FYS388_V15_Exercise07_Solution

March 18, 2015

1 Exercise 7, Sample solution

```
In [1]: import matplotlib.pyplot as plt
        import numpy as np

        %matplotlib inline

        plt.rcParams['figure.figsize'] = (12, 4)
```

1.1 Task 1

```
In [2]: import sys
        sys.path.append('/Users/plesser/NEST/code/releases/nest-2.6.0/ins/lib/python2.7/site-packages/')
```

```
In [3]: import nest
```

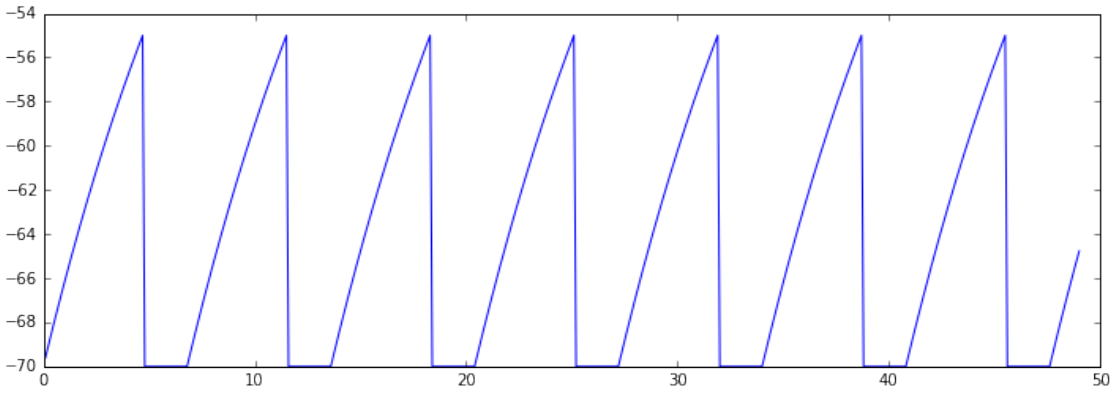
```
In [4]: def build_network(Ie):
            nest.ResetKernel()

            n = nest.Create('iaf_psc_delta', params={'I_e': Ie})
            vm = nest.Create('voltmeter', params={'interval': 0.1})
            sd = nest.Create('spike_detector')

            nest.Connect(vm, n)
            nest.Connect(n, sd)

            return vm, sd
```

1.1.1 Exploration 1

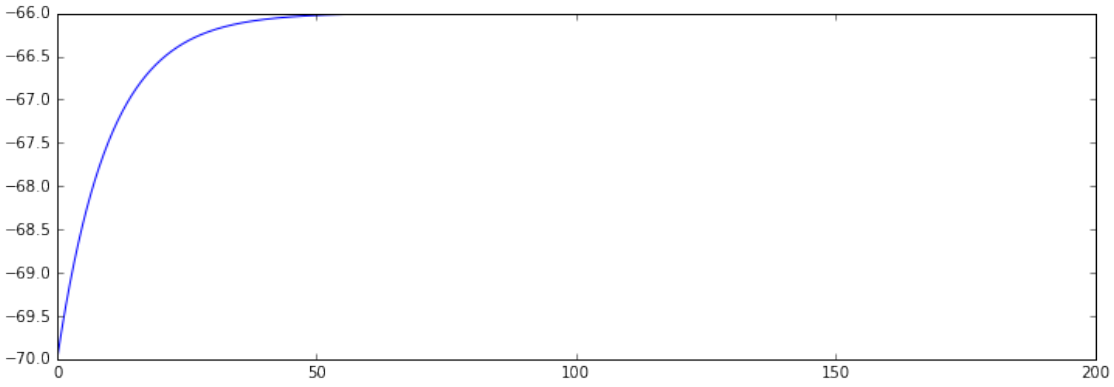
```
In [5]: vm, sd = build_network(1000.)
        nest.Simulate(50)
```

```
In [6]: vme = nest.GetStatus(vm, 'events')[0]
        V, t = vme['V_m'], vme['times']
```

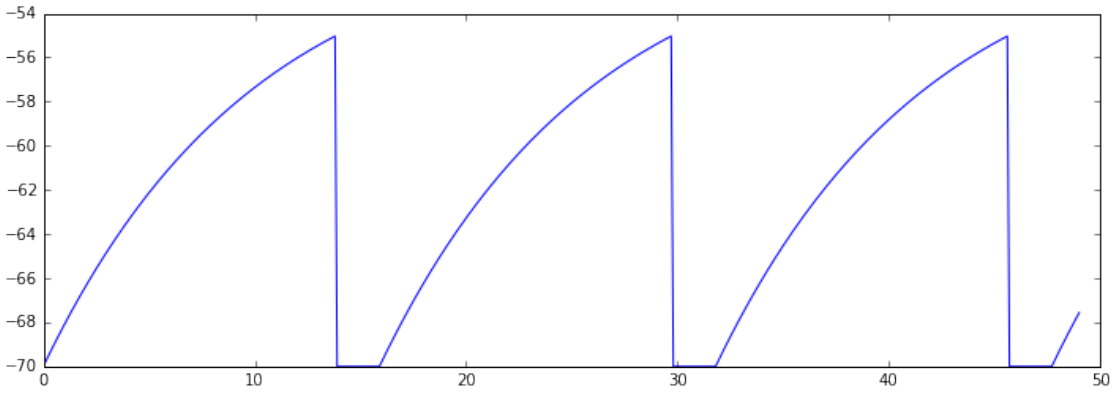
```
In [7]: plt.plot(t, V);
```



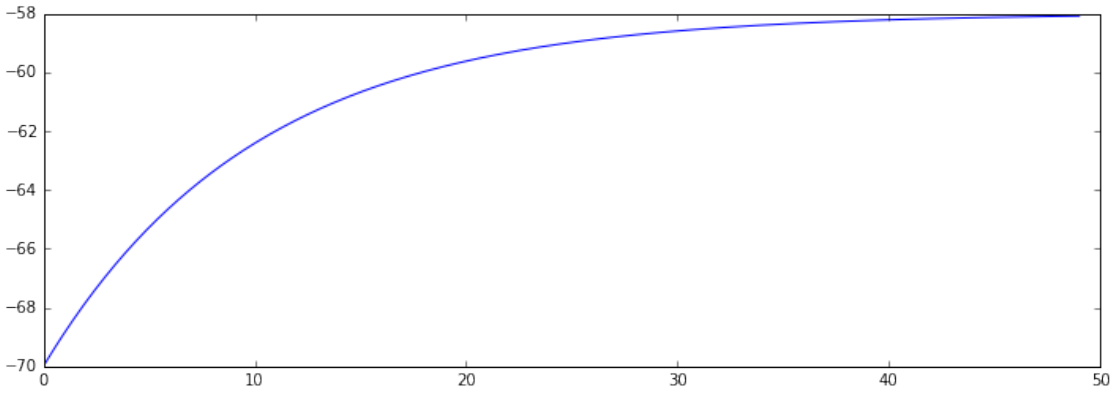
In [8]:
```
vm, sd = build_network(100.)
nest.Simulate(200)
vme = nest.GetStatus(vm, 'events')[0]
V, t = vme['V_m'], vme['times']
plt.plot(t, V);
```



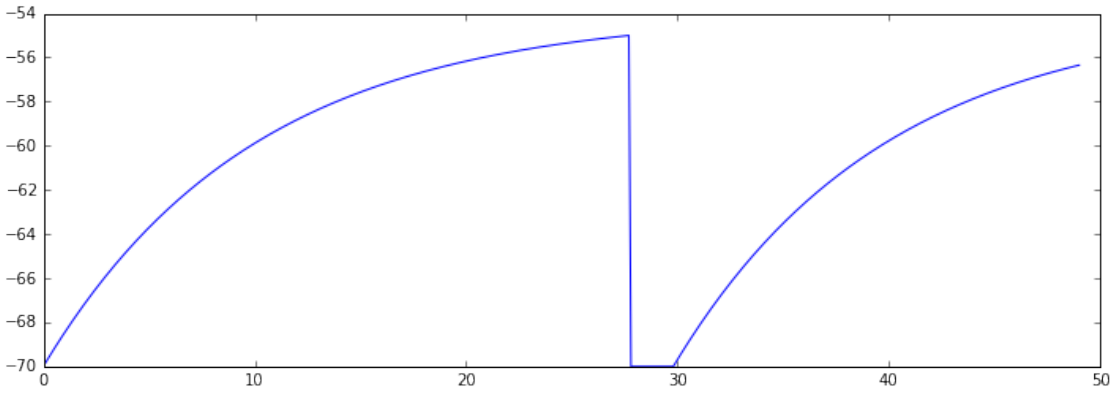
In [9]:
```
vm, sd = build_network(500.)
nest.Simulate(50)
vme = nest.GetStatus(vm, 'events')[0]
V, t = vme['V_m'], vme['times']
plt.plot(t, V);
```



