat{\alpha}_s).$$

Putting the last three equations together we get:

$$\frac{d}{dt}(\Phi_t^* \hat{\alpha}_t) = \Phi_t^* (\mathfrak{L}_{v_t} \hat{\alpha}_t) + \Phi_t^* \left(\frac{d}{dt} \hat{\alpha}_t \right) = \Phi_t^* \left(d(i_{v_t} \hat{\alpha}_t) + \frac{d}{dt} \hat{\alpha}_t \right). \tag{A3}$$

The theorem is proven if one can show that $v_t \in \mathfrak{X}(\mathcal{M})$ exists such that $d(i_{v_t} \hat{\alpha}_t) + \frac{d}{dt} \hat{\alpha}_t = 0$. The divergence operator is defined by the equality $d(i_w dV) = \operatorname{div}(w) dV$, for a vector field $w \in \mathfrak{X}(\mathcal{M})$. Therefore $d(i_{v_t} \hat{\alpha}_t) = \operatorname{div}(\alpha_t v_t) dV$. Denote $\hat{\gamma}_t = \frac{d}{dt} \hat{\alpha}_t$. Then we need to show that $v_t \in \mathcal{M}$ exists such that

$$d(i_{v_t} \hat{\alpha}_t) + \hat{\gamma}_t = 0. \tag{A4}$$

By the Hodge decomposition (see Theorem 4.18 in Morita (2001)) $\hat{\gamma}_t$ can be written as a sum of an exact and harmonic forms: $\hat{\gamma}_t = d\hat{\beta}_t + \hat{h}_t$. Since every harmonic form on a connected, compact,

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oriented Riemannian manifold is a constant multiple of the Riemannian volume form, cdV (see Corollary 4.14 in Morita (2001)), we have

$$0 = \frac{d}{dt}1 = \frac{d}{dt}\int_{\mathcal{M}} \hat{\alpha}_t = \int_{\mathcal{M}} \hat{\gamma}_t = \int_{\mathcal{M}} d\hat{\beta}_t + \int_{\mathcal{M}} \hat{h}_t = \int_{\mathcal{M}} \hat{h}_t = c\int_{\mathcal{M}} dV,$$

where in the second from the right equality we used Stokes Theorem (see e.g., Theorem 16.11 in Lee (2013)) and the fact that $\mathcal{M}$ has no boundary. This implies that $c = 0$, and

$$\hat{\gamma}_t = d\hat{\beta}_t. \tag{A5}$$

Using the correspondence between vector fields and $d-1$ forms we let $\beta_t = i_{u_t}dV$, where $u_t \in \mathfrak{X}(\mathcal{M})$, and $d\beta_t = d(i_{u_t}dV) = \mathrm{div}(u_t)dV$.

Lastly, consider v_t defined as follows:

$$v_t = -\frac{u_t}{\alpha_t}. \tag{A6}$$

With this choice equation A4 is satisfied:

$$d(i_{v_t}\hat{\alpha}_t) + \hat{\gamma}_t = -d(i_{\frac{u_t}{\alpha_t}}(\alpha_t dV)) + i_{u_t}dV = 0.$$

The theorem is proven. □

One comment is that for practically finding v_t, according to equation A6, we need to get u_t, which amounts to solving the Hodge decomposition equation, $\mathrm{div}(u_t)dV = \hat{\gamma}_t$, that is equivalent to the following PDE on the manifold $\mathcal{M}$:

$$\mathrm{div}(u_t) = \frac{d}{dt}\alpha_t. \tag{A7}$$

Proof of Lemma 1. The proof uses Stokes theorem:

$$\int_{\mathcal{M}} \mathrm{div}(u)dV = \int_{\mathcal{M}} d(i_u dV) = \int_{\partial\mathcal{M}} i_u dV = 0,$$

where the last equality is due to the fact that either $\partial\mathcal{M} = \emptyset$, or, for $x \in \partial\mathcal{M}$, we have that $u(x) \in T_x\partial\mathcal{M}$, and therefore $(i_u dV)(v_1, \ldots, v_{n-1}) = dV(u, v_1, \ldots, v_{n-1}) = 0$, for all $v_1, \ldots, v_{n-1} \in T_x\partial\mathcal{M}$. This implies $i_u dV = 0$. □

