## Exercises

**Exercise 7.1** **Integrating over Dirac delta functions.** *Let us verify a few of the properties of the delta function and check (7.9), as well as the formulas (7.7) and (7.8) to be used later.*

**(a)** *If $f : \mathbb{R}^d \to \mathbb{R}^d$, then show that*

$$\int_{\mathbb{R}^d} dx\, \delta\left(f(x)\right) = \sum_{x \in f^{-1}(0)} \frac{1}{|\det \partial_x f|}\,.$$

**(b)** *The delta function can be approximated by delta sequences, for example*

$$\int dx\, \delta(x) f(x) = \lim_{\sigma \to 0} \int dx\, \frac{e^{-\frac{x^2}{2\sigma}}}{\sqrt{2\pi\sigma}} f(x)\,.$$

*Use this approximation to see whether the formal expression*

$$\int_{\mathbb{R}} dx\, \delta(x^2)$$

*makes sense.*

**Exercise 7.2** **Derivatives of Dirac delta functions.** *Consider $\delta^{(k)}(x) = \frac{\partial^k}{\partial x^k}\delta(x)$, and show that*

**(a)** *Using integration by parts, determine the value of*

$$\int_{\mathbb{R}} dx\, \delta'(y)\,.$$

*where $y = f(x) - x$.*

**(b)**
$$\int dx\, \delta^{(2)}\left(y\right) = \sum_{x:y(x)=0} \frac{1}{|y'|} \left\{ 3\frac{(y'')^2}{(y')^4} - \frac{y'''}{(y')^3} \right\}. \tag{7.40}$$

**(c)**
$$\int dx\, b(x)\delta^{(2)}(y) = \sum_{x:y(x)=0} \frac{1}{|y'|} \left\{ \frac{b''}{(y')^2} - \frac{b'y''}{(y')^3} + b\left( 3\frac{(y'')^2}{(y')^4} - \frac{y'''}{(y')^3} \right) \right\}. \tag{7.41}$$

*These formulas are useful incomputing effects of weak noise on deterministic dynamics [7.3].*

**Exercise 7.3** **$\mathcal{L}^t$ generates a semigroup.** *Check that the Perron-Frobenius operator has the semigroup property,*

$$\int_M dz \mathcal{L}^{t_2}(y,z)\, \mathcal{L}^{t_1}(z,x) = \mathcal{L}^{t_2+t_1}(y,x)\,, \qquad t_1, t_2 \geq 0\,. \tag{7.42}$$

*As the flows that we tend to be interested in are invertible, the $\mathcal{L}$'s that we will use often do form a group, with $t_1, t_2 \in \mathbb{R}$.*

**Exercise 7.4 Escape rate of the tent map.**

**(a)** *Calculate by numerical experimentation the log of the fraction of trajectories remaining trapped in the interval* $[0,1]$ *for the tent map*

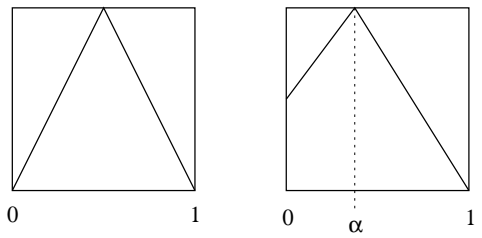
$$f(x) = a(1 - 2|x - 0.5|)$$

*for several values of* $a$.

**(b)** *Determine analytically the* $a$ *dependence of the escape rate* $\gamma(a)$.

**(c)** *Compare your results for (a) and (b).*

**Exercise 7.5** **Invariant measure.** *We will compute the invariant measure for two different piecewise linear maps.*




**(a)** *Verify the matrix* $\mathcal{L}$ *representation (7.13).*

**(b)** *The maximum of the first map has value 1. Compute an invariant measure for this map.*

**(c)** *Compute the leading eigenvalue of* $\mathcal{L}$ *for this map.*

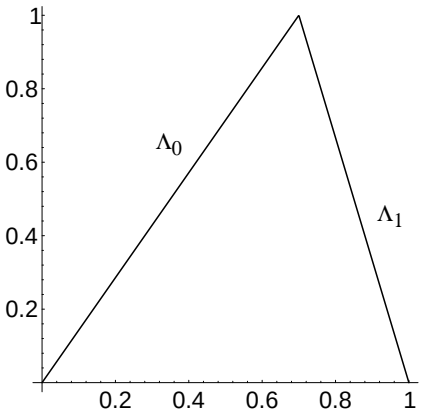
**(d)** *For this map there is an infinite number of invariant measures, but only one of them will be found when one carries out a numerical simulation. Determine that measure, and explain why your choice is the natural measure for this map.*

**(e)** *In the second map the maximum is at* $\alpha = (3 - \sqrt{5})/2$ *and the slopes are* $\pm(\sqrt{5} + 1)/2$. *Find the natural measure for this map. Show that it is piecewise linear and that the ratio of its two values is* $(\sqrt{5} + 1)/2$.

*(medium difficulty)*

**Exercise 7.6 Escape rate for a flow conserving map.** *Adjust* $\Lambda_0$, $\Lambda_1$ *in (7.11) so that the gap between the intervals* $\mathcal{M}_0$, $\mathcal{M}_1$ *vanishes. Check that in that case the escape rate equals zero.*

**Exercise 7.7 Eigenvalues of the skew Ulam tent map Perron-Frobenius operator.** *Show that for the skew Ulam tent map*




$$f(x) = \begin{cases} f_0(x) = \Lambda_0 x\,, & x \in \mathcal{M}_0 = [0, 1/\Lambda_0) \\ f_1(x) = \frac{\Lambda_0}{\Lambda_0 - 1}(1-x)\,, & x \in \mathcal{M}_1 = (1/\Lambda_0, 1]\,. \end{cases} \tag{7.43}$$

*the eigenvalues are available analytically, compute the first few.*

**Exercise 7.8 "Kissing disks"**$^*$ *(continuation of exercises 5.1 and 5.2). Close off the escape by setting $R = 2$, and look in the real time at the density of the Poincaré section iterates for a trajectory with a randomly chosen initial condition. Does it look uniform? Should it be uniform? (hint - phase space volumes are preserved for Hamiltonian flows by the Liouville theorem). Do you notice the trajectories that loiter around special regions of phase space for long times? These exemplify "intermittency", a bit of unpleasantness that we shall return to in chapter 18.*

**Exercise 7.9 Invariant measure for the Gauss map.** *Consider the Gauss map (we shall need this map in chapter 21):*

$$f(x) = \begin{cases} \frac{1}{x} - \left[\frac{1}{x}\right] & x \neq 0 \\ 0 & x = 0 \end{cases}$$

*where [ ] denotes the integer part.*

**(a)** *Verify that the density*

$$\rho(x) = \frac{1}{\log 2}\frac{1}{1+x}$$

*is an invariant measure for the map.*

**(b)** *Is it the natural measure?*

**Exercise 7.10 Exponential form of the semigroup.** *Check that the Koopman operator and the evolution generator commute, $\mathcal{K}^t\mathcal{A} = \mathcal{A}\mathcal{K}^t$, by considering the action of both operators on an arbitrary phase space function $a(x)$.*

**Exercise 7.11 $\mathcal{A}$ as a generator of translations.** *Verify that for a constant velocity field the evolution generator $\mathcal{A}$ n (7.30) is the generator of translations,*

$$e^{tv\frac{\partial}{\partial x}}a(x) = a(x+tv)\,.$$

*(hint: expand $a(x)$ in a Tylor series.)*

**Exercise 7.12 Incompressible flows.** *Show that (7.9) implies that $\rho_0(x) = 1$ is an eigenfunction of a volume preserving flow with eigenvalue $s_0 = 0$. In particular, this implies that the natural measure of hyperbolic and mixing Hamiltonian flows is uniform. Compare with the numerical experiment of exercise 7.8.*