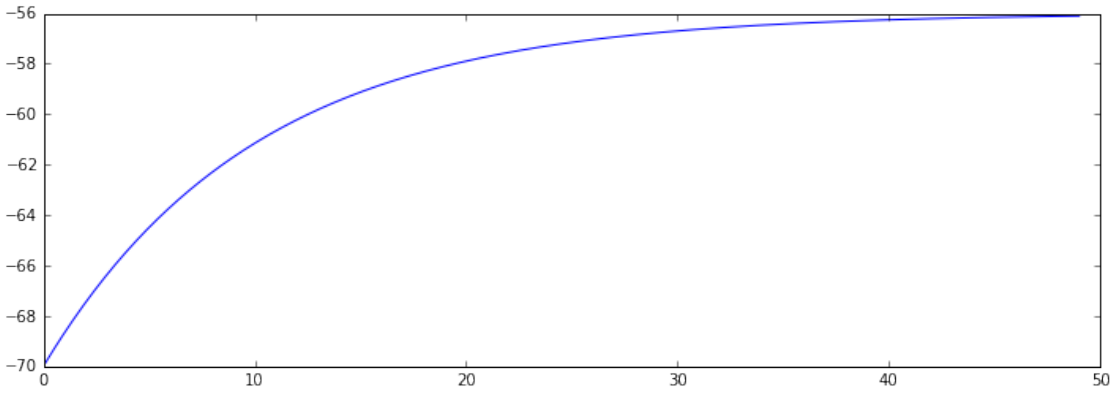
In [10]:
```
vm, sd = build_network(300.)
nest.Simulate(50)
vme = nest.GetStatus(vm, 'events')[0]
V, t = vme['V_m'], vme['times']
plt.plot(t, V);
```



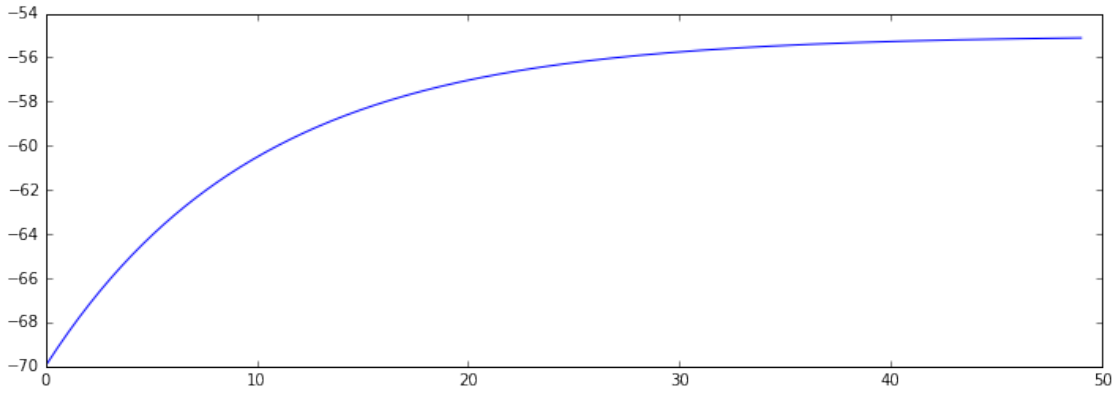
In [11]:
```
vm, sd = build_network(400.)
nest.Simulate(50)
vme = nest.GetStatus(vm, 'events')[0]
V, t = vme['V_m'], vme['times']
plt.plot(t, V);
```



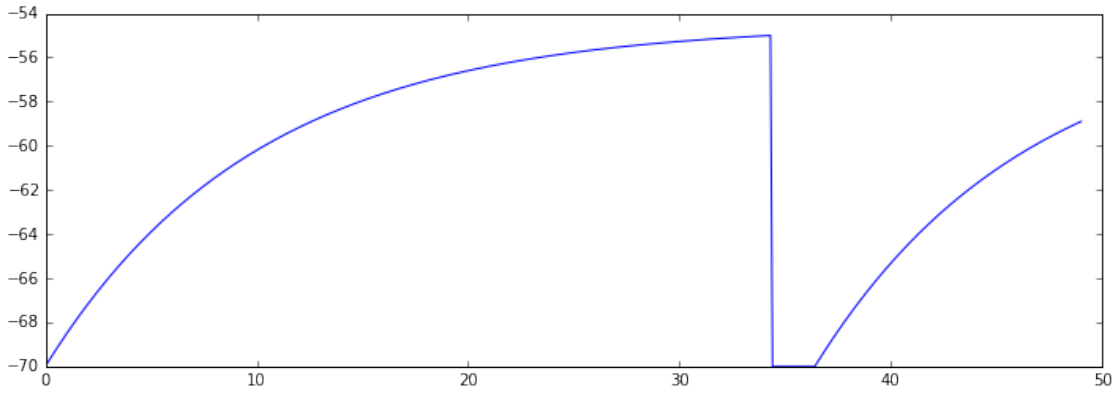
In [12]:
```
vm, sd = build_network(350.)
nest.Simulate(50)
vme = nest.GetStatus(vm, 'events')[0]
V, t = vme['V_m'], vme['times']
plt.plot(t, V);
```



In [13]:
```
vm, sd = build_network(375.)
nest.Simulate(50)
vme = nest.GetStatus(vm, 'events')[0]
V, t = vme['V_m'], vme['times']
plt.plot(t, V);
```




```
In [14]: vm, sd = build_network(387.5)
         nest.Simulate(50)
         vme = nest.GetStatus(vm, 'events')[0]
         V, t = vme['V_m'], vme['times']
         plt.plot(t, V);
```



We have now found one value for which we find one spike within 50 ms. To find the smallest and largest I_e evoking exactly one spike in 50 ms, starting with a "fresh" (non-refractory neuron), we first look compute the value of I_e that yields $V(t^*) = V_{\text{th}}$ (note that $V_0 = E_L$):

$$V_{\text{th}} = E_L e^{-t*/\tau_m} + \left(E_L + \frac{I_e \tau_m}{C}\right)\left(1 - e^{-t^*/\tau_m}\right) \tag{1}$$

$$= E_L + \frac{I_e \tau_m}{C}\left(1 - e^{-t^*/\tau_m}\right) \tag{2}$$

$$\Leftrightarrow \quad I_e = \frac{C}{\tau_m}\frac{V_{\text{th}} - E_L}{1 - e^{-t^*/\tau_m}} \tag{3}$$

$$= \frac{250\text{pA}}{10\text{ms}}\frac{-55\text{mV} - (-70\text{mV})}{1 - e^{-50\text{ms}/10\text{ms}}} \tag{4}$$

which we can evaluate in Python:

```
In [15]: I1min = 250./10. * (-55. - -70.) / (1 - np.exp(-50./10.))
         print I1min
```

```
377.54387059
```

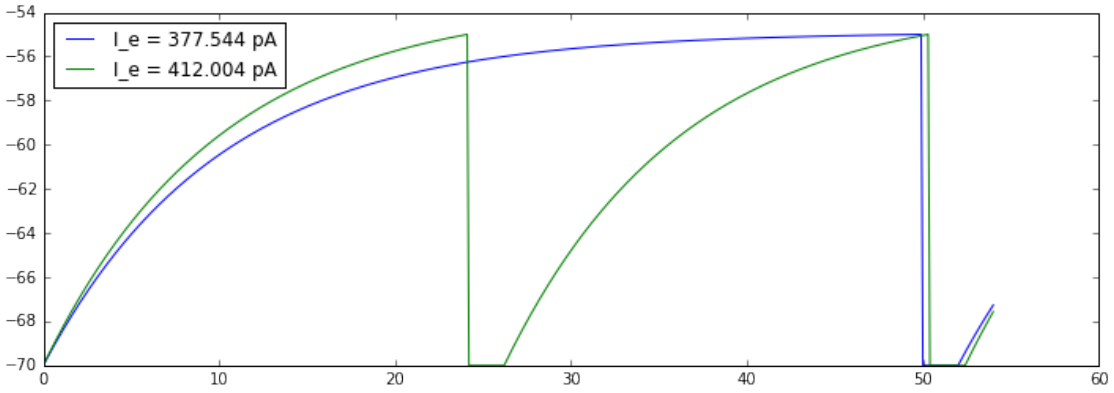
When considering the other extreme, just not firing a second spike, we must take the refractory period of 2 ms into account: The first spike should be fired after 24.1 ms, followed by 2 ms refractory time, then another 24.1 ms until the second spike. We can thus use the same equation as above, just with $t^* = 24.1$ ms:

```
In [16]: I1max = 250./10. * (-55. - -70.) / (1 - np.exp(-24.1/10.))
         print I1max
```

```
412.004286343
```

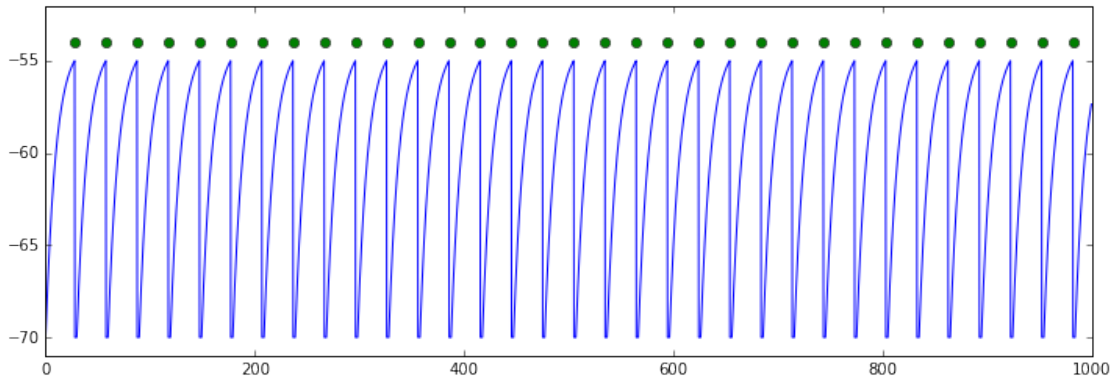
```
In [17]: vm, sd = build_network(I1min)
         nest.Simulate(55)
         vme = nest.GetStatus(vm, 'events')[0]
         V1min, t = vme['V_m'], vme['times']
         print "I1min spike times:", nest.GetStatus(sd, 'events')[0]['times']

         vm, sd = build_network(I1max)
         nest.Simulate(55)
         vme = nest.GetStatus(vm, 'events')[0]
         V1max, t = vme['V_m'], vme['times']
         print "I1max spike times:", nest.GetStatus(sd, 'events')[0]['times']

         plt.plot(t, V1min, label="I_e = {:.3f} pA".format(I1min));
         plt.plot(t, V1max, label="I_e = {:.3f} pA".format(I1max));
         plt.legend(loc='best');
```

```
I1min spike times: [ 50.]
I1max spike times: [ 24.2  50.4]
```

