The Market Generator

Alexei Kondratyev
Managing Director, Global Head of Data Analytics, CCIB
Standard Chartered Bank

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Here for good
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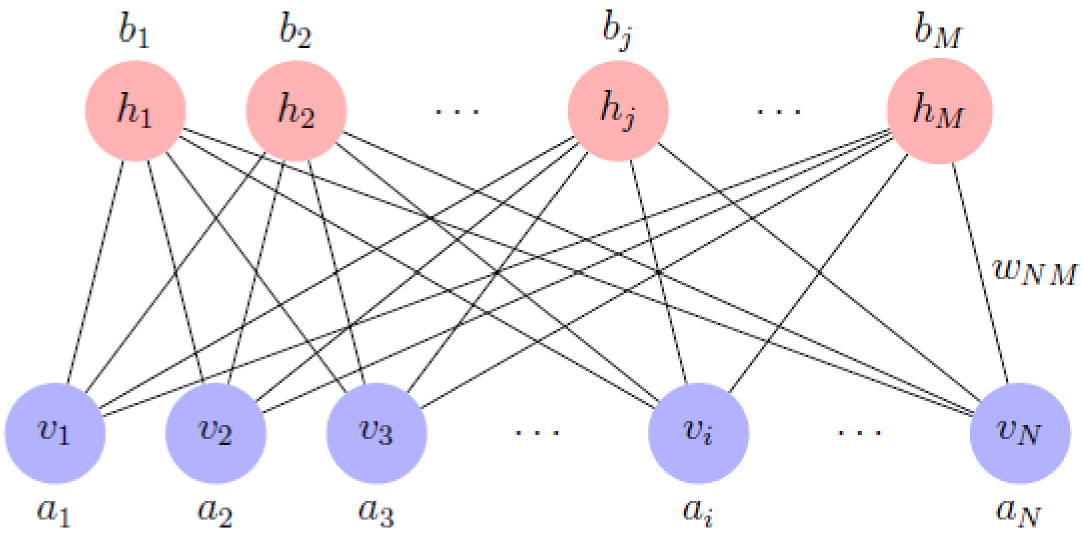
Restricted Boltzmann Machine (RBM)

Hidden layer stochastic binary units

Hidden layer biases



Weights

Visible layer stochastic binary units

Visible layer biases

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:

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

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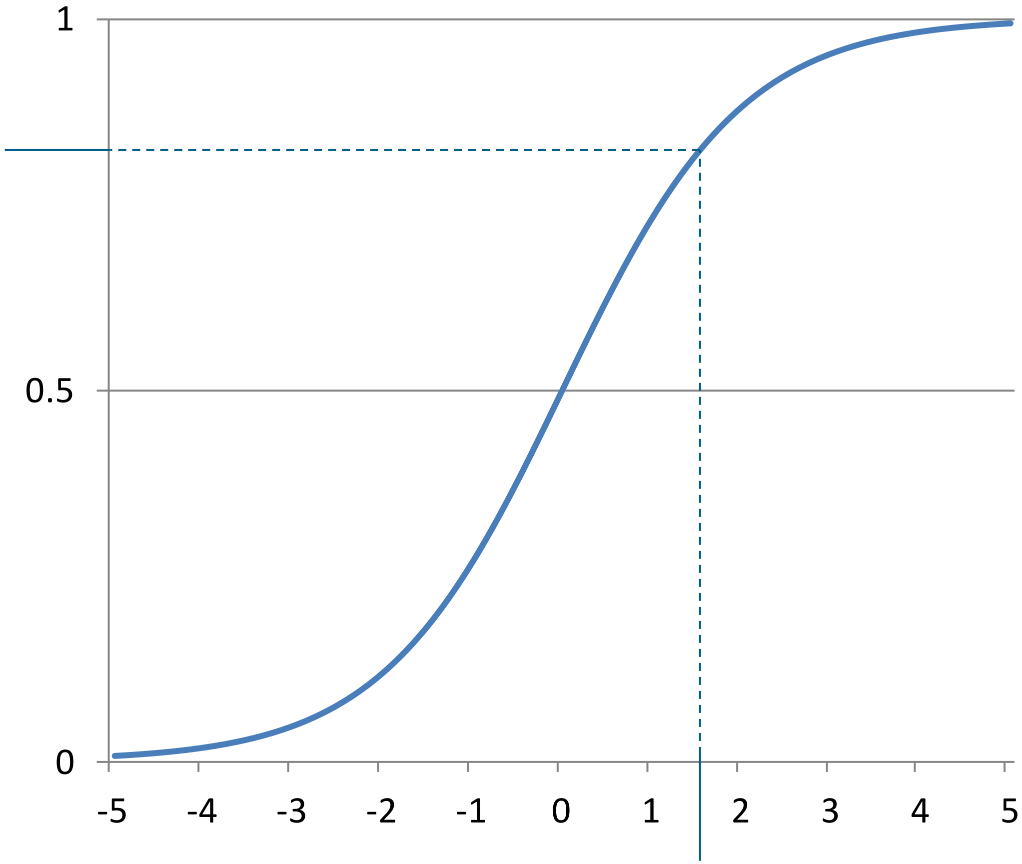
Stochastic activation units

