Answering the Queen: Machine Learning and Financial Crises

Jérémy Fouliard, Michael Howell, Hélène Rey

Banque de France

December 20, 2019
Visiting the LSE and being shown how terrible the situation was and had been, the Queen asked: “Why did nobody notice it?”
The Queen got a terse answer. The economic and finance profession have a bad record at predicting crises.
Motivation

- The Queen got a terse answer. The economic and finance profession have a bad record at predicting crises.
- After several months, the Economic Section of the British Academy wrote a three-page missive to Her Majesty blaming the lack of foresight of the crisis on the ”failure of the collective imagination of many bright people”.

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This paper aims at predicting systemic crises well in advance (12 quarters ahead) using cutting-edge machine learning tools.
Short Literature Review


- **Machine Learning**: Davis and Karim [2008], Duttagupta and Cashin [2012], Ward [2014], Joy et al. [2017], Alessi and Detken [2018].
Short Literature Review

- **Theory of Financial Crises**: Booms go bust (credit growth) [Kindleberger (1978), Shularick and Taylor (2012), Reinhart and Rogoff (2008), Coimbra and Rey (2018); Household debt, Mian and Sufi (2018); behavioural explanations, Bordalo Gennaioli Shleifer (2019) (bubbles in asset prices); excessive risk taking (leverage, moral hazard) Allen and Gale, Rajan; search for yield (Stein); real shock amplified by a capital constraint (real economy; macro finance Gertler Kiyotaki, Brunnermeier Sannikov, Krishnamurthy He); balance of payment (real exchange rate, capital flows); concentrated exposures of banking system (real estate, oil), ...

Many different variables, non linear interactions, time varying effects.
New Framework: Online learning: NOT BIG DATA but MODEL AGGREGATION

This framework is very suitable for crisis prediction in real time:

- **Multivariate**: Which variables cause a financial crisis?
- **Time-varying weights**: Causes of financial crises may be different over time.
- **Statistically robust**: overfitting is a problem in the literature.
- **Not ”black-box”**: assess the role each model plays to predict the pre-crisis.
- **Theoretically grounded**: asymptotic properties of our aggregation rules ensure convergence.

- More general than Bayesian Model Averaging
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- **Theoretically grounded**: asymptotic properties of our aggregation rules ensure convergence.

- **More general than Bayesian Model Averaging**
- This framework has been used to predict French electricity load (EDF); the tracking of climate models; the network traffic demand.
Online learning is performed in a sequence of consecutive rounds where at time instance \( t \) the forecaster:

1. Receives a question.
2. Uses expert advice \( \{f_{j,t} \in D : j \in \mathcal{E}\} \)
3. Predicts \( \hat{y}_t \in \mathcal{Y} \)
4. Receives true answer \( y_t \in \mathcal{Y} \)
5. Suffers a loss \( \ell(\hat{y}_t, y_t) \).
To combine experts’ advice, the forecaster chooses a sequential aggregation rule $S$ which consists in setting a time-varying weight vector $(p_{1,t}, \ldots, p_{N,t}) \in \mathcal{P}$:

$$\hat{y}_t = \sum_{j=0}^{N} p_{j,t} f_{j,t}$$

The forecaster and each expert incur a cumulative loss defined by:

$$L_T(S) = \sum_{t=1}^{T} \ell(\sum_{j=0}^{N} p_{j,t} f_{j,t}) = \sum_{t=1}^{T} (\hat{y}_t - y_t)^2$$
How can we measure the performance of a sequential aggregation rule?
Sequential prediction with expert advice

- How can we measure the performance of a sequential aggregation rule?

- We do not have any ideas about the generating process of the observations.