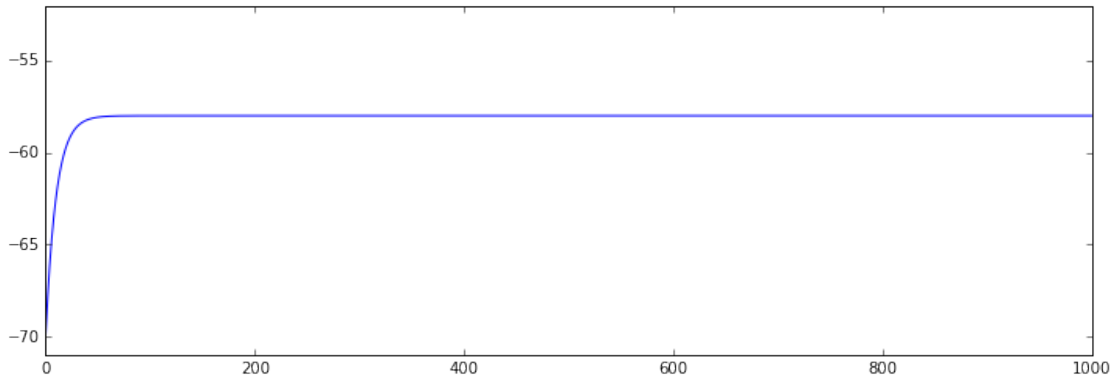


1.1.2 Exploration 2

```
In [18]: vm, sd = build_network(400.)
         nest.Simulate(1000)
         vme = nest.GetStatus(vm, 'events')[0]
         V, t = vme['V_m'], vme['times']
         t_spikes = nest.GetStatus(sd, 'events')[0]['times']
         plt.plot(t, V);
         plt.plot(t_spikes, -54. * np.ones_like(t_spikes), 'o');
         plt.ylim(-71, -52);
```



In [19]:
```
vm, sd = build_network(300.)
nest.Simulate(1000)
vme = nest.GetStatus(vm, 'events')[0]
V, t = vme['V_m'], vme['times']
t_spikes = nest.GetStatus(sd, 'events')[0]['times']
plt.plot(t, V);
plt.plot(t_spikes, -54. * np.ones_like(t_spikes), 'o');
plt.ylim(-71, -52);
```

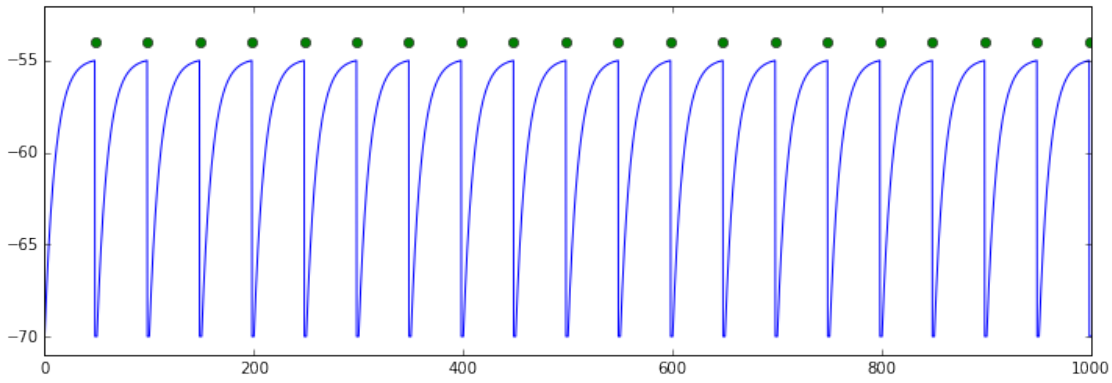


In [20]:
```
a, b = 300., 400.
n_sp = 0
n_sp_wanted = 20

while n_sp != n_sp_wanted:
    I_e_opt = ( a + b ) / 2

    vm, sd = build_network(I_e_opt)
    nest.Simulate(1000)
    n_sp = len(nest.GetStatus(sd, 'events')[0]['times'])

    print I_e_opt, n_sp
```

```
            if n_sp < n_sp_wanted:
                a = I_e_opt
            else:
                b = I_e_opt
```

```
350.0 0
375.0 0
387.5 27
381.25 23
378.125 20
```

```
In [21]: vm, sd = build_network(I_e_opt)
         nest.Simulate(1000)
         vme = nest.GetStatus(vm, 'events')[0]
         V, t = vme['V_m'], vme['times']
         t_spikes = nest.GetStatus(sd, 'events')[0]['times']
         plt.plot(t, V);
         plt.plot(t_spikes, -54. * np.ones_like(t_spikes), 'o');
         plt.ylim(-71, -52);
```



1.1.3 Exploration 3

```
In [22]: vm, sd = build_network(375.05)
         nest.Simulate(1000)
         t_spikes = nest.GetStatus(sd, 'events')[0]['times']
         isi = np.diff(t_spikes)
         print isi.min(), isi.mean(), isi.max(), isi.max()-isi.min()
```

```
91.3 91.3 91.3 1.13686837722e-13
```

```
In [23]: vm, sd = build_network(800.)
         nest.Simulate(1000)
         t_spikes = nest.GetStatus(sd, 'events')[0]['times']
         isi = np.diff(t_spikes)
         print isi.min(), isi.mean(), isi.max(), isi.max()-isi.min()
```

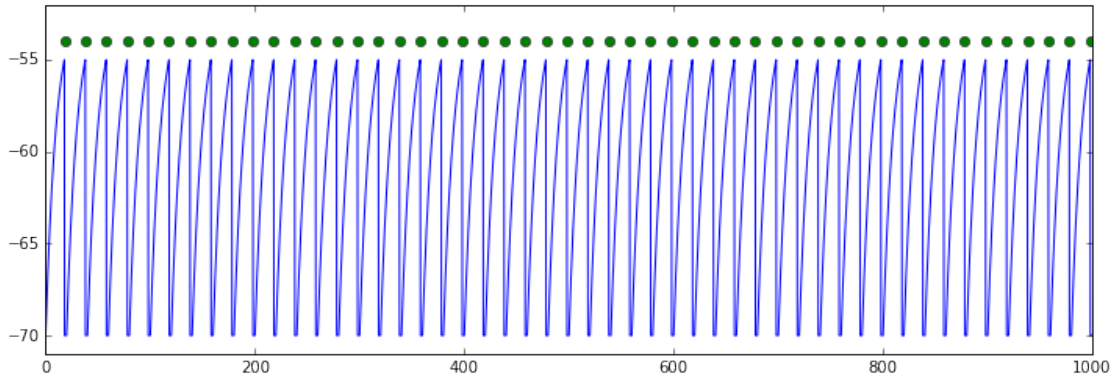
```
8.4 8.4 8.4 1.70530256582e-13
```

```
In [24]: a, b = 375.05, 800.
         isi_wanted = 20.
```

```
        while True:

            I_opt_isi = ( a + b ) / 2

            vm, sd = build_network(I_opt_isi)
            nest.Simulate(1000)
            mean_isi = np.diff(nest.GetStatus(sd, 'events')[0]['times']).mean()

            print I_opt_isi, mean_isi

            if mean_isi == isi_wanted:
                break

            if mean_isi < isi_wanted:
                b = I_opt_isi
            else:
                a = I_opt_isi
```

```
587.525 12.2
481.2875 17.2
428.16875 22.9
454.728125 19.5
441.4484375 21.0
448.08828125 20.2
451.408203125 19.8
449.748242188 20.0
```

```
In [25]: vm, sd = build_network(I_opt_isi)
         nest.Simulate(1000)
         vme = nest.GetStatus(vm, 'events')[0]
         V, t = vme['V_m'], vme['times']
         t_spikes = nest.GetStatus(sd, 'events')[0]['times']
         plt.plot(t, V);
         plt.plot(t_spikes, -54. * np.ones_like(t_spikes), 'o');
         plt.ylim(-71, -52);
```