2 Hidden node j firing probability

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



3 Deciding whether node j fires or not:

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

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

1 Aggregated input for the hidden node j

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

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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.

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Contrastive Divergence Algorithm

Algorithm 1 k-step contrastive divergence

Result: Weights and biases updates
Input: training minibatch S
Input: model parameters $a_i, b_j, w_{ij},\ i = 1, \dots, N,\ j = 1, \dots, M$ (before update)
Initialization: $\forall i, j : \Delta w_{ij} = \Delta a_i = \Delta b_j = 0$

```
for v ∈ S do
    v^(0) ← v
    for t = 0, ..., k − 1 do
        for j = 1, ..., M do
            sample Bernoulli random variable h_j^(t) ~ p(h_j | v^(t))
        end
        for i = 1, ..., N do
            sample Bernoulli random variable v_i^(t+1) ~ p(v_i | h^(t))
        end
    end
    for i = 1, ..., N, j = 1, ..., M do
        Δw_ij ← Δw_ij + η (p(h_j = 1 | v^(0)) v_i^(0) − p(h_j = 1 | v^(k)) v_i^(k))
    end
    for i = 1, ..., N do
        Δa_i ← Δa_i + η (v_i^(0) − v_i^(k))
    end
    for j = 1, ..., M do
        Δb_j ← Δb_j + η (p(h_j = 1 | v^(0)) − p(h_j = 1 | v^(k)))
    end
end
```

Asja Fischer and
Christian Igel (2014)
Training Restricted Boltzmann Machines: An Introduction
Pattern Recognition, Volume 47

Geoffrey Hinton (2010)
A Practical Guide to Training Restricted Boltzmann Machines
Department of Computer Science
University of Toronto
UTML TR 2010-003
https://www.cs.toronto.edu/~hinton/absps/guideTR.pdf

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

for $n = 1, \ldots, N_{variables}$ **do**

$X_{min}^{(n)} \leftarrow \min_{\{l\}}(X_{real}^{(n)}) - \epsilon_{min}^{(n)}, \quad \epsilon_{min}^{(n)} \geq 0$

$X_{max}^{(n)} \leftarrow \max_{\{l\}}(X_{real}^{(n)}) + \epsilon_{max}^{(n)}, \quad \epsilon_{max}^{(n)} \geq 0$

for $l = 1, \ldots, N_{samples}$ **do**

$X_{integer}^{(n)}(l) \leftarrow \text{int}\left(65535 \times \left(X_{real}^{(n)}(l) - X_{min}^{(n)}\right) / \left(X_{max}^{(n)} - X_{min}^{(n)}\right)\right)$

$X_{binary}^{(n)}(l) \leftarrow \text{binarize}\left(X_{integer}^{(n)}(l)\right)$