- Forecaster’s performance is relative. We define the regret:

\[
R_{j,T} = \sum_{t=1}^{T} (\ell(\hat{y}_t, y_t) - \ell(f_{j,t}, y_t)) = \hat{L}_T - L_{j,T}
\]

where \( \hat{L}_T = \sum_{t=1}^{T} \ell(\hat{y}_t, y_t) \) denotes the forecaster’s cumulative loss and \( L_{j,T} = \sum_{t=1}^{T} \ell(f_{j,t}, y_t) \) is the cumulative loss of expert \( j \).
We **minimize the regret** with respect to the best combination of experts:

\[ R(S) = \hat{L}_T(S) - \inf_{q \in \mathcal{P}} L_T(q) \]

We only select aggregation rules with a ”vanishing per-round regret” (regret goes to zero asymptotically).

The Regret can be bounded (bound depends on $T$, on the learning rate and on $\log(\text{number of experts})$).
Sequential prediction with expert advice

This approach is a **meta-statistic approach**: the aim is to find the best sequential combination of experts (who can be any economic models or judgement).

\[
\hat{L}_T(S) = \inf_{q \in \mathcal{P}} L_T(q) + R(S)
\]

Forecaster’s cumulative loss is the sum of:

- **An approximation error**: given by the cumulative loss of the best combination of experts.

- **An estimation error**: given by the regret. It measures the difficulty to approach the best combination of experts.

The rule of the game is to minimize the regret and to find the best experts.
We adapt the approach to incorporate delayed feedback. We take into account the fact that we only know whether we are in a pre-crisis period after 12 quarters.

Experts at $t$ are estimated on the batch sample using information available at $t-1$.

Aggregation rules at $t$ use only $t-12$ information.
We used four aggregation rules:

1. The Exponentially weighted average aggregation rule (EWA) [Littlestone and Warmuth, 1994; Vovk, 1990].

2. The Multiple learning rates aggregation rule (ML) [Gaillard, Erven and Stoltz, 2014].

3. The Online Gradient Descent aggregation rule (OGD) [Zinkevich, 2003].

4. The Ridge Regression aggregation rule (Ridge) [Azoury and Warmuth, 2001; Vovk, 2001].
Convex aggregation rules combining experts’ predictions with a time-varying vector $p_t = (p_{1,t}, \ldots, p_{N,t})$ in a simplex $\mathcal{P}$ of $\mathbb{R}^N$:

$$\forall j \in \{1, \ldots, N\}, p_{j,t} \geq 0 \text{ et } \sum_{k=1}^{N} p_{k,t} = 1$$

- We use the gradient-based version of the EWA aggregation rule.
- The weights are computable in a simple incremental way.
- Easy to interpret.
Weights are defined by:

\[ p_{j,t} = \frac{\exp(-\eta_t \sum_{s=1}^{t-1} \tilde{L}_{j,s})}{\sum_{k=1}^{N} \exp(-\eta_t \sum_{s=1}^{t-1} \tilde{L}_{k,s})} \]

where \( \tilde{L}_{j,s} = \nabla \ell(\sum_{k=1}^{N} p_{k,s} f_{k,s}, y_s) \cdot f_{j,s} \) and where \( \eta_t \) is the learning rate.

If j’s advice \( f_{j,s} \) points in the direction of the largest increase of the loss function (large inner products \( \nabla \ell(\sum_{k=1}^{N} p_{k,s} f_{k,s}, y_s) \cdot f_{j,s} \) in the past) the weight assigned to expert \( j \) will be small.
The EWA Aggregation rule

Theorem

Theorem 1 [Cesa-Bianchi and Lugosi, 2003]

We assume that

- Functions $L(\cdot, y)$ are differentiable.
The EWA Aggregation rule

Theorem

**Theorem 1** [Cesa-Bianchi and Lugosi, 2003]

We assume that

- Functions $L(\cdot, y)$ are differentiable.
- The losses $L_{j,t}$ are bounded.

Therefore, for all learning rate $\eta_t > 0$,

$$\sup \{ R_T(\mathcal{E}_{\eta}^{grad}) \} \leq \frac{\ln(N)}{\eta_t} + \eta_t \frac{T}{2}$$
The bound depends on three parameters:

- The number of experts $N$.
- The number of time instances $T$.
- The learning rate $\eta_t$. 
For the gradient-based EWA aggregation rule, the forecaster chooses the parameter $\eta_t$ with the best past performance:

$$\eta_t \in \arg\min_{\eta > 0} \hat{L}_{t-1}(\mathcal{E}_\eta)$$

To find the value of $\eta_t$ which minimizes the cumulative loss, at each time instance, we minimize the cumulative loss on a grid.
The ECB provides an official database of systemic crisis episodes [Lo Duca et al., 2017q] and additional smaller crises. Judgement of national authorities is involved.