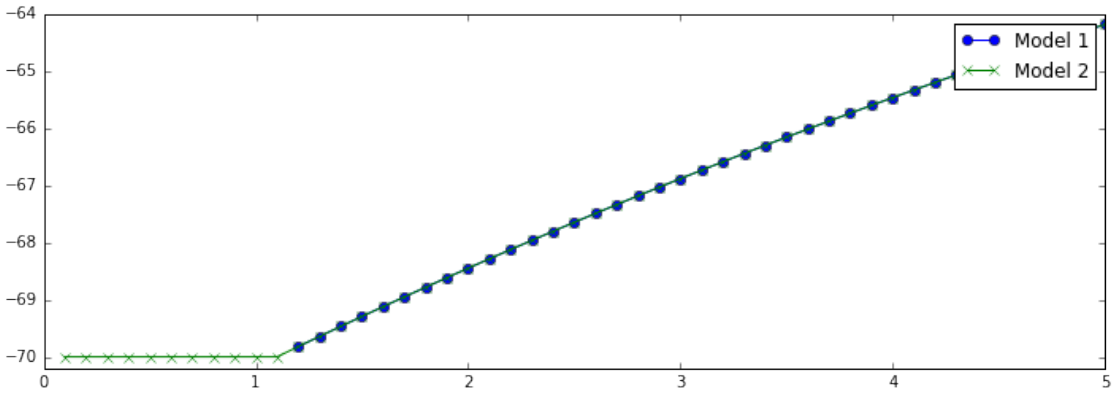


1.2 Task 2

```
In [26]: def build_network2(Ie, mu, sigma, my_seed):
             nest.ResetKernel()
             nest.SetKernelStatus({'grng_seed': my_seed, 'rng_seeds': [my_seed + 1]})

             n = nest.Create('iaf_psc_delta', params={'I_e': Ie})
             vm = nest.Create('voltmeter', params={'interval': 0.1})
             sd = nest.Create('spike_detector')
             ng = nest.Create('noise_generator', params={'mean': mu, 'std': sigma})

             nest.Connect(vm, n)
             nest.Connect(n, sd)
             nest.Connect(ng, n)

             return vm, sd
```

1.2.1 Validation

```
In [27]: vm1, _ = build_network(I_opt_isi)
         nest.Simulate(200.)
         vme1 = nest.GetStatus(vm1, 'events')[0]
         t1, v1 = vme1['times'], vme1['V_m']

         vm2, _ = build_network2(0., I_opt_isi, 0., 1234)
         nest.Simulate(200.)
         vme2 = nest.GetStatus(vm2, 'events')[0]
         t2, v2 = vme2['times'], vme2['V_m']

         plt.plot(t1 + 1.1, v1, 'o-', label='Model 1')
         plt.plot(t2, v2, 'x-', label='Model 2')
         plt.legend()
         plt.xlim(0, 5);
         plt.ylim(-70.2, -64.);
```



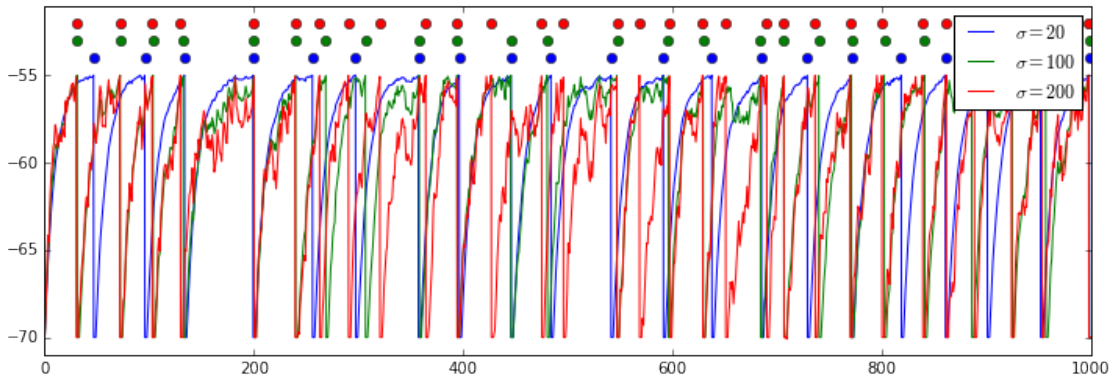

```
In [28]: dv = v1[:-11] - v2[11:]
         print dv.min(), dv.max()
```

```
0.0 0.0
```

1.2.2 Exploration 1

```
In [29]: vm, sd = build_network2(I_e_opt, 0., 20., 1234)
         nest.Simulate(1000.)
         vme = nest.GetStatus(vm, 'events')[0]
         t, v_20 = vme['times'], vme['V_m']
         t_sp_20 = nest.GetStatus(sd, 'events')[0]['times']

         vm, sd = build_network2(I_e_opt, 0., 100., 1234)
         nest.Simulate(1000.)
         vme = nest.GetStatus(vm, 'events')[0]
         t, v_100 = vme['times'], vme['V_m']
         t_sp_100 = nest.GetStatus(sd, 'events')[0]['times']

         vm, sd = build_network2(I_e_opt, 0., 200., 1234)
         nest.Simulate(1000.)
         vme = nest.GetStatus(vm, 'events')[0]
         t, v_200 = vme['times'], vme['V_m']
         t_sp_200 = nest.GetStatus(sd, 'events')[0]['times']
```

```
In [30]: plt.plot(t, v_20, label=r'$\sigma = 20$')
         plt.plot(t, v_100, label=r'$\sigma = 100$')
         plt.plot(t, v_200, label=r'$\sigma = 200$')

         plt.plot(t_sp_20, -54 * np.ones_like(t_sp_20), 'bo')
         plt.plot(t_sp_100, -53 * np.ones_like(t_sp_100), 'go')
         plt.plot(t_sp_200, -52 * np.ones_like(t_sp_200), 'ro')

         plt.ylim(-71, -51)
         plt.legend();
```

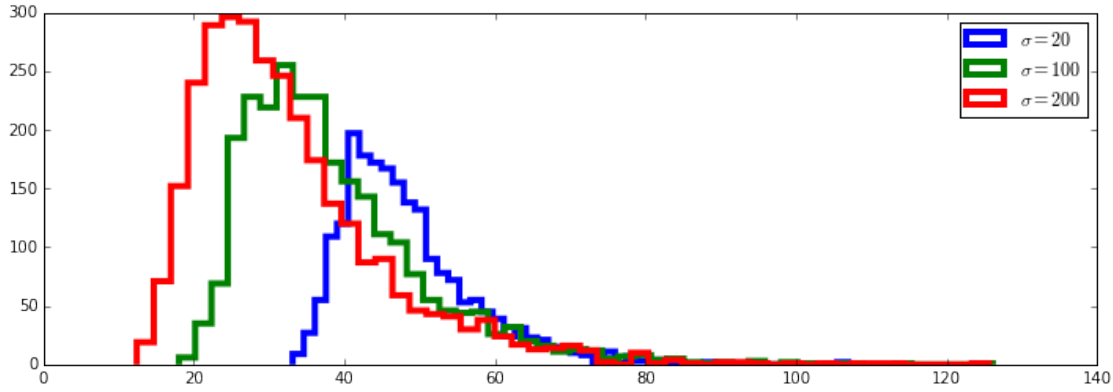


1.2.3 Exploration 2

```
In [31]: vm, sd = build_network2(I_e_opt, 0., 20., 1234)
         nest.Simulate(100000.)
         vme = nest.GetStatus(vm, 'events')[0]
         t, v_20 = vme['times'], vme['V_m']
         t_sp_20 = nest.GetStatus(sd, 'events')[0]['times']
```

```
vm, sd = build_network2(I_e_opt, 0., 100., 1234)
nest.Simulate(100000.)
vme = nest.GetStatus(vm, 'events')[0]
t, v_100 = vme['times'], vme['V_m']
t_sp_100 = nest.GetStatus(sd, 'events')[0]['times']

vm, sd = build_network2(I_e_opt, 0., 200., 1234)
nest.Simulate(100000.)
vme = nest.GetStatus(vm, 'events')[0]
t, v_200 = vme['times'], vme['V_m']
t_sp_200 = nest.GetStatus(sd, 'events')[0]['times']
```

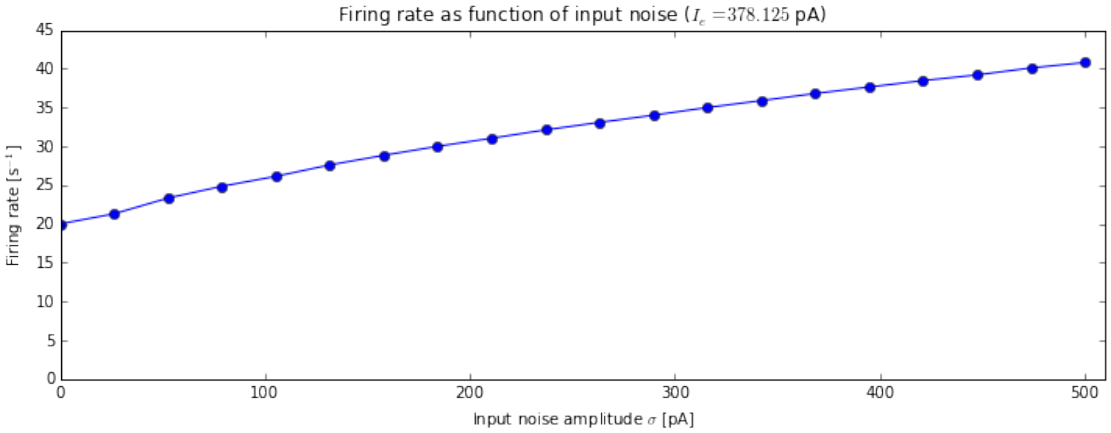
In [32]:
```
plt.hist(np.diff(t_sp_20), bins=50, histtype='step', alpha=1, lw=4, label=r'$\sigma = 20$');
plt.hist(np.diff(t_sp_100), bins=50, histtype='step', alpha=1, lw=4, label=r'$\sigma = 100$');
plt.hist(np.diff(t_sp_200), bins=50, histtype='step', alpha=1, lw=4, label=r'$\sigma = 200$');
plt.legend();
```