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

$\hat{X}_{real}^{(n)} \leftarrow X_{min}^{(n)} + \hat{X}_{integer}^{(n)} \times \left(X_{max}^{(n)} - X_{min}^{(n)}\right)$

end

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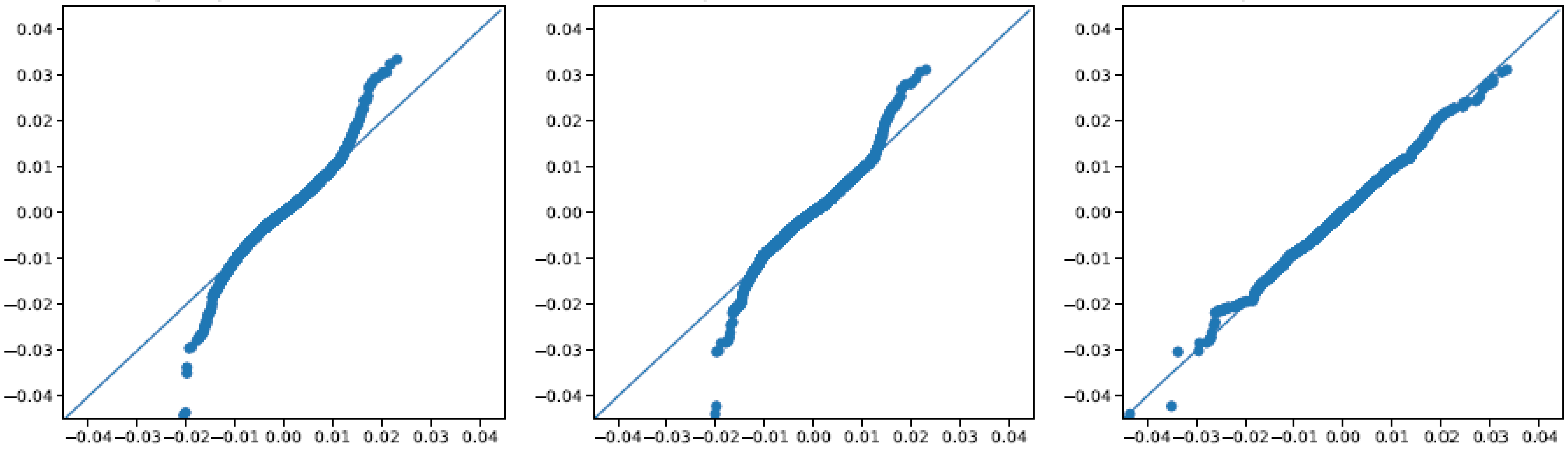
https://ssrn.com/abstract=3384948

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



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Generation of synthetic market data (continued)

Reconstruction of correlations

Currency pairs	data set Pearson	data set Spearman	data set Kendall	RBM-generated samples Pearson	RBM-generated samples Spearman	RBM-generated samples Kendall
EURUSD/GBPUSD	63.7%	62.5%	45.3%	55.7% (±4.4%)	59.1% (±2.2%)	42.7% (±1.8%)
EURUSD/USDJPY	−28.2%	−31.2%	−21.8%	−26.0% (±2.5%)	−28.7% (±1.4%)	−20.0% (±1.0%)
EURUSD/USDCAD	−44.3%	−38.6%	−26.8%	−40.1% (±3.8%)	−37.1% (±1.8%)	−25.7% (±1.3%)
GBPUSD/USDJPY	−13.5%	−21.2%	−14.7%	−15.5% (±5.4%)	−21.2% (±0.9%)	−14.6% (±0.7%)
GBPUSD/USDCAD	−43.1%	−35.8%	−24.8%	−38.5% (±3.2%)	−34.3% (±2.4%)	−23.7% (±1.7%)
USDJPY/USDCAD	3.0%	7.4%	5.1%	5.6% (±2.5%)	8.5% (±1.5%)	5.8% (±1.0%)

Reconstruction of tail behaviour

Currency pair	data set 1st percentile	data set 99th percentile	RBM-generated samples 1st percentile	RBM-generated samples 99th percentile
EURUSD	−1.58%	1.53%	−1.65% (±0.05%)	1.61% (±0.05%)
GBPUSD	−1.48%	1.34%	−1.55% (±0.04%)	1.53% (±0.10%)
USDJPY	−1.73%	1.66%	−1.84% (±0.07%)	1.78% (±0.07%)
USDCAD	−1.42%	1.50%	−1.47% (±0.04%)	1.55% (±0.06%)

Reconstruction of annualised volatilities

Currency pair	Historical volatility	RBM-generated samples
EURUSD	9.7%	9.8% (±0.7%)
GBPUSD	9.4%	9.5% (±0.7%)
USDJPY	10.2%	10.4% (±0.4%)
USDCAD	8.9%	8.6% (±0.8%)