Our sample starts in 1985q1 (depending on data availability) and ends in 2018q1.

Our sample includes 7 countries: France, Germany, Italy, Spain, Sweden, UK, US.

Today, we focus on France, the UK, Germany and Spain. We predict systemic pre-crises.
Data of crisis episodes: off-the-shelf

The ECB data uses a characteristic function $C_{n,t}$:

$$
C_{n,t} = \begin{cases} 
1 & \text{If there is a systemic crisis in country } n \text{ at time } t \\
0 & \text{Otherwise}
\end{cases}
$$

Let’s define the pre-crisis indicator $I_{n,t}$:

$$
I_{n,t} = \begin{cases} 
1 & \text{if } \exists h \in H = [0, 12] \text{ such that } C_{n,t+h} = 1 \\
0 & \text{otherwise}
\end{cases}
$$
Variables

Our database contains commonly used Early Warning Indicators with transformations (1-y, 2-y, 3-y change and gap-to-trend). It could be enriched. They are not vintage data.

- **Real economy indicators**: Current account, Consumer Price Index, GDP, productivity, Unemployment rate, real exchange rate.

- **Credit indicators**: Bank (or Total) credit to financial and non financial sector, M3, Household debt, Debt Service Ratios, bank equity.

- **Interest rates indicators**: 3-month rate, 10 years rate, slope of the yield curve (10y-3m), gap of 10-y rate to real GDP.

- **Housing indicators**: Residential real estate prices, Price-to-income ratio, Price-to-rent ratio.

- **Market indicators: Risk taking**: Real effective exchange rate, Stock prices, Financial Conditions Index, Risk Appetite Index, Cross-border flows, Total Liquidity Index.
Oecumenical Choice of Experts
Experts using country specific and all country panel information

We take as given the models used by some European Central Banks to predict pre-crisis periods and summarized by the Macro-prudential Research Network:

- These models are Dynamic Probit Models, logit models at the country or at the whole panel level, bayesian model averaging models (country specific or on the whole sample)

We add different classes of experts:

- Logit with elastic-net penalty with 5 different sets of variables
- Classification tree models at the country and at the panel level
- Random forest models at the country and at the panel level

We end up with 22 experts combining country specific and panel information.
Experts 1

- **Expert P2**: Panel logit fixed effect, Panel 2. Variables selected with a country-specific PCA analysis in-sample.
- **Expert P3**: Panel logit fixed effect, Panel 3. Many credit variables and transforms of credit variables.
- **Expert P4**: Random Coefficient Logit, Panel 4. Share Price 1y change; Real GDP 1y change; Banking credit to private sector 1y change; Rent Price Index 1y change; Total Liquidity Index 1y change; Financial Condition Index 1y change.
- **Expert B1**: Bayesian Model Averaging, BMA 1 (panel). We pre-select indicators with a Panel Auroc analysis on the batch sample.
Experts 2

- **Expert T1**: Binary Classification Tree, (panel)
- **Expert T2**: Binary Classification Tree, (country-specific)
- **Expert F1**: Random Forests, (panel)
- **Expert F2**: Random Forests, (country-specific)
- **Expert B**: Logit regression, Bashful
  Best variables selected with a country-specific AUROC Analysis
- **Expert G**: Logit regression, Grumpy
  All variables available in 1987q3. We also introduce some logit
  with elastic-net penalty which are country-specific.
- **Expert Lh**: Logit with elastic-net penalty, Logit housing.
  Price-to-rent; Price to income; Price to rent 1y change; Price to
  income 1y change; Real estate price 1y change; Real estate price
  2y change.
**Experts 3**

- **Expert Lr**: Logit with elastic-net penalty, Logit real economy. GDP (1y 2 y change); GDP (Per capita per person per hour); Multifactor productivity; Oil price 1y 2 y change.

- **Expert Lcr**: Logit with elastic-net penalty, Logit credit Every credit variable with every transformation (1y, 2y, 3y change and gap to trend)

- **Expert Lba**: Logit with elastic-net penalty, Logit risk taking Risk Appetite; Financial Condition Index; Share price Index; Equity holding; Liquid Assets with two transformations: 1y change and 2y change.

- **Expert Lm**: Logit with elastic-net penalty, Logit monetary. M3; Short term interest rate (nominal); Short term interest rate (real); Consumer prices.

- **Expert Lc**: Logit with elastic-net penalty, Logit CrossBorder Capital (Risk appetite; financial condition index; total liquidity index (including capital flows); share price index).
- **Expert Lc1**: Logit with elastic-net penalty, Logit Combination 1 Housing + Real Economy
- **Expert Lc2**: Logit with elastic-net penalty, Logit Combination 2 Credit + Risk taking
- **Expert Lc3**: Logit with elastic-net penalty, Logit Combination 3 Monetary + risk taking
Figure 1: Predicted probability - EWA
Forecasting the pre-crisis period out-of-sample

Figure 2: Predicted probability - ML
Figure 3: Predicted probability - OGD
Forecasting the pre-crisis period out-of-sample

Figure 4: Predicted probability - Ridge
Figure 5: Weights - EWA
Figure 6: Weights - EWA
France: Sequence of Experts

- Period [1987Q3-2000Q1]: estimation in-sample. Winners are models with many variables. Probably overfitting.

- Period [2000Q2-2003Q2]: out-of-sample with frozen weights (delayed feedback).

- Period [2003Q3-2017Q4]: out-of-sample with sequential weights adjustment.
France: Out-of-sample: Endogenous reweighting

Period [2000Q2-2005Q1]: Quiet period. Models dominating are the random forest $F_2$ and selastic net models models with monetary $Lm$, bubble variables $Lbu$, risk taking $Lba$.

Period [2005q2-2008q2]: pre systemic crisis. $B$ (Price-to-rent ratio; Price-to-income ratio; Unemployment ratio; Total Credit to non-financial corporations, % GDP; gap to trend; 1y change; Total Credit to private non-financial sector 1y change; Banking credit to private non-financial sector 1y change; GDP1y change; M3 1y change; Financial Conditions Index 2y change; 3y change; Total Liquidity Index 3y change; Bank equity.); $P_1$ (Total Credit to private non-financial sector 1y change, Total credit to non-financial firms 2y change, Real GDP 2y change, Rent Price Index 2y change); $Lc_1$ (housing; real economy).

Period [2008q3-2009q4]: systemic crisis: $B$; $P_1$; $Lc_1$ and $Lba$, $Lm$, $Lc_3$ (risk taking and monetary).
**France: Out-of-sample: Endogenous reweighting**

- **Period [2010q1-2010q4]:** pre euro-crisis. Models dominating are $P_1$, $L_{bu}$, $L_m$ (monetary), $L_{ba}$ (risk appetite, financial conditions, share price), $L_{c1}$ (housing; real economy), $L_{c3}$ (risk taking and monetary), $B_1$ (Consumer Prices, Short-term interest rates (nominal), Banking credit to private sector 1y change, Banking credit to private sector 2y change, Rent Price Index 2y change.).