1.2.4 Exploration 3

In [33]:
```
sigma = np.linspace(0, 500, 20)
rate = np.nan * np.zeros_like(sigma)
t_sim = 100000.

for idx, sig in enumerate(sigma):
    _, sd = build_network2(I_e_opt, 0., sig, 1234)
    nest.Simulate(t_sim)
    rate[idx] = nest.GetStatus(sd, 'n_events')[0] / t_sim * 1000.
```

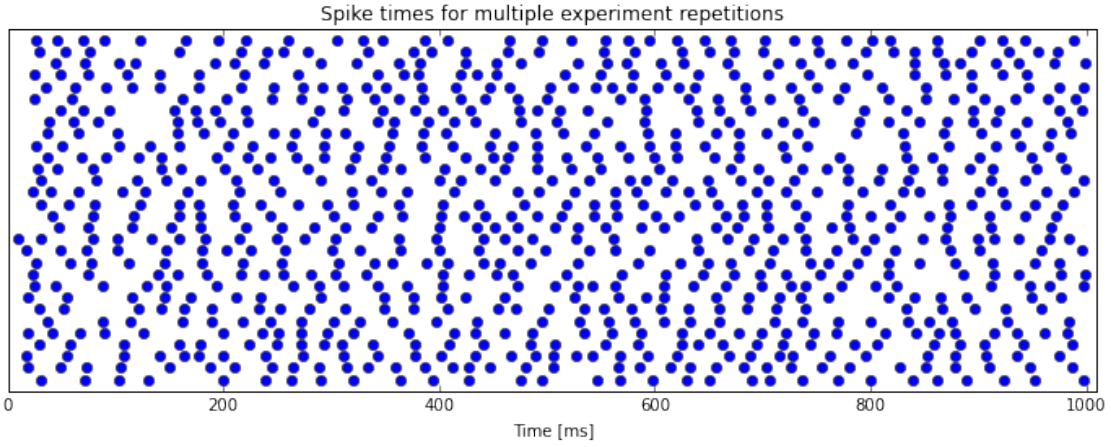
In [34]:
```
plt.plot(sigma, rate, 'o-')
plt.xlim(0, 510)
plt.ylim(0, 45)
plt.xlabel(r'Input noise amplitude $\sigma$ [pA]')
plt.ylabel(r'Firing rate [s$^{-1}$]')
plt.title('Firing rate as function of input noise ($I_e = {:.3f}$ pA)'.format(I_e_opt));
```



1.2.5 Exploration 4

```
In [35]: sigma = 200.
         t_sim = 1000.
         t_spikes = []

         for idx in range(30):
             _, sd = build_network2(I_e_opt, 0., sigma, 1234 + 10 * idx)
             nest.Simulate(t_sim)
             t_spikes.append(nest.GetStatus(sd, 'events')[0]['times'])
```

```
In [36]: for idx, t_sp in enumerate(t_spikes):
             plt.plot(t_sp, idx * np.ones_like(t_sp), 'bo')
         plt.xlim(0, 1010)
         plt.ylim(-1, 30)
         plt.yticks([])
         plt.xlabel('Time [ms]')
         plt.title('Spike times for multiple experiment repetitions');
```

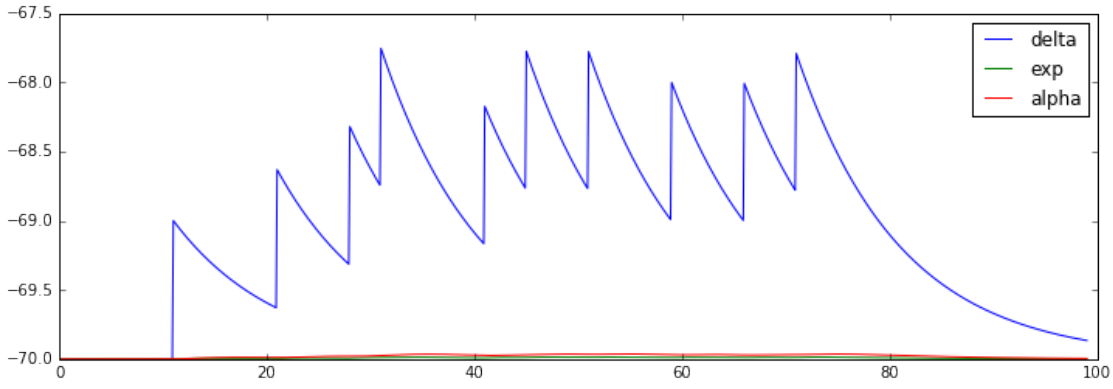


1.3 Task 3

```
In [37]: def build_network3(ts, wd, we, wa, dd=1., de=1., da=1.):
             nest.ResetKernel()

             d = nest.Create('iaf_psc_delta')
             e = nest.Create('iaf_psc_exp')
             a = nest.Create('iaf_psc_alpha')
             nrns = d + e + a
             vms = nest.Create('voltmeter', n=3, params={'interval': 0.1})
             sds = nest.Create('spike_detector', n=3)
             sg = nest.Create('spike_generator', params={'spike_times': ts})

             nest.Connect(vms, nrns, 'one_to_one')
             nest.Connect(nrns, sds, 'one_to_one')
             nest.Connect(sg, d, syn_spec={'weight': wd, 'delay': dd})
             nest.Connect(sg, e, syn_spec={'weight': we, 'delay': de})
             nest.Connect(sg, a, syn_spec={'weight': wa, 'delay': da})

             return vms, sds

In [38]: ts = [10., 20., 27., 30., 40., 44., 50., 58., 65., 70.]
```

1.3.1 Exploration 1

```
In [39]: vms, _ = build_network3(ts, 1., 1., 1.)
         nest.Simulate(100)

         vm_stat = nest.GetStatus(vms, 'events')
         t_Vm = vm_stat[0]['times']
         Vm_delta, Vm_exp, Vm_alpha = vm_stat[0]['V_m'], vm_stat[1]['V_m'], vm_stat[2]['V_m']

         plt.plot(t_Vm, Vm_delta, label='delta')
         plt.plot(t_Vm, Vm_exp, label='exp')
         plt.plot(t_Vm, Vm_alpha, label='alpha')
         plt.legend();
```

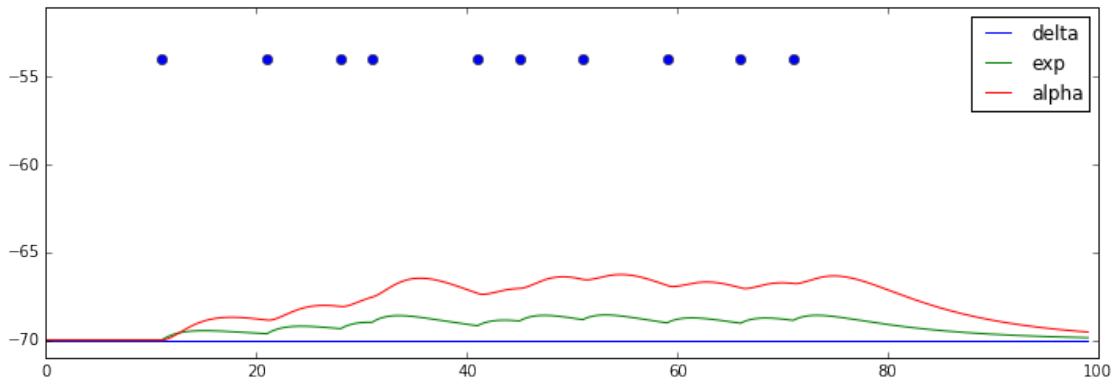


1.3.2 Exploration 2

```
In [40]: def task_3_2(ts, wd, we, wa, dd=1., de=1., da=1.):
             vms, sds = build_network3(ts, wd, we, wa, dd, de, da)
             nest.Simulate(100)

             vm_stat = nest.GetStatus(vms, 'events')
             t_Vm = vm_stat[0]['times']
             Vm_delta, Vm_exp, Vm_alpha = vm_stat[0]['V_m'], vm_stat[1]['V_m'], vm_stat[2]['V_m']
             sd_stat = nest.GetStatus(sds, 'events')
             sp_delta, sp_exp, sp_alpha = sd_stat[0]['times'], sd_stat[1]['times'], sd_stat[2]['times']

             print """
             Delta: {} spikes {}
             Exp  : {} spikes {}
             Alpha: {} spikes {}
             """.format(len(sp_delta), sp_delta, len(sp_exp), sp_exp, len(sp_alpha), sp_alpha)

             plt.plot(t_Vm, Vm_delta, label='delta')
             plt.plot(t_Vm, Vm_exp, label='exp')
             plt.plot(t_Vm, Vm_alpha, label='alpha')
             plt.plot(sp_delta, -54 * np.ones_like(sp_delta), 'bo')
             plt.plot(sp_exp, -53 * np.ones_like(sp_exp), 'go')
             plt.plot(sp_alpha, -52 * np.ones_like(sp_alpha), 'ro')
             plt.ylim(-71, -51)
             plt.legend();
```