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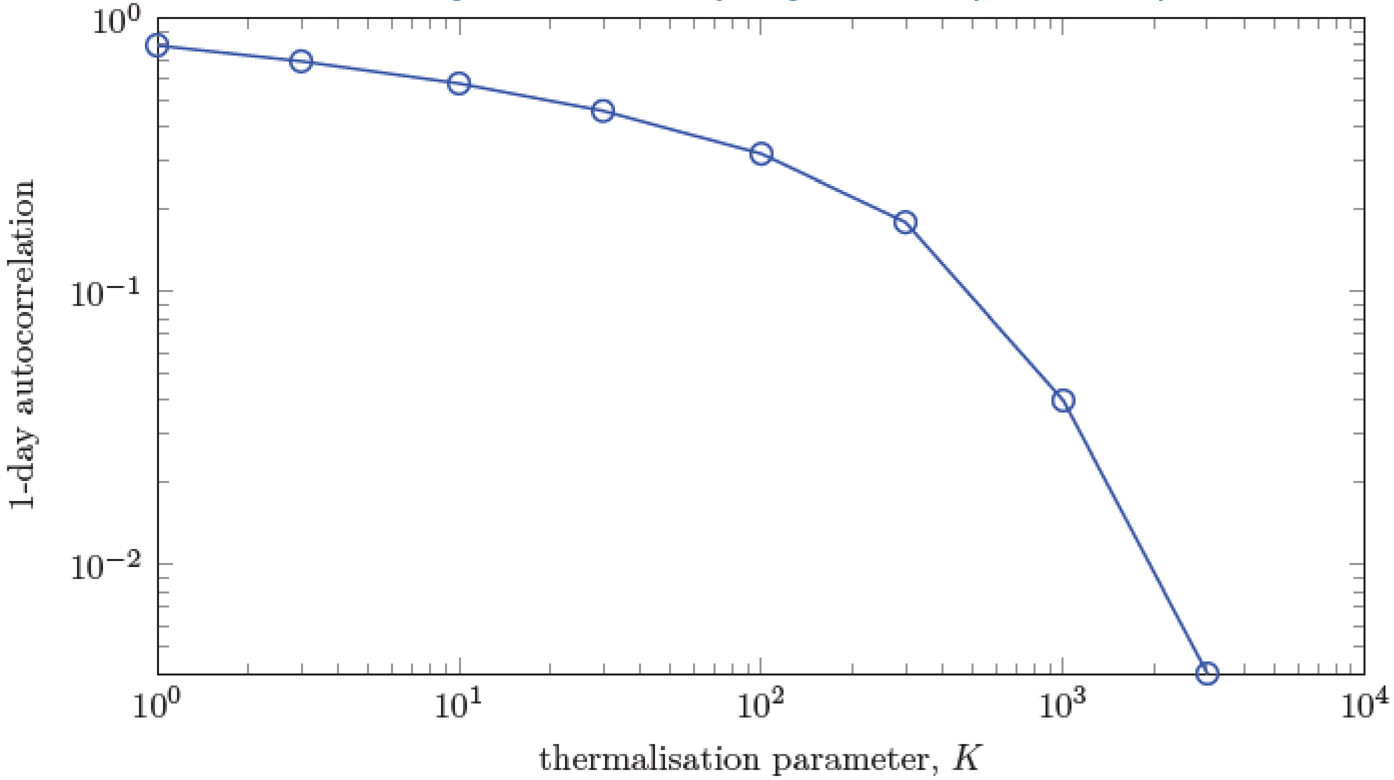
Generation of synthetic market data (continued)

RBM can be used to generate either fully independent or autocorrelated samples with desired degree of autocorrelation.

RBM-generated daily log-returns (EURUSD)



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Generation of synthetic market data (continued)

RBM is able to handle non-stationarity through conditional sampling.

Conditional sampling

Currency pair	Low volatility environment		High volatility environment	
	Historical volatility	RBM-generated samples	Historical volatility	RBM-generated samples
EURUSD	6.8%	6.7% (±0.2%)	12.2%	10.8% (±0.5%)
GBPUSD	6.9%	6.8% (±0.3%)	13.1%	13.7% (±0.7%)
USDJPY	8.0%	8.9% (±0.3%)	12.8%	12.7% (±0.6%)
USDCAD	6.2%	6.4% (±0.2%)	13.0%	11.6% (±0.7%)

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