- **Period [2010q4-2017q4]:** Models dominating are $L_{ba}$ (risk appetite, financial conditions, share price), $L_{c1}$ (housing; real economy), $L_{c3}$ (risk taking and monetary), $B_1$ (Consumer Prices, Short-term interest rates (nominal), Banking credit to private sector 1y change, Banking credit to private sector 2y change, Rent Price Index 2y change.), $L_m$ (monetary), $P_4$ (Share Price 1y change; Real GDP 1y change; Banking credit to private sector 1y change; Rent Price Index 1y change; Total Liquidity Index 1y change; Financial Condition Index 1y change).
Contributions to crisis prediction

- Spike in probability due to **P1** (Total Credit to private non-financial sector 1y change, Total credit to non-financial firms 2y change, Real GDP 2y change, Rent Price Index 2y change.); **Lc1** (housing; real economy) and **B** (Price-to-rent ratio; Price-to-income ratio; Unemployment ratio; Total Credit to non-financial corporations, % GDP; gap to trend; 1y change; Total Credit to private non-financial sector 1y change; Banking credit to private non-financial sector 1y change; GDP1y change; M3 1y change; Financial Conditions Index 2y change; 3y change; Total Liquidity Index 3y change; Bank equity.)

- Summary: For France, total and bank Credit to private non-financial sector, price to rent, financial conditions, unemployment, GDP are important variables to signal a crisis.
## Root Mean Square Errors

<table>
<thead>
<tr>
<th>Online aggregation Rule</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWA</td>
<td>0.23</td>
</tr>
<tr>
<td>ML</td>
<td>0.25</td>
</tr>
<tr>
<td>OGD</td>
<td>0.30</td>
</tr>
<tr>
<td>Ridge</td>
<td>0.23</td>
</tr>
<tr>
<td>Uniform</td>
<td>0.41</td>
</tr>
<tr>
<td>Best convex combination (ex post)</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**Table 1: RMSE France**
The ROC curve represents the ability of a binary classifier by plotting the true positive rate against the false positive rate for all thresholds.

The AUROC is the area under the ROC curve:

**Figure 7: ROC curve**
Figure 8: AUROC-EWA=0.95; ML=0.90; OGD=0.92; Ridge=0.98
**AUROC: France, out-of-sample**

**Figure 9:** AUROCs Ridge=0.98; Best fixed convex combination (ex post)=0.95; Uniform=0.59
Germany: pre-crisis period out-of-sample (different dates from France)
Germany: pre-crisis period out-of-sample

Figure 11: Predicted probability - ML
Germany: pre-crisis period out-of-sample

Figure 12: Predicted probability - OGD
Germany: pre-crisis period out-of-sample

Figure 13: Predicted probability - Ridge
Figure 14: Weights - EWA
Figure 15: Weights - EWA
Contributions to crisis prediction: Germany

- Spike in probability due to $\text{Lc3}$ (monetary and risk taking) and earlier $\text{Lm Lc Lba Lh}$. Strange spike in euro area crisis due to $\text{P1}$ (Share Price Indices, Rent Price Index 1y change, Total Credit to non-financial corporations 2y change, Equity Holdings.)

- Summary: For Germany, monetary and risk taking variables seem to be more important than for France to signal a crisis.
**AUROC: Germany, out-of-sample**

**Figure 16:** AUROCs $EWA = 0.92$; $ML = 0.95$; $OGD = 0.92$; $Ridge = 0.98$. Quasi-real time.
AUROC: Germany, out-of-sample

Figure 17: AUROCs Ridge=0.98; Best fixed convex combination (ex post)=0.86; Uniform=0.6
Spain: pre-crisis period out-of-sample

Figure 18: Predicted probability - EWA
Spain: pre-crisis period out-of-sample

Figure 19: Predicted probability - ML
Spain: pre-crisis period out-of-sample

Figure 20: Predicted probability - OGD
Spain: pre-crisis period out-of-sample

Figure 21: Predicted probability - Ridge
Figure 22: Weights - EWA
Figure 23: Weights - EWA
Contributions to crisis prediction: Spain

- Spike in probability due to $\text{Lc1}$ (housing; real economy) and $\text{Lc2}$ (credit and risk taking) and $\text{Lh}$ (housing); a bit of $\text{B1}$ Consumer Prices; Short-term interest rates (nominal); Banking credit to private sector 1y change; Total Credit to non-financial corporations 2y change; Total credit to non-financial sector – gap to trend; Consumer prices : 1y change and 3y change; M3 : 1y change and 2y change.

- Summary: Housing variables are really important to signal a crisis in Spain.
AUROC: Spain, out-of-sample

Figure 24: AUROC. EWA=0.93; ML=0.91; OGD= 0.86; Ridge=0.94. quasi-real time.
AUROC: Spain, out-of-sample

Figure 25: AUROC. Best convex (ex post) = 0.93; Uniform = 0.38; Ridge = 0.94. quasi-real time.
UK: pre-crisis period out-of-sample

Figure 26: Predicted probability - EWA
UK: pre-crisis period out-of-sample

Figure 27: Predicted probability - ML
UK: pre-crisis period out-of-sample

Figure 28: Predicted probability - OGD
Figure 29: Predicted probability - Ridge
Figure 30: Weights - EWA
Figure 31: Weights - EWA
Contributions to crisis prediction: UK

- Spike in probability due to $Lc1$ (housing; real economy). Thin spike at the end of the pre crisis period is due to $Lh$. 
Figure 32: AUROC. EWA=0.95; ML=0.93; OGD=0.89; Ridge=0.89. quasi-real time.
Figure 33: AUROC. Best convex (ex post) = 0.85; Uniform = 0.5; Ridge = 0.89. quasi-real time.
France: pre-crisis period real time

Figure 34: Predicted probability - EWA
France: pre-crisis period real time

Figure 35: Predicted probability - OGD
France: pre-crisis period real time

Figure 36: Predicted probability - Ridge
Conclusions

- This approach gives strong out-of-sample forecasting results to predict financial crises. Also gives interesting information on relevant variables. For France, it works also on vintage data (very stringent test as even for the batch sample we use vintage time series).

- We now work on the historical database as well (we predict the Great Depression out-of-sample). We can investigate which models are better for Great Depression versus Lehman Brothers.

- We can apply same framework to predicting recessions.

- We could improve data and improve experts.

- Open questions:
  - Using more microeconomic data from bank databases?
  - Causality?
  - How to test for the effect of macroprudential policies on crisis probabilities?
The ML aggregation rule

In the Multiple learning rates aggregation rule:
The ML aggregation rule

In the Multiple learning rates aggregation rule:

- Each expert has a specific online learning rate.
The ML aggregation rule

In the Multiple learning rates aggregation rule:

- Each expert has a specific online learning rate.
- The rest of the framework does not change.
The ML aggregation rule

Let's consider that every expert $j$ incurs a loss $\ell_{j,t} \in [0,1]$. As for the rest of the framework, the loss function is given by:

$$
\ell(\hat{y}_t) = \ell(N \sum_{j=0}^{p_{j,t}} f_{j,t}) = p_t \tilde{\ell}_t = N \sum_{j=1}^{p_k,t} \ell_{k,t}
$$

where $p_t = (p_{1,t}, ..., p_{N,t})$ and $\tilde{\ell}_t = (\ell_{1,t}, ..., \ell_{N,t})$. 

Jérémy Fouliard, Michael Howell, Hélène Rey (Banque de France)
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where $\mathbf{p}_t = (p_{1,t}, \ldots, p_{N,t})$ and $\tilde{\ell}_t = (\ell_{1,t}, \ldots, \ell_{N,t})$
The ML aggregation rule

We define the $\mathcal{M}_\eta^{grad}$ multiple learning rates aggregation rule strategy:

- Parameter: a vector $\eta = (\eta_1, \ldots, \eta_N)$ of learning rates.
- Initialization: a uniform vector $w_0$
- For each round $t = 1, 2, \ldots, T$
  - Form the mixture $p_t$ defined component-wise by $p_{j,t} = \eta_j w_{j,t} / \eta' w_{t-1}$
  - Observe the loss vector $\ell_t$ and incur loss $\ell_t' = p_t' \tilde{\ell}_t$.
  - For each expert $j$, perform the update $w_{j,t} = w_{j,t} - 1 / (1 + \eta_j (\ell_t - \ell_{j,t}))$. 

Jérémie Fouliard, Michael Howell, Hélène Rey (Banque de France)

EWS

December 20, 2019

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3. for each expert $j$ perform the update $w_{j,t} = w_{j,t-1}(1 + \eta_j(\ell_t - \ell_{j,t}))$
Multiple learning rates

Theorem

Theorem 3 [Gaillard, Stoltz Erven, 2014]

For all sequences of loss vectors $\ell_t \in [0, 1]^N$, the cumulative loss run with learning rates $\eta_k \leq \frac{1}{2}$ is bounded by

$$L_T(M \text{grad } \eta) = T \sum_{t=1}^{T} \ell_t \leq \min \sum_{j=1}^{N} \left( \sum_{t=1}^{T} \ell_{j,t} + \frac{1}{2} \eta_j \ln \left( \frac{1}{w_j,0} \right) + \eta_k \sum_{t=1}^{T} \left( \ell_t - \ell_{j,t} \right) \right)$$
Multiple learning rates

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For all sequences of loss vectors $\ell_t \in [0, 1]^N$, the cumulative loss run with learning rates $\eta_k \leq \frac{1}{2}$ is bounded by

$$L_T(M^{grad}_\eta) = \sum_{t=1}^{T} \ell_t \leq \min_{1 \leq j \leq N} \left\{ \sum_{t=1}^{T} \ell_{j,t} + \frac{1}{\eta_j} \ln\left(\frac{1}{w_{j,0}}\right) + \eta_k \sum_{t=1}^{T} (\ell_t - \ell_{j,t}) \right\}$$
The vector $\eta$ is theoretically calibrated.:

$$\eta_{j,t-1} = \frac{1}{1 + \sum_{s=1}^{t-1}(\ell - \ell_{j,s})^2}$$
Multiple learning rates

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- The loss function of the ML aggregation rule is bounded. Nevertheless, for the moment, the ML aggregation rule does not theoretically compete with the best convex combination of predictors.
Multiple learning rates

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Now we can relax the convex weights vector assumption. ⇒ Next
Aggregation rules

2 kinds of aggregation rule:

Follow-The-Leader: the forecaster chooses the convex weight vector $p_t$ to minimize the cumulative loss:

$$p_t = \arg\min_{p \in P} \hat{L}_{t-1}(S) = \arg\min_{p \in P} t-1 \sum_{i=1}^t \hat{\ell}_i \left( \sum_{j=0}^N p_{j,t} f_{j,t} \right)$$

Follow-The-Regularized leader: the forecaster chooses the weight vector $p_t$ to minimize the cumulative loss plus a regularization term:

$$p_t = \arg\min_{p \in P} \hat{L}_{t-1}(S) + R(p_t) = \arg\min_{p \in P} t-1 \sum_{i=1}^t \hat{\ell}_i \left( \sum_{j=0}^N p_{j,t} f_{j,t} \right) + R(p_t)$$

In the last case, $R(p_t)$ can be:

- a linear/convex function: Online Gradient Descent.
- a square-$\ell^2$-norm regularization: Ridge regression.
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Online Gradient Descent aggregation rule - General Framework

We define the $O_\eta$ OGD aggregation rule:
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For each round $t = 1, 2, \ldots, T$, the vector $p_{t+1}$ is selected according to:

$$p_{j,t+1} = P_j(p_{j,t} - \eta_t \partial \ell(N\sum_{j=1}^N p_{j,t} f_{j,t}, y_t))$$

where $P_j = \arg \min p_j d(p,y) = \arg \min p_j ||\sum_{j=1}^N p_{j,t} f_{j,t} - y_t||$.
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The Online Gradient Descent aggregation rule

Theorem 2 [Zinkevich, 2003]

If $\eta_t = \frac{1}{\frac{1}{2} t}$, the regret is:

$$R(O_{\text{grad}, \eta}) \leq \sqrt{T^2 + 4(\sqrt{T} - \frac{1}{2})}$$
Theorem 2 [Zinkevich, 2003]

If $\eta_t = t^{\frac{1}{2}}$, the regret is:
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R(O_{\eta}^{\text{grad}}) \leq \frac{\sqrt{T}}{2} + 4(\sqrt{T} - \frac{1}{2})
\]
The Online Gradient Descent aggregation rule