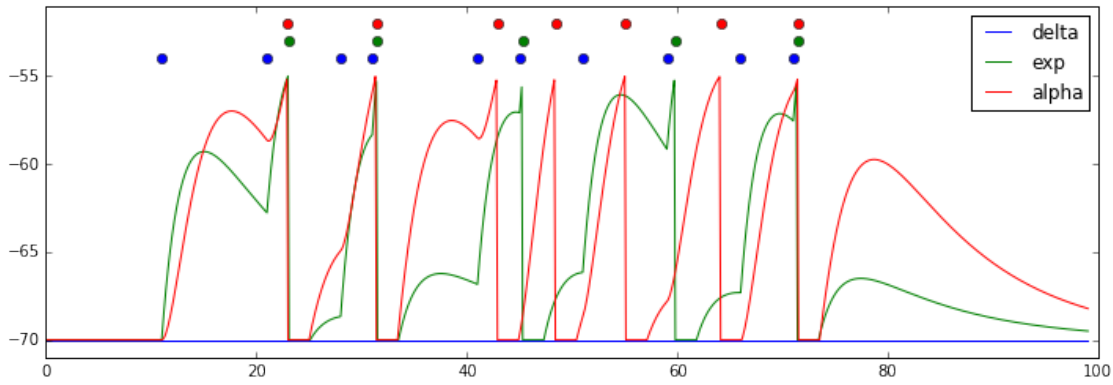
```
In [41]: task_3_2(ts, 15., 100., 100.)
```

```
Delta: 10 spikes [ 11.  21.  28.  31.  41.  45.  51.  59.  66.  71.]
    Exp  : 0 spikes []
    Alpha: 0 spikes []
```



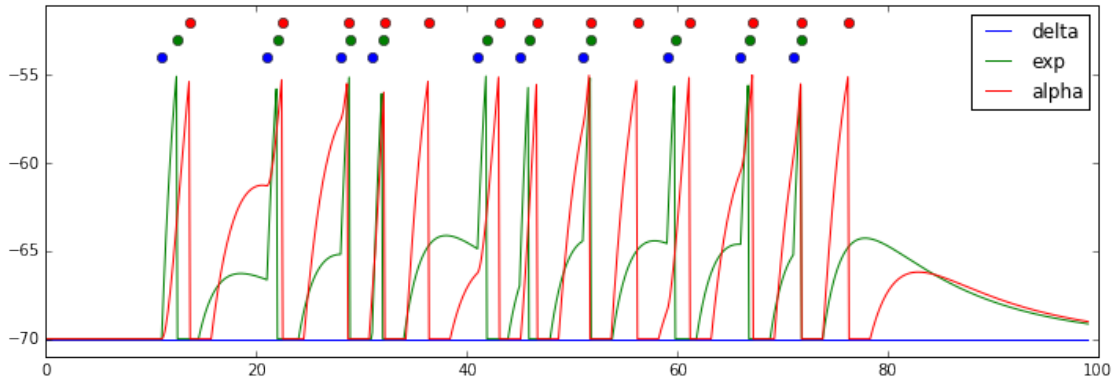

```
In [42]: task_3_2(ts, 15., 2000., 1000.)
```

```
Delta: 10 spikes [ 11.  21.  28.  31.  41.  45.  51.  59.  66.  71.]
    Exp  : 5 spikes [ 23.1  31.5  45.3  59.8  71.4]
    Alpha: 7 spikes [ 23.   31.4  42.9  48.4  55.1  64.1  71.5]
```



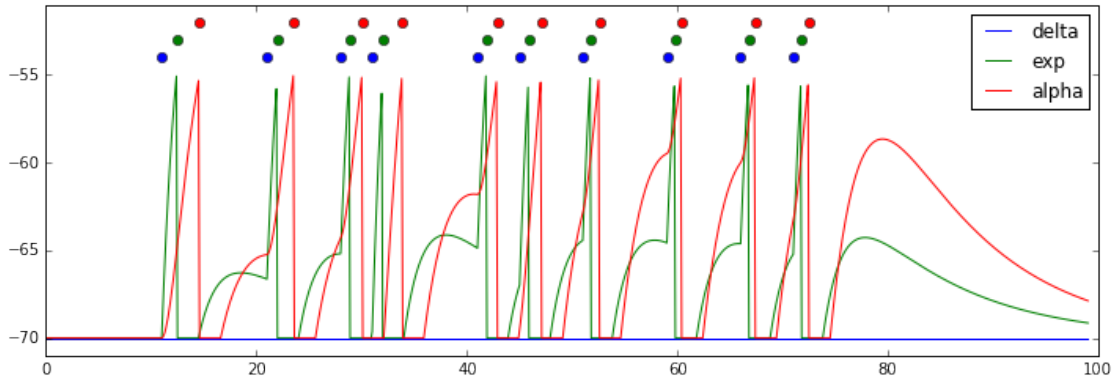
In [43]: task_3_2(ts, wd=15., we=4000., wa=2000.)

```
Delta: 10 spikes [ 11.  21.  28.  31.  41.  45.  51.  59.  66.  71.]
    Exp  : 10 spikes [ 12.5  22.   28.9  32.   41.9  45.9  51.8  59.8  66.8  71.8]
    Alpha: 13 spikes [ 13.7  22.5  28.7  32.2  36.4  43.1  46.7  51.7  56.2  61.2  67.2  71.8
  76.3]
```



In [44]: task_3_2(ts, 15., 4000., 1500.)

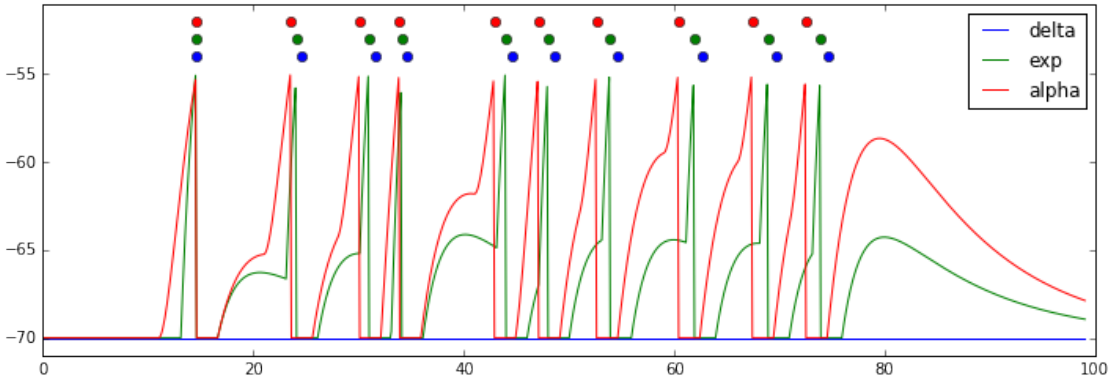
```
Delta: 10 spikes [ 11.  21.  28.  31.  41.  45.  51.  59.  66.  71.]
    Exp  : 10 spikes [ 12.5  22.   28.9  32.   41.9  45.9  51.8  59.8  66.8  71.8]
    Alpha: 10 spikes [ 14.6  23.6  30.1  33.9  42.9  47.1  52.6  60.4  67.4  72.5]
```



1.3.3 Challenge

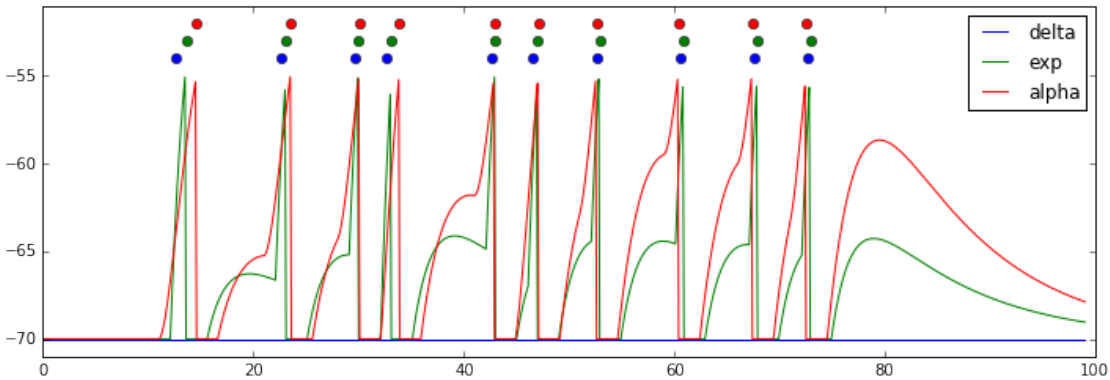
```
In [45]: task_3_2(ts, 15., 4000., 1500., 4.6, 3.1, 1.)
```

```
Delta: 10 spikes [ 14.6  24.6  31.6  34.6  44.6  48.6  54.6  62.6  69.6  74.6]
    Exp  : 10 spikes [ 14.6  24.1  31.   34.1  44.   48.   53.9  61.9  68.9  73.9]
    Alpha: 10 spikes [ 14.6  23.6  30.1  33.9  42.9  47.1  52.6  60.4  67.4  72.5]
```