B Other proofs

Proof of Theorem 2. As we showed in the paper, our loss can be equivalently presented (up to constant factors) as

$$l(\theta) = D(\mu, \bar{\mu}_+) + (\lambda - 1)\int_{\mathcal{M}} \bar{\mu}_- dV$$

Where the first term $D(\mu, \bar{\mu}_+)$ is the generalized KL divergence which is non-negative and equals zero iff $\bar{\mu}_+ = \mu$ and since $\lambda \geq 1$ the second term is also non-negative and equals zero iff $\mu_- = 0$ or $\lambda = 1$.
First we show that $\bar{\mu} = \mu$ is a minimizer of the loss. Since we assumed $\mu \geq \epsilon$ we have that $\bar{\mu}_+ = \max(\mu, \epsilon) = \mu$ and $\bar{\mu}_- = \bar{\mu}_+ - \bar{\mu} = 0$. So both $D(\mu, \bar{\mu}_+)$ and $\int_{\mathcal{M}} \bar{\mu}_- dV$ are minimized, which means the entire loss is minimized.
Now lets assume $\bar{\mu}$ is a minimizer of the loss. If $\lambda > 1$ $\bar{\mu}$ has to minimize both terms, as we know there exists a minimizer that minimizes both of them. In particular for any $\lambda \geq 1$ we have that $\bar{\mu}$ minimizes $D(\mu, \bar{\mu}_+)$ meaning $\bar{\mu}_+ = \mu$. Now we have that $0 = 1 - 1 = \int_{\mathcal{M}} \bar{\mu} dV - \int_{\mathcal{M}} \mu dV = \int_{\mathcal{M}} \bar{\mu}_+ dV + \int_{\mathcal{M}} \bar{\mu}_- dV - \int_{\mathcal{M}} \mu dV = \int_{\mathcal{M}} \bar{\mu}_- dV$. So we get that $\mu_- = 0$. Finally $\bar{\mu} = \bar{\mu}_+ + \bar{\mu}_- = \mu + 0 = \mu$. □

Proof of Lemma 2. Proposition 1.2 in Lang (2012) and Definition 1 in Section 4-4 in Do Carmo (2016) imply that for submanifolds with induced metric the Riemannian covariant derivative at $\boldsymbol{x} \in \mathcal{M}$ satisfies $\nabla_{\boldsymbol{e}_i} u = \boldsymbol{P}_{\boldsymbol{x}} \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{e}_i}$, where $\boldsymbol{P}_{\boldsymbol{x}}$ is the projection matrix on $T_{\boldsymbol{x}}\mathcal{M}$ introduced above.

Then, denoting $\boldsymbol{e}_1, \ldots, \boldsymbol{e}_n, \boldsymbol{n}_1, \ldots, \boldsymbol{n}_k$ an orthonormal basis of $\mathbb{R}^d$ where the first n vectors span $T_{\boldsymbol{x}}\mathcal{M}$ and the latter k span $N_{\boldsymbol{x}}\mathcal{M}$:

$$\begin{aligned}\operatorname{div}(\boldsymbol{u}) &= \sum_{i=1}^{n} \langle \nabla_{\boldsymbol{e}_i} \boldsymbol{u}, \boldsymbol{e}_i \rangle_g = \sum_{i=1}^{n} \left\langle \boldsymbol{P}_{\boldsymbol{x}} \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{e}_i}, \boldsymbol{e}_i \right\rangle = \sum_{i=1}^{n} \left\langle \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{e}_i}, \boldsymbol{P}_{\boldsymbol{x}} \boldsymbol{e}_i \right\rangle = \sum_{i=1}^{n} \left\langle \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{e}_i}, \boldsymbol{e}_i \right\rangle \\ &= \sum_{i=1}^{n} \left\langle \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{e}_i}, \boldsymbol{e}_i \right\rangle + \sum_{j=1}^{k} \left\langle \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{n}_j}, \boldsymbol{n}_j \right\rangle = \operatorname{div}_E(\boldsymbol{u}),\end{aligned}$$

