The Market Generator

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Restricted Boltzmann Machine (RBM)

The probability of configuration \((v, h)\) is given by Boltzmann (Gibbs) distribution:

\[
P(v, h) = \frac{1}{Z} e^{-E(v, h)} , \quad Z = \sum_{\{v, h\}} e^{-E(v, h)}
\]

where the energy of a configuration \((v, h)\) is given by expression:

\[
E(v, h) = \sum_{i=1}^{m} a_i v_i + \sum_{j=1}^{n} b_j h_j + \sum_{i=1}^{m} \sum_{j=1}^{n} w_{ij} v_i h_j
\]
Stochastic activation units

2. Hidden node $j$ firing probability

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$

3. Deciding whether node $j$ fires or not:

$$z \sim U[0,1]$$

IF $\sigma(x) \geq z$
THEN $h_j = 1$
ELSE $h_j = 0$

1. Aggregated input for the hidden node $j$

$$x = b_j + \sum_{i=1}^{m} w_{ij} v_i$$
Training algorithm for RBM

Marginal probability of visible state:

\[ P(v) = \frac{1}{Z} \sum_h e^{-E(v,h)} \]

Weight updates with stochastic gradient ascent (maximisation of the likelihood of the observed data):

\[ \Delta w_{ij} = \eta \frac{\partial \log(P(v))}{\partial w_{ij}} \]

The gradient has the form:

\[ \frac{\partial \log(P(v))}{\partial w_{ij}} = \langle v_i h_j \rangle_{\text{data}} - \langle v_i h_j \rangle_{\text{model}} \]

where \(\langle \ldots \rangle\) denotes expectations under the distribution specified by the subscript.
Algorithm 1 $k$-step contrastive divergence

Result: Weights and biases updates

Input: training minibatch $S$

Input: model parameters $a_i, b_j, w_{ij}, i = 1, \ldots, N, j = 1, \ldots, M$ (before update)

Initialization: $\forall i, j : \Delta w_{ij} = \Delta a_i = \Delta b_j = 0$

for $v \in S$ do

$v^{(0)} \leftarrow v$

for $t = 0, \ldots, k - 1$ do

for $j = 1, \ldots, M$ do

| sample Bernoulli random variable $h_j^{(t)} \sim p(h_j | v^{(t)})$

end

for $i = 1, \ldots, N$ do

| sample Bernoulli random variable $v_i^{(t+1)} \sim p(v_i | h_j^{(t)})$

end

end

for $i = 1, \ldots, N, j = 1, \ldots, M$ do

| $\Delta w_{ij} \leftarrow \Delta w_{ij} + \eta \left( p(h_j = 1 | v^{(0)}) v_i^{(0)} - p(h_j = 1 | v^{(k)}) v_i^{(k)} \right)$

end

for $i = 1, \ldots, N$ do

| $\Delta a_i \leftarrow \Delta a_i + \eta \left( v_i^{(0)} - v_i^{(k)} \right)$

end

for $j = 1, \ldots, M$ do

| $\Delta b_j \leftarrow \Delta b_j + \eta \left( p(h_j = 1 | v^{(0)}) - p(h_j = 1 | v^{(k)}) \right)$

end

end
Transformation of the real-valued datasets

Algorithm 2 Real-valued to integer to binary transformation (training phase)

Result: Conversion of real-valued data set into binary features

Input: $X_{real}(l) - a$ real-valued data set: $l = 1, \ldots, N_{samples}$, $n = 1, \ldots, N_{variables}$

for $n = 1, \ldots, N_{variables}$ do
  $X_{min}^{(n)} \leftarrow \min_{l}(X^{(n)}_{{real}}) - \epsilon_{min}^{(n)}$, $\epsilon_{min}^{(n)} \geq 0$
  $X_{max}^{(n)} \leftarrow \max_{l}(X^{(n)}_{{real}}) + \epsilon_{max}^{(n)}$, $\epsilon_{max}^{(n)} \geq 0$
  for $l = 1, \ldots, N_{samples}$ do
    $X_{integer}^{(n)}(l) \leftarrow \text{int}\left(65535 \times \frac{X^{(n)}_{{real}}(l) - X_{min}^{(n)}}{X_{max}^{(n)} - X_{min}^{(n)}}\right)$
    $X_{binary}^{(n)}(l) \leftarrow \text{binarize}\left(X_{integer}^{(n)}(l)\right)$
  end
end

Each data sample is represented by a 16-digit binary number ($2^{16} - 1 = 65535$) with every digit becoming a separate feature. The total number of features is $16 \times N_{variables}$.