The bound of the regret is obtained using two facts:

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\max |\hat{y}_t - y_t| = 1
\]

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\max \frac{\partial \ell}{\partial \hat{y}_t} = \max 2(\hat{y}_t - y_t) = 2
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\[\Rightarrow \]
The Online Gradient Descent aggregation rule

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$\Rightarrow$ Next
$\Leftarrow$ Contents
The ridge regression aggregation rule

In this framework, weights $u_t = (u_{1,t}, ..., u_{N,t}) \in \mathbb{R}$ are not chosen in a simplex $\mathcal{P}$ anymore. The forecaster prediction is defined by:

\[ \tilde{y}_t = \sum_{j=1}^{N} u_{j,t} f_{j,t} \]
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We define by:

$$f_t = (f_{1,t}, \ldots, f_{N,t})$$ the vector of forecaster predictions.

The rest of the framework does not change.
The ridge regression aggregation rule

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The ridge regression aggregation rule

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- $f_t = (f_{1,t}, \ldots, f_{N,t})$ the vector of forecaster predictions.
- the euclidian norm of a vector $u \in \mathbb{R}$:
  $$\|u\|_2 = \sqrt{\sum_{j=1}^{\infty} u_j^2}$$

The rest of the framework does not change.
The ridge regression aggregation rule

We choose $u_t$ as follows:

$$u_t \in \arg \min_{v \in \mathbb{R}^N} \left\{ \lambda ||v||^2_2 + \sum_{s=1}^t \left( y_s - \sum_{j=1}^N v_j f_{j,s} \right)^2 \right\}$$

An explicit solution is given by:

$$u_t = \left( \lambda I_N + M_t - 1 \right)^{-1} \sum_{s=1}^t y_s f_s$$
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An explicit solution is given by:

$$u_t = (\lambda I_N + M_{t-1})^{-1} \sum_{s=1}^{t-1} y_s f_s$$
Theorem 4 [Vovk, 2001]

\[ R(\eta) \leq \inf_{v \in \mathbb{R}^N} \left\{ \lambda ||v||^2 + N \times \ln(1 + T\lambda N) \right\} \]

Since \( N \) is very large in our case, this online aggregation rule should have a great performance.
Since $\hat{y}_t \in [0, 1]$: 

\[
R(\eta) \leq \inf_{v \in \mathbb{R}^N} \{ \lambda ||v||^2 + N \times \ln(1 + T\lambda N) \}
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**Theorem 4 [Vovk, 2001]**

Since \( \hat{y}_t \in [0, 1] \):

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Theorem 4 [Vovk, 2001]

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US: pre-crisis period out-of-sample

Figure 37: Predicted probability - EWA
US: pre-crisis period out-of-sample

Figure 38: Predicted probability - ML
Figure 39: Predicted probability - OGD
Figure 40: Predicted probability - Ridge
Figure 41: Weights - EWA
Figure 42: Weights - EWA
Contributions to crisis prediction: US

- Spike in probability due to B: many variables but in particular include banking variables (leverage and assets). All variables: GDP per person Index; Share price; Unemployment; GDP; Cross border flows; Slope of the yield curve; Golden rule 2y change; Golden rule 3y change; Consumer price 1y change and 2y change; Price-to-income ratio 1y change; Equity Holdings; Equity holdings 1y change, 2y change, 3y change; Financial assets; Financial assets 1y change, 2y change, 3y change; Fixed Holding 1y change, 2y change, 3y change; Liquid Assets 1y change, 3y change; Bank assets 1y change; Bank equity 1y change; Leverage 1y change; Economic Uncertainty Policy Index 1y change; Oil price 1y change.
Figure 43: AUROC. EWA=0.91; ML=0.95; OGD=0.80; Ridge=0.88. quasi-real time.
Figure 44: AUROC. Best convex (ex post) = 0.91; Uniform = 0.81; Ridge = 0.88. quasi-real time.