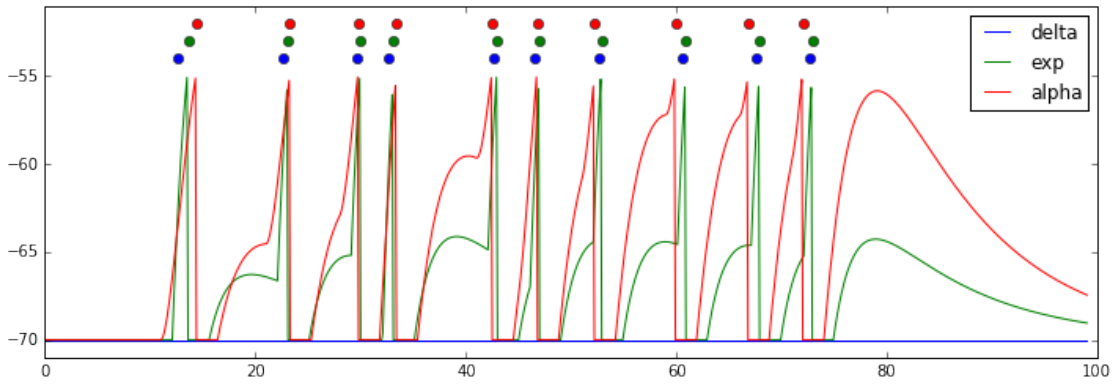

```
In [46]: task_3_2(ts, 15., 4000., 1500., 2.6, 2.1, 1.)
```

```
Delta: 10 spikes [ 12.6  22.6  29.6  32.6  42.6  46.6  52.6  60.6  67.6  72.6]
    Exp  : 10 spikes [ 13.6  23.1  30.   33.1  43.   47.   52.9  60.9  67.9  72.9]
    Alpha: 10 spikes [ 14.6  23.6  30.1  33.9  42.9  47.1  52.6  60.4  67.4  72.5]
```



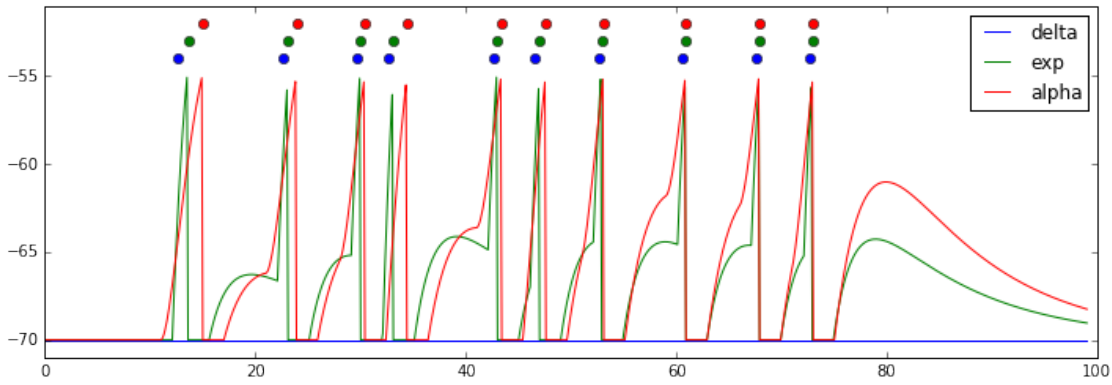

```
In [47]: task_3_2(ts, 15., 4000., 1600., 2.6, 2.1, 1.)
```

```
Delta: 10 spikes [ 12.6  22.6  29.6  32.6  42.6  46.6  52.6  60.6  67.6  72.6]
    Exp  : 10 spikes [ 13.6  23.1  30.   33.1  43.   47.   52.9  60.9  67.9  72.9]
    Alpha: 10 spikes [ 14.4  23.3  29.8  33.4  42.5  46.8  52.2  59.9  66.8  72. ]
```



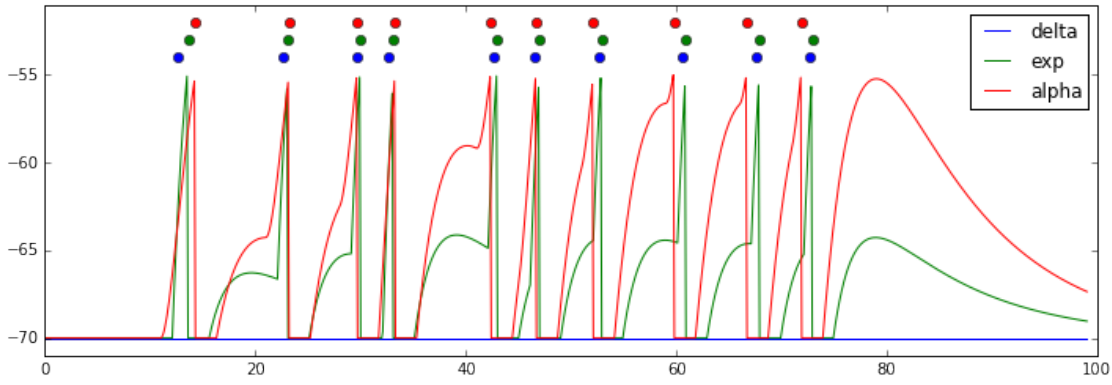
In [48]: task_3_2(ts, 15., 4000., 1400., 2.6, 2.1, 1.)

```
Delta: 10 spikes [ 12.6  22.6  29.6  32.6  42.6  46.6  52.6  60.6  67.6  72.6]
    Exp  : 10 spikes [ 13.6  23.1  30.   33.1  43.   47.   52.9  60.9  67.9  72.9]
    Alpha: 10 spikes [ 15.   23.9  30.4  34.4  43.4  47.6  53.1  60.9  67.9  73. ]
```



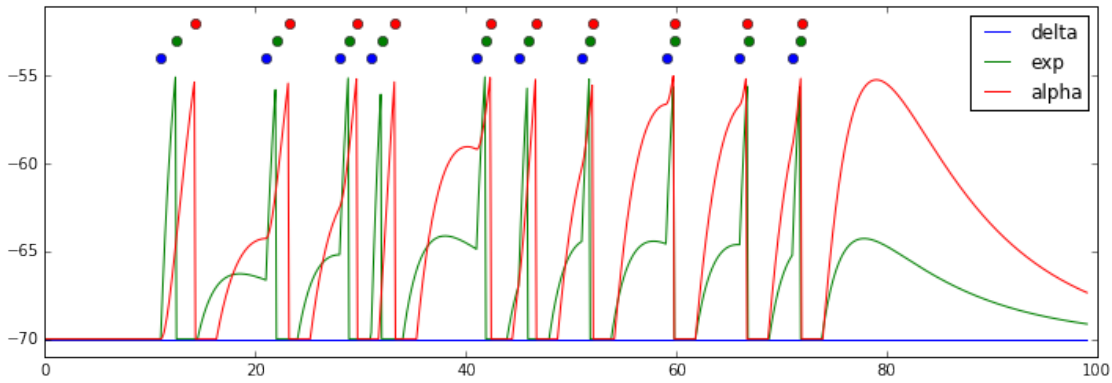
In [49]: task_3_2(ts, 15., 4000., 1620., 2.6, 2.1, 1.)

```
Delta: 10 spikes [ 12.6  22.6  29.6  32.6  42.6  46.6  52.6  60.6  67.6  72.6]
    Exp  : 10 spikes [ 13.6  23.1  30.   33.1  43.   47.   52.9  60.9  67.9  72.9]
    Alpha: 10 spikes [ 14.3  23.2  29.7  33.3  42.4  46.7  52.1  59.8  66.7  71.9]
```



```
In [50]: task_3_2(ts, 15., 4000., 1620., 1., 1., 1.)
```

```
Delta: 10 spikes [ 11.  21.  28.  31.  41.  45.  51.  59.  66.  71.]
    Exp  : 10 spikes [ 12.5  22.   28.9  32.   41.9  45.9  51.8  59.8  66.8  71.8]
    Alpha: 10 spikes [ 14.3  23.2  29.7  33.3  42.4  46.7  52.1  59.8  66.7  71.9]
```



1.4 Task 4

```
In [51]: def build_network4(rE, rI, wEd, wEe, wEa, wId, wIe, wIa):
             nest.ResetKernel()

             d = nest.Create('iaf_psc_delta')
             e = nest.Create('iaf_psc_exp')
             a = nest.Create('iaf_psc_alpha')
             nrns = d + e + a

             pgE = nest.Create('poisson_generator', params={'rate': rE})
             pgI = nest.Create('poisson_generator', params={'rate': rI})

             pnE = nest.Create('parrot_neuron')
             pnI = nest.Create('parrot_neuron')

             nest.Connect(pgE, pnE)
             nest.Connect(pgI, pnI)

             nest.Connect(pnE, d, syn_spec={'weight': wEd})
             nest.Connect(pnI, d, syn_spec={'weight': wId})
             nest.Connect(pnE, e, syn_spec={'weight': wEe})
             nest.Connect(pnI, e, syn_spec={'weight': wIe})
             nest.Connect(pnE, a, syn_spec={'weight': wEa})
             nest.Connect(pnI, a, syn_spec={'weight': wIa})

             vms = nest.Create('voltmeter', n=3, params={'interval': 0.1})
             sds = nest.Create('spike_detector', n=3)

             nest.Connect(vms, nrns, 'one_to_one')
```

```
            nest.Connect(nrns, sds, 'one_to_one')

            return vms, sds
```

```
In [52]: def task_4_rate(tsim, rE, rI, wEd, wEe, wEa, wId, wIe, wIa):

            _, sds = build_network4(rE, rI, wEd, wEe, wEa, wId, wIe, wIa)
            nest.Simulate(tsim)

            rates = [nsp / tsim * 1000 for nsp in nest.GetStatus(sds, 'n_events')]
            print """
            Delta: {} 1/s
            Exp  : {} 1/s
            Alpha: {} 1/s
            """.format(rates[0], rates[1], rates[2])
```