Algorithm 3 Binary to integer to real-valued transformation (sampling phase)

Result: Conversion of the generated 16-digit binary sample into real-valued sample

Input: $\hat{X}^{(n)}[m] - generated$ 16-digit binary sample: $m = 0, \ldots, 15$, $n = 1, \ldots, N_{variables}$

for $n = 1, \ldots, N_{variables}$ do
  $\hat{X}_{integer}^{(n)} \leftarrow 0$
  for $m = 0, \ldots, 15$ do
    $\hat{X}_{integer}^{(n)} \leftarrow \hat{X}_{integer}^{(n)} + 2^m \times \hat{X}^{(n)}[15 - m]$
  end
  $\hat{X}^{(n)} \leftarrow X_{min}^{(n)} + \hat{X}_{integer}^{(n)} \times \left(X_{max}^{(n)} - X_{min}^{(n)}\right)$
end

Alexei Kondratyev and Christian Schwarz (2019)

The Market Generator

https://ssrn.com/abstract=3384948
Generation of synthetic market data

QQ-plots of USDJPY spot FX daily log-returns (dataset: 1999-2019)

Dataset vs. Normal
RBM-generated samples vs. Normal
RBM-generated samples vs. Dataset

Alexei Kondratyev and Christian Schwarz (2019)
The Market Generator
https://ssrn.com/abstract=3384948
## Generation of synthetic market data (continued)

### Reconstruction of correlations

<table>
<thead>
<tr>
<th>Currency pairs</th>
<th>Pearson</th>
<th>Spearman</th>
<th>Kendall</th>
<th>Pearson</th>
<th>Spearman</th>
<th>Kendall</th>
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</thead>
<tbody>
<tr>
<td>EURUSD/GBPUSD</td>
<td>63.7%</td>
<td>62.5%</td>
<td>45.3%</td>
<td>55.7%</td>
<td>59.1%</td>
<td>42.7%</td>
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<td>EURUSD/USDJPY</td>
<td>-28.2%</td>
<td>-31.2%</td>
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<td>-20.0%</td>
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<td>EURUSD/USDCAD</td>
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<td>-38.6%</td>
<td>-26.8%</td>
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<td>-25.7%</td>
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<td>GBPUSD/USDJPY</td>
<td>-13.5%</td>
<td>-21.2%</td>
<td>-14.7%</td>
<td>-15.5%</td>
<td>-21.2%</td>
<td>-14.6%</td>
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<td>GBPUSD/USDCAD</td>
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<td>-35.8%</td>
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<td>-23.7%</td>
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<tr>
<td>USDJPY/USDCAD</td>
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<td>7.4%</td>
<td>5.1%</td>
<td>5.6%</td>
<td>8.5%</td>
<td>5.8%</td>
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### Reconstruction of tail behaviour

<table>
<thead>
<tr>
<th>Currency pair</th>
<th>data set</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>1st percentile</td>
<td>99th percentile</td>
<td>1st percentile</td>
<td>99th percentile</td>
<td></td>
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<tr>
<td>EURUSD</td>
<td>-1.58%</td>
<td>1.53%</td>
<td>-1.65%</td>
<td>1.61%</td>
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<td>GBPUSD</td>
<td>-1.48%</td>
<td>1.34%</td>
<td>-1.55%</td>
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<tr>
<td>USDJPY</td>
<td>-1.73%</td>
<td>1.66%</td>
<td>-1.84%</td>
<td>1.78%</td>
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<tr>
<td>USDCAD</td>
<td>-1.42%</td>
<td>1.50%</td>
<td>-1.47%</td>
<td>1.55%</td>
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</table>

### Reconstruction of annualised volatilities

<table>
<thead>
<tr>
<th>Currency pair</th>
<th>Historical volatility</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>EURUSD</td>
<td>9.7%</td>
<td>9.8%</td>
</tr>
<tr>
<td>GBPUSD</td>
<td>9.4%</td>
<td>9.5%</td>
</tr>
<tr>
<td>USDJPY</td>
<td>10.2%</td>
<td>10.4%</td>
</tr>
<tr>
<td>USDCAD</td>
<td>8.9%</td>
<td>8.6%</td>
</tr>
</tbody>
</table>

Alexei Kondratyev and Christian Schwarz (2019)

*The Market Generator*

https://ssrn.com/abstract=3384948
RBM can be used to generate either fully independent or autocorrelated samples with desired degree of autocorrelation.

RBM-generated daily log-returns (EURUSD)

Alexei Kondratyev and Christian Schwarz (2019)
*The Market Generator*
https://ssrn.com/abstract=3384948
RBM is able to handle non-stationarity through conditional sampling.

### Conditional sampling

<table>
<thead>
<tr>
<th>Currency pair</th>
<th>Low volatility environment</th>
<th>High volatility environment</th>
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<tbody>
<tr>
<td></td>
<td>Historical volatility</td>
<td>Historical volatility</td>
</tr>
<tr>
<td></td>
<td>RBM-generated samples</td>
<td>RBM-generated samples</td>
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<tr>
<td>EURUSD</td>
<td>6.8%</td>
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<tr>
<td></td>
<td>6.7% (±0.2%)</td>
<td>10.8% (±0.5%)</td>
</tr>
<tr>
<td>GBPUSD</td>
<td>6.9%</td>
<td>13.1%</td>
</tr>
<tr>
<td></td>
<td>6.8% (±0.3%)</td>
<td>13.7% (±0.7%)</td>
</tr>
<tr>
<td>USDJPY</td>
<td>8.0%</td>
<td>12.8%</td>
</tr>
<tr>
<td></td>
<td>8.9% (±0.3%)</td>
<td>12.7% (±0.6%)</td>
</tr>
<tr>
<td>USDCAD</td>
<td>6.2%</td>
<td>13.0%</td>
</tr>
<tr>
<td></td>
<td>6.4% (±0.2%)</td>
<td>11.6% (±0.7%)</td>
</tr>
</tbody>
</table>
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