□

Proof of Theorem 3. From Theorem 6.24 in Lee (2013) there exists a neighbourhood $\Omega \subset \mathbb{R}^d$ of $\mathcal{M}$ such that the projection $\pi : \Omega \to \mathcal{M}$ is smooth over $\bar{\Omega}$ (i.e., can be extended to a smooth function over a neighborhood of $\bar{\Omega}$). Since $\mathcal{M}$ is compact, $\bar{\Omega}$ is also compact. According to Theorem 1 there exists a vector field $\boldsymbol{u}^\star \in \mathfrak{X}(\mathcal{M})$ so that $\mu = \nu - \operatorname{div}(\boldsymbol{u}^\star)$. We extend $\boldsymbol{u}^\star$ to $\bar{\Omega}$ by setting $\boldsymbol{u}^\star(\boldsymbol{x}) = \boldsymbol{u}^\star(\pi(\boldsymbol{x}))$, for $\boldsymbol{x} \notin \mathcal{M}$. Note that for $\boldsymbol{x} \in \mathcal{M}$ this definition coincides with the former $\boldsymbol{u}^\star$ defined over $\mathcal{M}$. Similarly to equation 18 we have that $\boldsymbol{u}^\star(\boldsymbol{x}) = \boldsymbol{P}_{\pi(\boldsymbol{x})} \boldsymbol{u}^\star(\pi(\boldsymbol{x}))$.

Corollary 3.4 in Hornik et al. (1990) shows that given a target smooth function $f : \bar{\Omega} \to \mathbb{R}$ and $\epsilon > 0$, there exists an MLP with l-finite smooth activation that uniformly approximate the first $0 \le m \le l$ derivatives of f over $\bar{\Omega}$ with error at most ϵ. An activation $\sigma : \mathbb{R} \to \mathbb{R}$ is l-finite if it is l-times continuously differentiable and satisfies $0 < \int_{-\infty}^{\infty} \left|\sigma^{(l)}\right| < \infty$. Note that sigmoid and $\tanh$ are l-finite for all $l \ge 1$, and Softplus is l-finite for $l \ge 2$.

Using this approximation result (adapted to vector valued MLP) there exists an MLP $\boldsymbol{v}_\theta : \mathbb{R}^d \to \mathbb{R}^d$ such that each coordinate of $\boldsymbol{u}^\star$ and $\boldsymbol{v}_\theta$ are ϵ close in value and first partial derivatives over $\bar{\Omega}$.

Now for arbitrary $\boldsymbol{x} \in \mathcal{M}$ we have

$$\begin{aligned}\bar{\mu}(\boldsymbol{x}) &= \nu(\boldsymbol{x}) - \operatorname{div}_E(\boldsymbol{P}_{\pi(\boldsymbol{x})} \boldsymbol{v}_\theta(\pi(\boldsymbol{x}))) \\ &= \nu(\boldsymbol{x}) - \operatorname{div}_E\Big(\boldsymbol{P}_{\pi(\boldsymbol{x})} \boldsymbol{v}_\theta(\pi(\boldsymbol{x})) - \boldsymbol{P}_{\pi(\boldsymbol{x})} \boldsymbol{u}^\star(\pi(\boldsymbol{x}))\Big) - \operatorname{div}(\boldsymbol{u}^\star(\boldsymbol{x})) \\ &= \mu(\boldsymbol{x}) - \operatorname{div}_E\Big(\boldsymbol{P}_{\pi(\boldsymbol{x})} \left[\boldsymbol{v}_\theta(\pi(\boldsymbol{x})) - \boldsymbol{u}^\star(\pi(\boldsymbol{x}))\right]\Big) \\ &= \mu(\boldsymbol{x}) - \operatorname{div}_E\Big(\boldsymbol{P}_{\pi(\boldsymbol{x})} \boldsymbol{e}(\boldsymbol{x})\Big),\end{aligned}$$

where we denote $\boldsymbol{e}(\boldsymbol{x}) = \boldsymbol{v}_\theta(\pi(\boldsymbol{x})) - \boldsymbol{u}^\star(\pi(\boldsymbol{x}))$. We will finish the proof by showing that

$$\left|\operatorname{div}_E\Big(\boldsymbol{P}_{\pi(\boldsymbol{x})} \boldsymbol{e}(\boldsymbol{x})\Big)\right| < c\epsilon$$

for some constant $c > 0$ depending only on $\mathcal{M}$. Note that the l.h.s. of this equation is a sum of terms of the form $\frac{\partial}{\partial x^i}\left((\boldsymbol{P}_{\pi(\boldsymbol{x})})_{i,j} \boldsymbol{e}(\boldsymbol{x})_j\right)$, where $(\boldsymbol{P}_{\pi(\boldsymbol{x})})_{i,j}$ is the (i,j)-th entry of the matrix $\boldsymbol{P}_{\pi(\boldsymbol{x})}$ and $\boldsymbol{e}(\boldsymbol{x})_j$ is the j-th entry of $\boldsymbol{e}(\boldsymbol{x})$. Since the value and first partial derivatives of π and $\boldsymbol{P}$ (as the differential of π) over $\mathcal{M}$ can be bounded, depending only on $\mathcal{M}$, the theorem is proved.

□

C Laplacian eigen function calculation

Given a triangular surface mesh $\mathcal{M}'$, we wish to calculate the k-th eigenfunction of the (discrete) Laplace-Beltrami operator over $\mathcal{M}'$. We will use the standard (cotangent) discretization of the Laplacian over meshes (Botsch et al., 2010). That is, we define $\boldsymbol{L}$ to be the cotangent-Laplacian matrix of the graph defined by $\mathcal{M}'$, and $\boldsymbol{M}$ the mass matrix of $\mathcal{M}'$, i.e., a diagonal matrix where $\boldsymbol{M}_{ii}$ is the area of the the Voroni cell of the i-th vertex in the mesh. We then calculate the eigenfunctions as the solution to the generalized eigenvalue problem $\boldsymbol{L}\boldsymbol{x} = \lambda_k \boldsymbol{M}\boldsymbol{x}$ where λ_k is the k-th eigenvalue. We sample these $\mathcal{M}'$ piecewise-linear functions at centroids of faces.

D Linearization of the projection operator π

Since we only sample and derivate the projection operator $\pi : \mathbb{R}^d \to \mathcal{M}$ over $\mathcal{M}$, implementing equation 18 does not require knowledge of the full projection π. Rather, it is enough to use its first order expansion over $\mathcal{M}$. For $\boldsymbol{x}_0 \in \mathcal{M}$

$$\pi(\boldsymbol{x}) \approx \pi(\boldsymbol{x}_0) + \boldsymbol{P}_{\boldsymbol{x}_0}(\boldsymbol{x} - \boldsymbol{x}_0) = \boldsymbol{x}_0 + \boldsymbol{P}_{\boldsymbol{x}_0}(\boldsymbol{x} - \boldsymbol{x}_0) = \hat{\pi}(\boldsymbol{x}_0, \boldsymbol{x}).$$

Now since $\pi(\cdot)$ and $\hat{\pi}(\boldsymbol{x}_0, \cdot)$ have the same value and first partial derivatives at $\boldsymbol{x}_0$ we can replace equation 18 for each sample point $\boldsymbol{x}_0 \in \mathcal{X} \cup \mathcal{Y}$, with

$$\boldsymbol{u}(\boldsymbol{x}) = \boldsymbol{P}_{\hat{\pi}(\boldsymbol{x}_0, \boldsymbol{x})} \boldsymbol{v}_\theta(\hat{\pi}(\boldsymbol{x}_0, \boldsymbol{x})).$$

E Unnormalized densities

As described in section 4, our formulation of the loss is dependent on knowing the volume of the manifold $\mathcal{M}$. For simple cases like the flat torus or the sphere, we have a closed form formula for this volume. For more general cases, we can show that we don't actually require to know this value, since we can work with unnormalized density functions:

$$\begin{aligned}
\ell(\theta) &= -\frac{1}{m} \sum_{i=1}^{m} \log \max \left\{\epsilon, \nu(\boldsymbol{x}_i) - \operatorname{div}_E \boldsymbol{u}(\boldsymbol{x}_i)\right\} \\
&\quad + \frac{V(\mathcal{M})\lambda_-}{l} \sum_{j=1}^{l} \Big(\epsilon - \min\left\{\epsilon, \nu(\boldsymbol{y}_j) - \operatorname{div}_E \boldsymbol{u}(\boldsymbol{y}_j)\right\}\Big), \\
&= \log V(\mathcal{M}) - \frac{1}{m} \sum_{i=1}^{m} \log \max \left\{\epsilon', \nu'(\boldsymbol{x}_i) - \operatorname{div}_E \boldsymbol{u}'(\boldsymbol{x}_i)\right\} \\
&\quad + \frac{\lambda_-}{l} \sum_{j=1}^{l} \Big(\epsilon' - \min\left\{\epsilon', \nu'(\boldsymbol{y}_j) - \operatorname{div}_E \boldsymbol{u}'(\boldsymbol{y}_j)\right\}\Big),
\end{aligned}$$

where $\nu' = V(\mathcal{M})\nu \equiv 1$, $\boldsymbol{u}' = V(\mathcal{M})\boldsymbol{u}$, $\epsilon' = V(\mathcal{M})\epsilon'$, and $\log V(\mathcal{M})$ is a constant. Lastly note that the definition of $\boldsymbol{v}_t$ is invariant to this scaling and can be computed with the unnormalized quantities.

F Additional Experimental Details

We used an internal academic cluster with NVIDIA Quadro RTX 6000 GPUs. Every run and seed configuration required 1 GPU. All other experimental details are mentioned in the main paper. Our codebase, implemented in PyTorch, is attached in the supplementary materials. We will open-source it post the review process.

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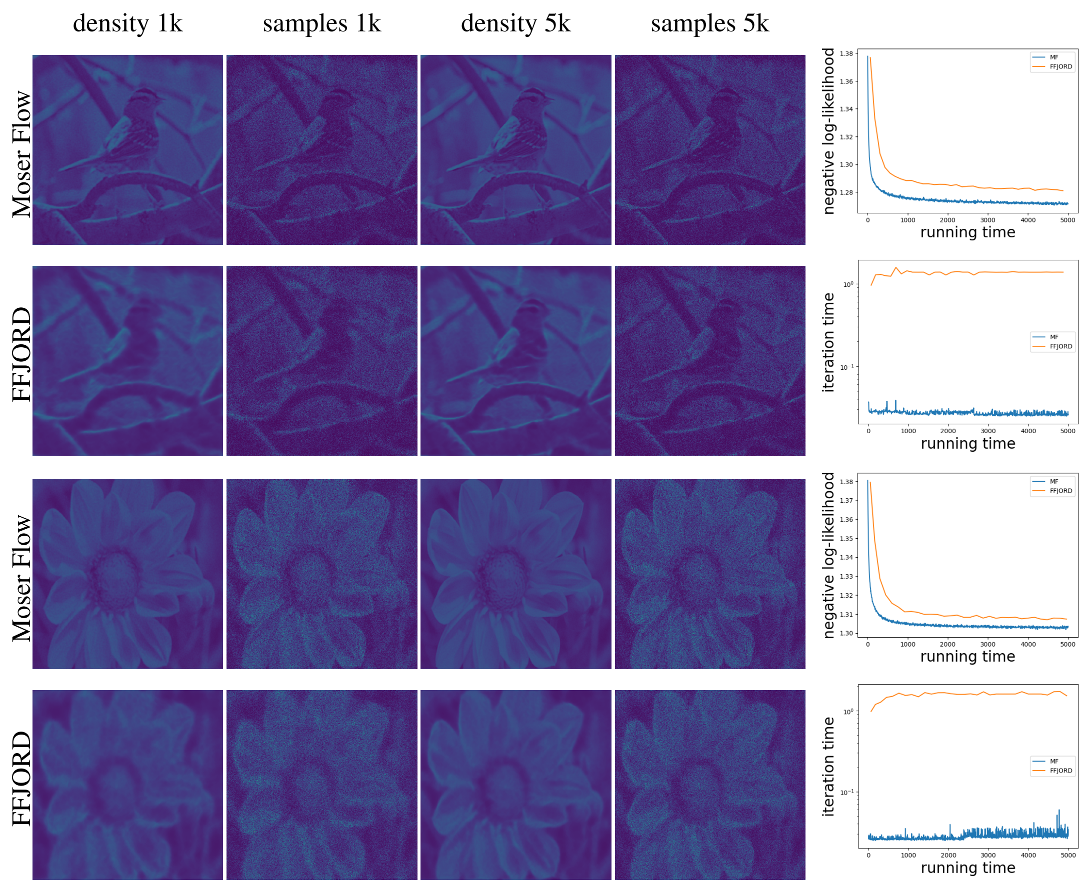

Figure A1: Comparing learned density and generated samples with MF and FFJORD at different times (in k-sec); top right shows NLL scores for both MF and FFJORD at different times; bottom right shows time per iteration (in log-scale, sec) as a function of total running time (in sec); FFJORD iterations take longer as training progresses. Flickr images (license CC BY 2.0): Bird by Flickr user "lakeworth" `https://www.flickr.com/photos/lakeworth/46657879995/`; Flower by Flickr user "daiyaan.db" `https://www.flickr.com/photos/daiyaandb/23279986094/`.