1.4.1 Exploration 1

```
In [53]: task_4_rate(1000., 1000., 0., 100., 200., 200., 0., 0., 0.)
```

```
Delta: 334.0 1/s
    Exp  : 34.0 1/s
    Alpha: 146.0 1/s
```

```
In [54]: task_4_rate(1000., 1000., 0., 50., 400., 180., 0., 0., 0.)
```

```
Delta: 334.0 1/s
    Exp  : 105.0 1/s
    Alpha: 133.0 1/s
```

```
In [55]: task_4_rate(1000., 1000., 0., 10., 390., 150., 0., 0., 0.)
```

```
Delta: 245.0 1/s
    Exp  : 104.0 1/s
    Alpha: 109.0 1/s
```

```
In [56]: task_4_rate(1000., 1000., 0., 5., 350., 120., 0., 0., 0.)
```

```
Delta: 164.0 1/s
    Exp  : 92.0 1/s
    Alpha: 83.0 1/s
```

```
In [57]: task_4_rate(1000., 1000., 0., 2., 370., 140., 0., 0., 0.)
```

```
Delta: 64.0 1/s
    Exp  : 96.0 1/s
    Alpha: 101.0 1/s
```

```
In [58]: task_4_rate(1000., 1000., 0., 3., 380., 140., 0., 0., 0.)
```

```
Delta: 105.0 1/s
    Exp  : 100.0 1/s
    Alpha: 101.0 1/s
```

```
In [59]: task_4_rate(10000., 1000., 0., 2.8, 380., 135., 0., 0., 0.)
```

```
Delta: 103.5 1/s
    Exp  : 105.0 1/s
    Alpha: 102.4 1/s
```

```
In [60]: task_4_rate(10000., 1000., 0., 2.6, 375., 130., 0., 0., 0.)

Delta: 94.8 1/s
    Exp  : 103.5 1/s
    Alpha: 98.4 1/s

In [61]: task_4_rate(10000., 1000., 0., 2.7, 370., 132., 0., 0., 0.)

Delta: 99.0 1/s
    Exp  : 102.1 1/s
    Alpha: 100.0 1/s
```

1.4.2 Exploration 2

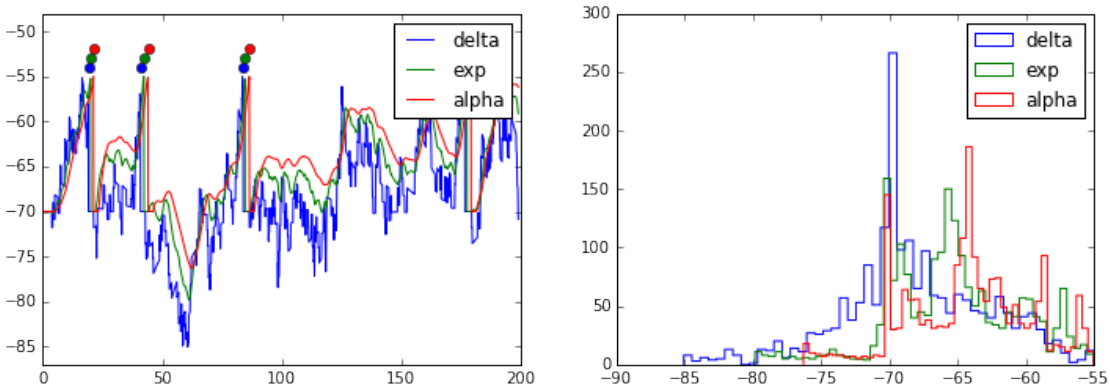
```
In [62]: task_4_rate(10000., 1000., 1000., 2.7, 370., 132., -1., -100., -50.)

Delta: 59.4 1/s
    Exp  : 65.4 1/s
    Alpha: 47.0 1/s

In [63]: task_4_rate(10000., 1000., 1000., 2.7, 370., 132., -2., -200., -60.)

Delta: 26.1 1/s
    Exp  : 33.7 1/s
    Alpha: 38.2 1/s

In [64]: task_4_rate(10000., 1000., 1000., 2.7, 370., 132., -1.8, -210., -65.)

Delta: 30.3 1/s
    Exp  : 31.3 1/s
    Alpha: 33.7 1/s

In [65]: task_4_rate(10000., 1000., 1000., 2.7, 370., 132., -1.8, -220., -70.)

Delta: 30.3 1/s
    Exp  : 28.3 1/s
    Alpha: 30.0 1/s

In [66]: task_4_rate(10000., 1000., 1000., 2.7, 370., 132., -1.8, -215., -70.)

Delta: 30.3 1/s
    Exp  : 29.7 1/s
    Alpha: 30.0 1/s
```

1.4.3 Exploration 3

```
In [67]: vms, sds = build_network4(1000., 1000., 2.7, 370., 132., -1.8, -215., -70.)
         nest.Simulate(200)

         vm_stat = nest.GetStatus(vms, 'events')
         t_Vm = vm_stat[0]['times']
         Vm_delta, Vm_exp, Vm_alpha = vm_stat[0]['V_m'], vm_stat[1]['V_m'], vm_stat[2]['V_m']
         sd_stat = nest.GetStatus(sds, 'events')
         sp_delta, sp_exp, sp_alpha = sd_stat[0]['times'], sd_stat[1]['times'], sd_stat[2]['times']

         print """
         Delta: {} spikes {}
```

```
Exp   : {} spikes {}
Alpha: {} spikes {}
""".format(len(sp_delta), sp_delta, len(sp_exp), sp_exp, len(sp_alpha), sp_alpha)

plt.subplot(121)
plt.plot(t_Vm, Vm_delta, label='delta')
plt.plot(t_Vm, Vm_exp, label='exp')
plt.plot(t_Vm, Vm_alpha, label='alpha')
plt.plot(sp_delta, -54 * np.ones_like(sp_delta), 'bo')
plt.plot(sp_exp, -53 * np.ones_like(sp_exp), 'go')
plt.plot(sp_alpha, -52 * np.ones_like(sp_alpha), 'ro')
plt.ylim(-87, -48)
plt.legend();

plt.subplot(122)
plt.hist(Vm_delta, bins=50, histtype='step', label='delta')
plt.hist(Vm_exp, bins=50, histtype='step', label='exp')
plt.hist(Vm_alpha, bins=50, histtype='step', label='alpha')
plt.legend();
```

```
Delta: 4 spikes [  19.1   40.9   83.9  176.7]
Exp   : 4 spikes [  20.1   42.4   84.7  177.6]
Alpha: 4 spikes [  21.3   44.1   86.5  179.3]
```

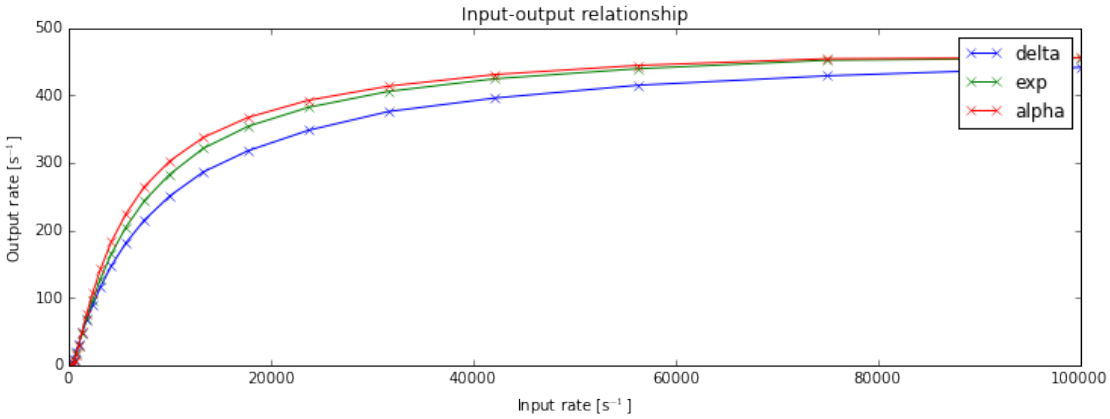


1.4.4 Exploration 4

```
In [68]: r_in = np.logspace(2, 5, num=25)
         r_d = np.nan * np.ones_like(r_in)
         r_e = np.nan * np.ones_like(r_in)
         r_a = np.nan * np.ones_like(r_in)

         t_sim = 10000.

         for idx, r in enumerate(r_in):
             _, sds = build_network4(r, r, 2.7, 370., 132., -1.8, -215., -70.)
             nest.Simulate(t_sim)

             n_d, n_e, n_a = nest.GetStatus(sds, 'n_events')
```

```
            r_d[idx] = n_d / t_sim * 1000.
            r_e[idx] = n_e / t_sim * 1000.
            r_a[idx] = n_a / t_sim * 1000.
```

In [69]:
```
plt.plot(r_in, r_d, 'x-', label='delta')
plt.plot(r_in, r_e, 'x-', label='exp')
plt.plot(r_in, r_a, 'x-', label='alpha')
plt.xlabel('Input rate [s$^{-1}$]')
plt.ylabel('Output rate [s$^{-1}$]')
plt.legend()
plt.title('Input-output relationship');
```



In [69]: