Learning to Rank in Theory and Practice

From Gradient Boosting to Neural Networks and Unbiased Learning

Tutorial @ ACM SIGIR 2019
http://ltr-tutorial-sigir19.isti.cnr.it/

Session I: Efficiency/Effectiveness Trade-offs

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The Ranking Problem

Ranking is at the core of several IR Tasks:

- Document Ranking in Web Search
- Ads Ranking in Web Advertising
- Query suggestion & completion
- Product Recommendation
- Song Recommendation
- …

Agenda

Session I: Efficiency/Effectiveness Trade-offs

(Claudio Lucchese and Franco Maria Nardini)

- *Theory*: Background, sources of cost, learning algorithms, Fast Scoring
- *Practice*: Training models, Pruning strategies, Efficient scoring
    - At the end of the day you'll be able to train a high quality ranking model, and to exploit SoA tools and techniques to ***reduce its computational cost up to 18x !***

Session II: Neural Learning to Rank using TensorFlow

(Rama Kumar Pasumarthi, Sebastian Bruch, Michael Bendersky and Xuanhui Wang)

- *Theory*: The fundamental building blocks of neural learning-to-rank models in TF-Ranking: losses, metrics and scoring functions
- *Practice*: Hands-on training of a basic ranking model with sparse textual features
    - At the end of the end of the day, you should be able to ***train a basic TF-Ranking model in Google Colab***, and understand simple model customizations

Session III: Unbiased Learning to Rank

(Harrie Oosterhuis, Maarten de Rijke and Rolf Jagerman)

- *Theory*: Biases in User Interactions, Counterfactual and Online Methods
- *Practice*: Learning and Evaluating from User Interactions
    - After this part you should understand and be able to ***choose between unbiased LTR methodologies***

Effectiveness vs. Efficiency

Definition:

Given a query q and a set of objects/documents D,
to rank D so as to maximize users' satisfaction Q.

Goal #1: Effectiveness

- Maximize Q !
  - but how to measure Q?

Goal #2: Efficiency

- Make sure the ranking process is feasible and not too expensive
  - In Bing ... "every 100msec improves revenue by 0.6%. Every millisecond counts."[KDF+13]

[KDF+13] Kohavi, R., Deng, A., Frasca, B., Walker, T., Xu, Y., & Pohlmann, N. (2013, August). **Online controlled experiments at large scale**. In *Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining* (pp. 1168-1176). ACM.

Document Representations and Ranking

Document Representations

A document is a multi-set of words

A document may have fields, it can be split into zones, it can be enriched with external text data (e.g., anchors)

Additional information may be useful, e.g., In-Links, Out-Links, PageRank, # clicks, social links, etc.

Hundred signals in public LtR Datasets

Ranking Functions

Term-weighting [SJ72]
Vector Space Model [SB88]

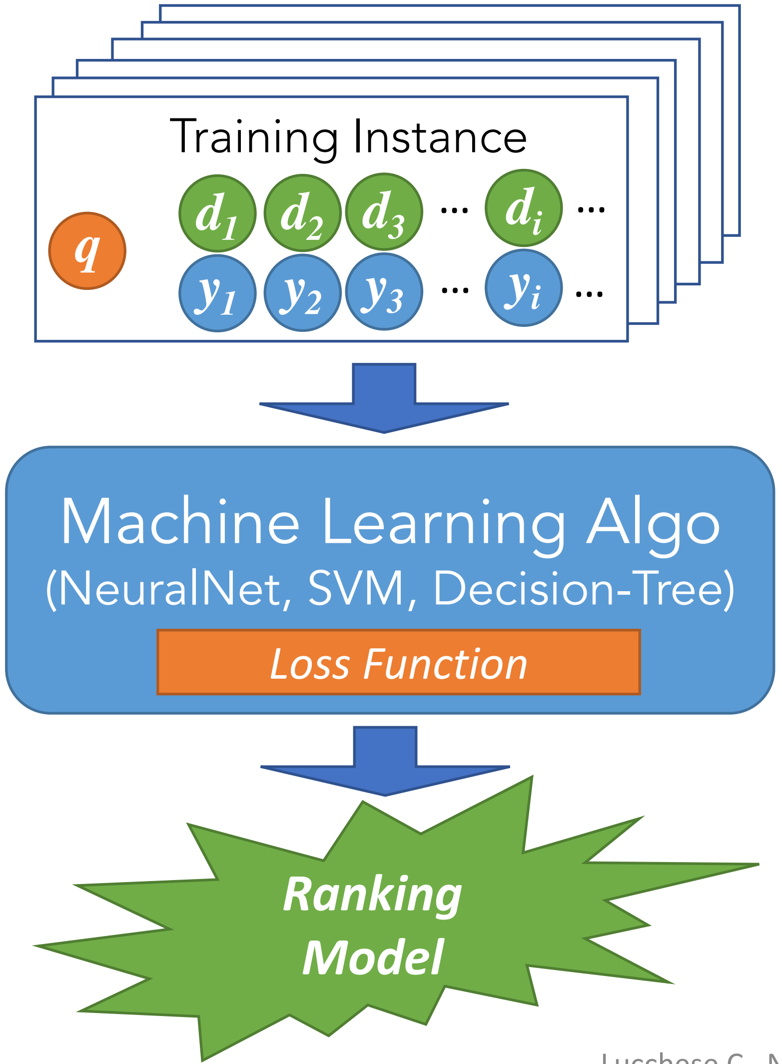
BM25 [JWR00], BM25f [RZT04]
Language Modeling [PC98]

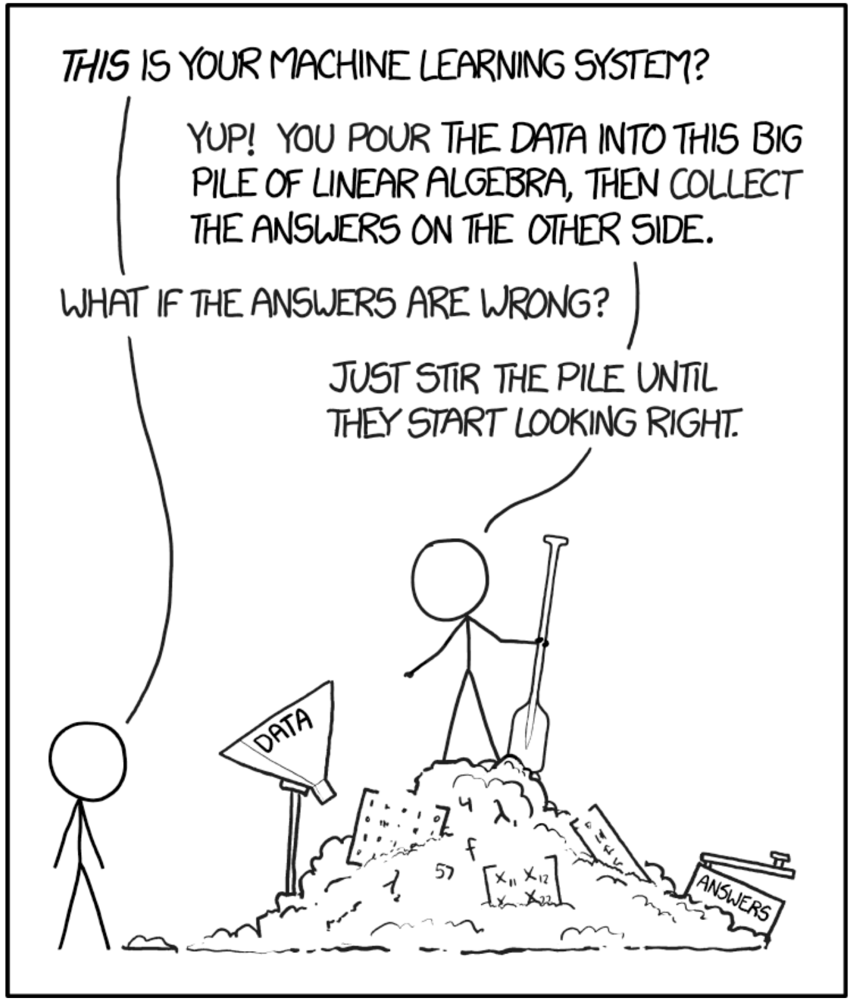
Linear Combination of features [MC07]

How to combine hundreds of signals?

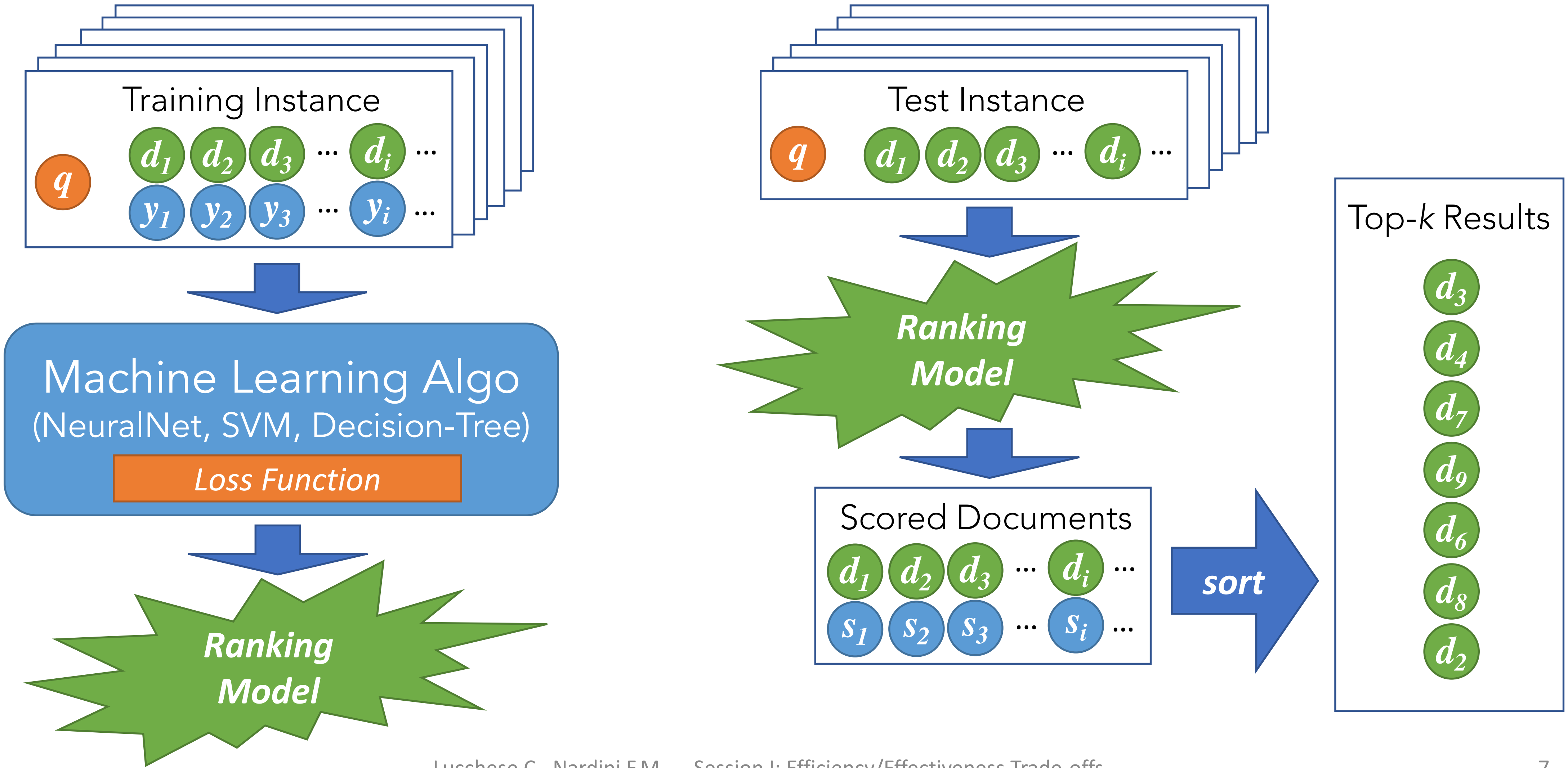
[SJ72] Karen Sparck Jones. **A statistical interpretation of term specificity and its application in retrieval**. Journal of documentation, 28(1):11–21, 1972.
[SB88] Gerard Salton and Christopher Buckley. **Term-weighting approaches in automatic text retrieval**. Information processing & management, 24(5):513–523, 1988.
[JWR00] K Sparck Jones, Steve Walker, and Stephen E. Robertson**. A probabilistic model of information retrieval: development and comparative experiments**. Information processing & management, 36(6):809–840, 2000
[RZT04] Stephen Robertson, Hugo Zaragoza, and Michael Taylor. **Simple bm25 extension to multiple weighted fields**. In Proceedings of the thirteenth ACM international conference on Information and knowledge management, pages 42–49. ACM, 2004.
[PC98] Jay M Ponte and W Bruce Croft. **A language modeling approach to information retrieval**. In Proceedings of the 21st annual international ACM SIGIR conference on Research and development in information retrieval, pages 275–281. ACM, 1998.
[MC07] Donald Metzler and W Bruce Croft**. Linear feature-based models for information retrieval**. Information Retrieval, 10(3):257–274, 2007.

Ranking as a Supervised Learning Task





Ranking as a Supervised Learning Task



Query/Document Representation

q d

Useful signals

- Link Analysis [H+00]
- Term proximity [RS03]
- Query classification [BSD10]
- Query intent mining [JLN16, LOP+13]
- Finding entities documents [MW08] and in queries [BOM15]
- Document recency [DZK+10]
- Distributed representations of words and their compositionality [MSC+13]
- Convolutional neural networks [SHG+14]
- ....

Relevance Labels Generation

y

- ***Explicit Feedback***
  - Thousands of Search Quality Raters
  - Absolute vs. Relative Judgments [CBCD08]
- ***Minimize annotation cost***
  - Active Learning [LCZ+10]
  - Deep versus Shallow labelling [YR09]
- ***Implicit Feedback***
  - Clicks/query chains [JGP+05, Joa02, RJ05]
  - Unbiased learning-to-rank [JSS17]

Evaluation Measures for Ranking

Rank	Top 10 Retrieved Documents	Binary Relevance Labels		Graded Relevance Labels	
1	d_3	y_3	✓	y_3	☆ ☆ ☆ ☆
2	d_4	y_4	✗	y_4	✗
3	d_7	y_7	✓	y_7	☆
4	d_9	y_9	✗	y_9	✗
5	d_6	y_6	✗	y_6	✗
6	d_8	y_8	✗	y_8	✗
7	d_2	y_2	✓	y_2	☆ ☆ ☆
8	d_5	y_5	✗	y_5	✗
9	d_1	y_1	✗	y_1	✗
10	d_{10}	y_{10}	✗	y_{10}	✗

Precision @10

$$P@10 = \frac{3}{10}$$

Account for labels:

$$Q@10 = 4 + 1 + 3$$

Account for labels and ranks:

$$Q@10 = \frac{4}{1} + \frac{1}{3} + \frac{3}{7}$$

Evaluation Measures for Ranking

Many are in the form: $$Q@k = \sum_{\texttt{ranks}\ r=1\ldots k} \text{Gain}(d^r) \cdot \text{Discount}(r)$$

- (N)DCG [JK00]: $\text{Gain}(d) = 2^y - 1 \quad \text{Discount}(r) = \frac{1}{\log(r+1)}$
- RBP [MZ08]: $\text{Gain}(d) = y \quad \text{Discount}(r) = (1-p)p^{r-1}$
- ERR [CMZG09]: $\text{Gain}(d) = R_i \quad \text{Discount}(r) = \frac{1}{r}\prod_{i=1}^{r-1}(1-R_i)\ \textit{with}\ R_i = (2^y - 1)/2^{y_{max}}$

Do they match User satisfaction ?

- ERR correlates better with user satisfaction (clicks and editorials) [CMZG09]
- Results Interleaving to compare two rankings [CJRY12]
  - "major revisions of the web search rankers [Bing] ... The differences between these rankers involve changes of over *half a percentage point*, in absolute terms, of NDCG"

[JK00] Kalervo J arvelin and Jaana Kekalainen. **IR evaluation methods for retrieving highly relevant documents**. In Proceedings of the 23rd annual international ACM SIGIR conference on Research and development in information retrieval, pages 41–48. ACM, 2000.
[MZ08] Alistair Moffat and Justin Zobel. **Rank-biased precision for measurement of retrieval effectiveness**. ACM Transactions on Information Systems (TOIS), 27(1):2, 2008.
[CMZG09] Olivier Chapelle, Donald Metlzer, Ya Zhang, and Pierre Grinspan. **Expected reciprocal rank for graded relevance**. In Proceedings of the 18th ACM conference on Information and knowledge management, pages 621–630. ACM, 2009.
[CJRY12] Olivier Chapelle, Thorsten Joachims, Filip Radlinski, and Yisong Yue. **Large-scale validation and analysis of interleaved search evaluation**. ACM Transactions on Information Systems (TOIS), 30(1):6, 2012.

Is it an easy or difficult task?

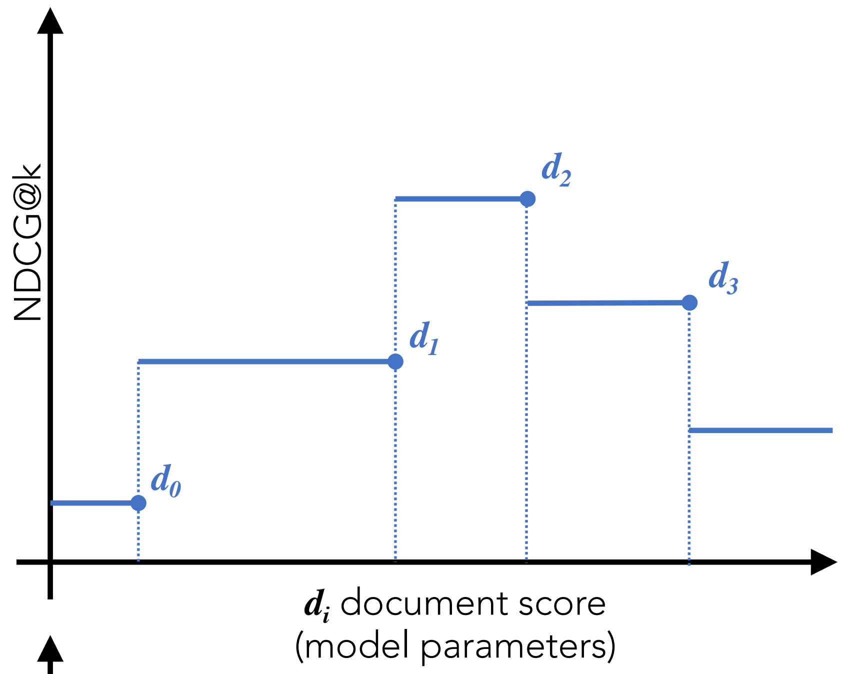
Gradient descent cannot be applied directly

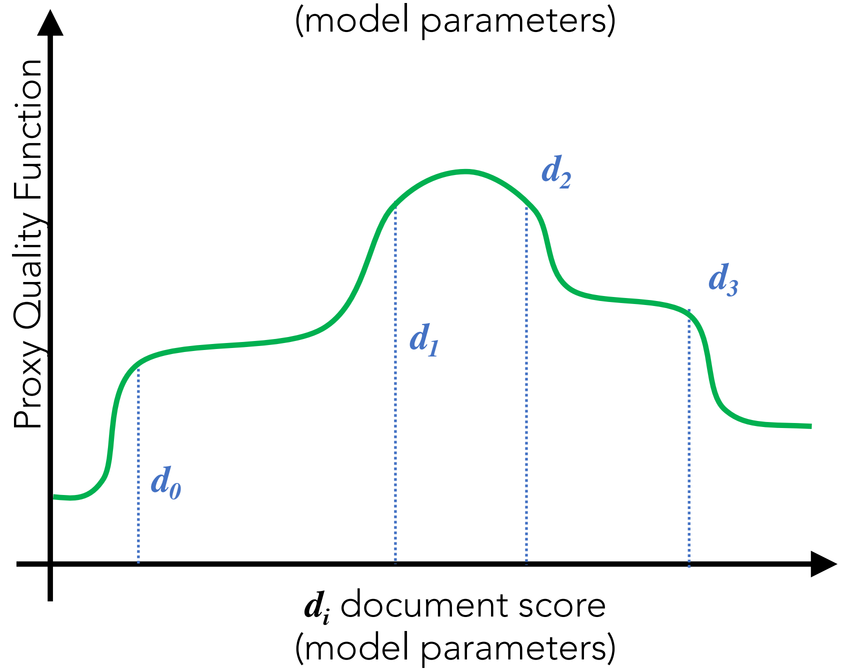
Rank-based measures (NDCG, ERR, MAP, …) depend on ***documents sorted order***

- ***gradient is either 0*** (sorted order did not change) or ***undefined*** (discontinuity)

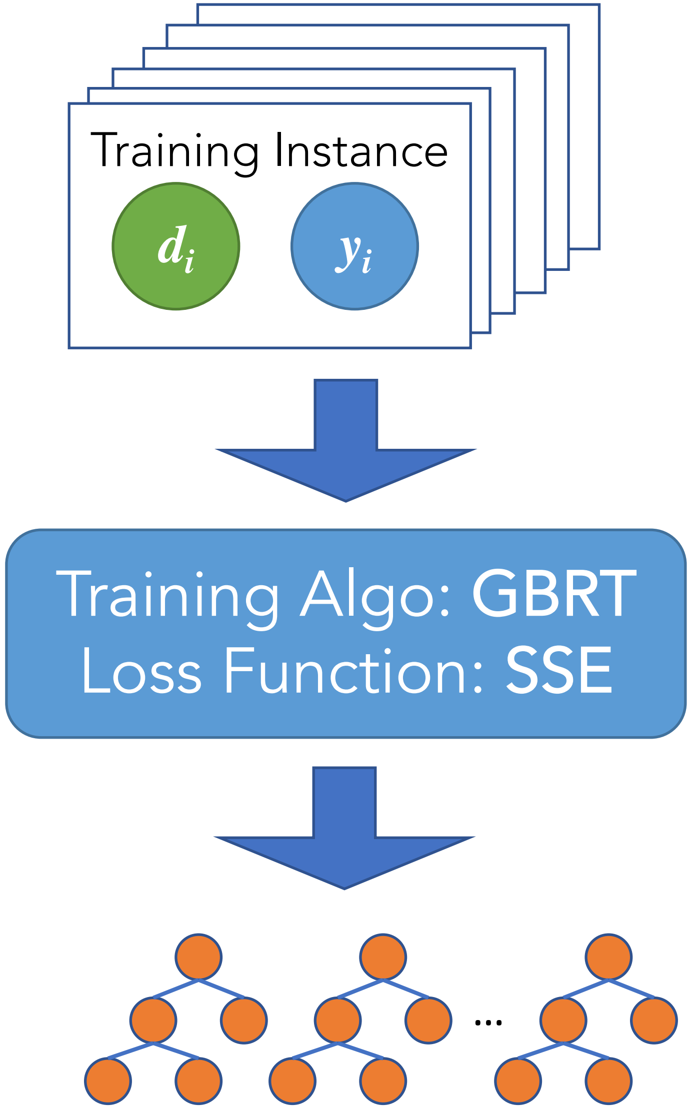
Solution: we need a proxy Loss function

- it should be ***differentiable***
- and with a ***similar behavior of the original cost function***





Point-Wise Algorithms



Each document is considered independently from the others

- No information about other candidates for the same query is used at training time

A different cost-function is optimized

- Several approaches: Regression, Multi-Class Classification, Ordinal regression, … [Liu11]

Among Regression-Based:

Gradient Boosting Regression Trees [Fri01]

- ***Sum of Squared Errors (SSE)*** is minimized

[Liu11] Tie-Yan Liu. **Learning to rank for information retrieval**, 2011. Springer.

[Fri01] Jerome H Friedman. **Greedy function approximation: a gradient boosting machine**. Annals of statistics, pages 1189–1232, 2001.

Gradient Boosting Regression Trees

Iterative algorithm: $$F(d) = \sum_i f_i(d)$$

Weak Learner

Each f_i is regarded as a step in the best optimization direction, i.e., a ***steepest descent step***:

by line-search

negative gradient

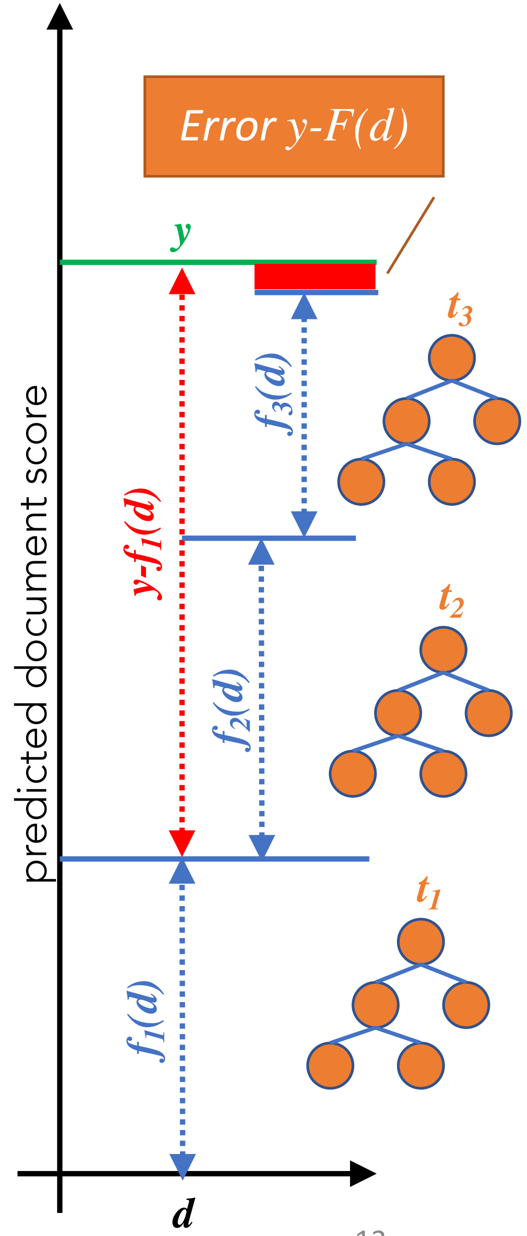
$$f_i(d) = -\rho_i \; g_i(d) \qquad -g_i(d) = -\left[\frac{\partial L(y, f(d))}{\partial f(d)}\right]_{f=\sum_{j<i} f_j}$$

Given $L = SSE/2$:

pseudo-response

$$-\frac{\partial[\frac{1}{2}SSE(y, f(d))]}{\partial f(d)} = -\frac{\partial[\frac{1}{2}\sum(y - f(d))^2]}{\partial f(d)} = y - f(d)$$

Gradient g_i is approximated by a Regression Tree t_i



Pair-wise Algorithms: RankNet[BSR+05]

Documents are considered in pairs

Estimated probability that ***d_i is better than d_j*** is:

$$P_{ij} = \frac{e^{o_{ij}}}{1 + e^{o_{ij}}}$$

$o_{ij} = F(d_i)\text{-}F(d_j)$

Let T_{ij} be the true probability, the ***Cross Entropy Loss*** is:

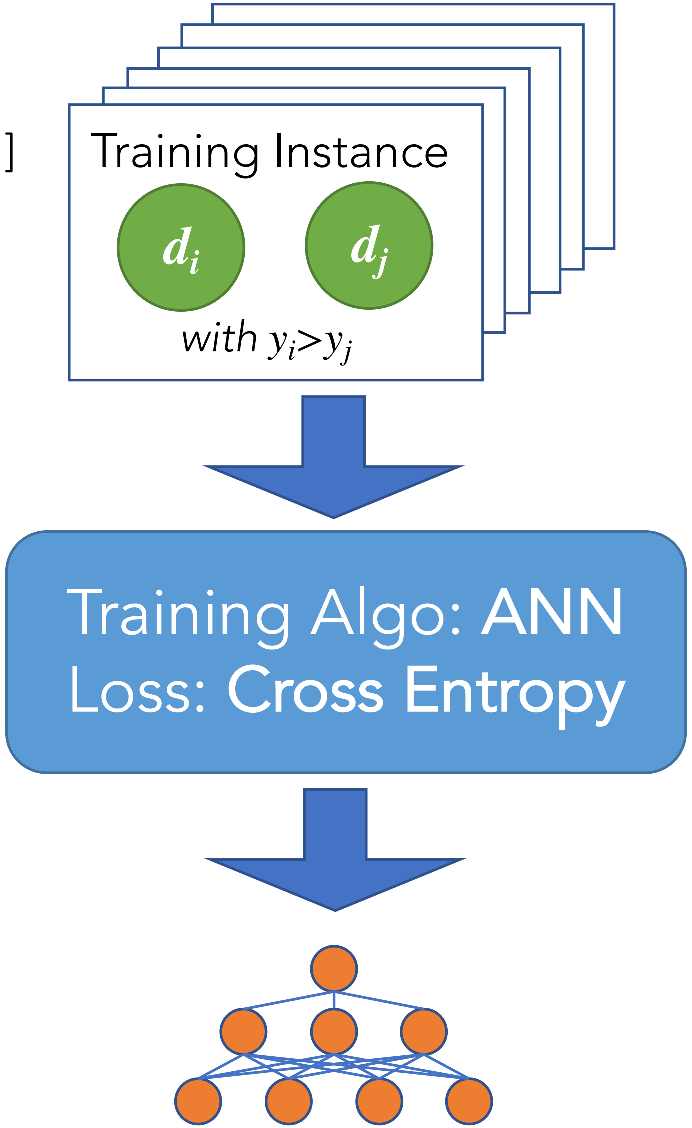
$$C_{ij} = -T_{ij} \log P_{ij} - (1 - T_{ij}) \log(1 - P_{ij})$$

We consider ***only pairs where d_i is better than d_j, ie., $y_i > y_j$:***

If $o_{ij} \rightarrow +\infty$
(i.e., correctly ordered)
$C_{ij} \rightarrow 0$

$$C_{ij} = \log(1 + e^{-o_{ij}})$$

If $o_{ij} \rightarrow -\infty$
(i.e., mis-ordered)
$C_{ij} \rightarrow +\infty$



This is ***differentiable***: used to train a ***Neural Network with back-propagation***.

Other approaches: Ranking-SVM[Joa02], RankBoost[FISS03], …

[BSR+05] Chris Burges, Tal Shaked, Erin Renshaw, Ari Lazier, Matt Deeds, Nicole Hamilton, and Greg Hullender. **Learning to rank using gradient descent**. In Proceedings of the 22nd international conference on Machine learning, pages 89–96. ACM, 2005.

[Joa02] Thorsten Joachims. **Optimizing search engines using clickthrough data**. In Proceedings of the eighth ACM SIGKDD international conference on Knowledge discovery and data mining, pages 133–142. ACM, 2002.

[FISS03] Yoav Freund, Raj Iyer, Robert E Schapire, and Yoram Singer. **An efficient boosting algorithm for combining preferences**. Journal of machine learning research, 4(Nov):933–969, 2003.

Pair-wise Algorithms

***RankNet** performs __**better**__ than other pairwise algorithms*

***RankNet** cost is __**not**__ nicely correlated with NDCG quality*

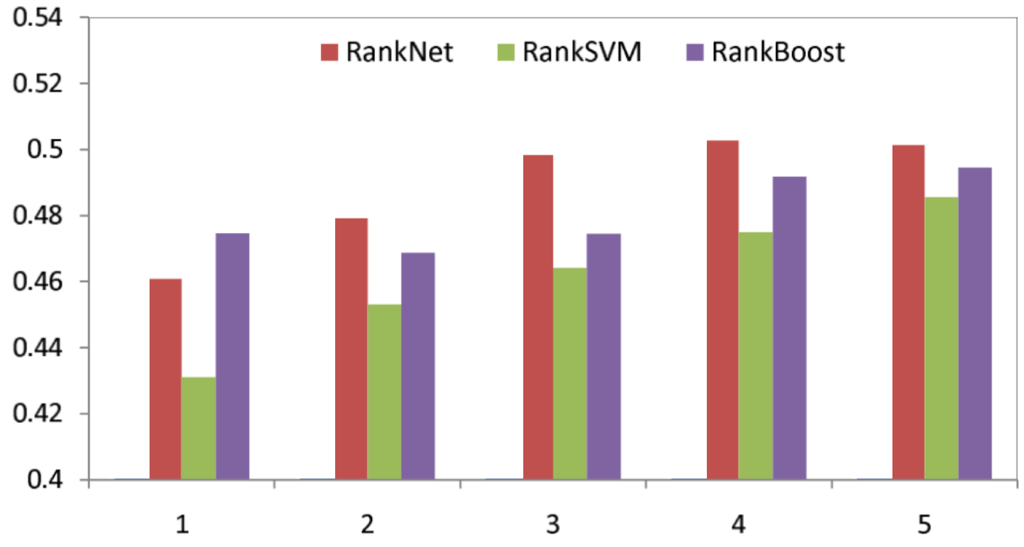


Figure 1. Ranking accuracies in terms of NDCG@n on TREC

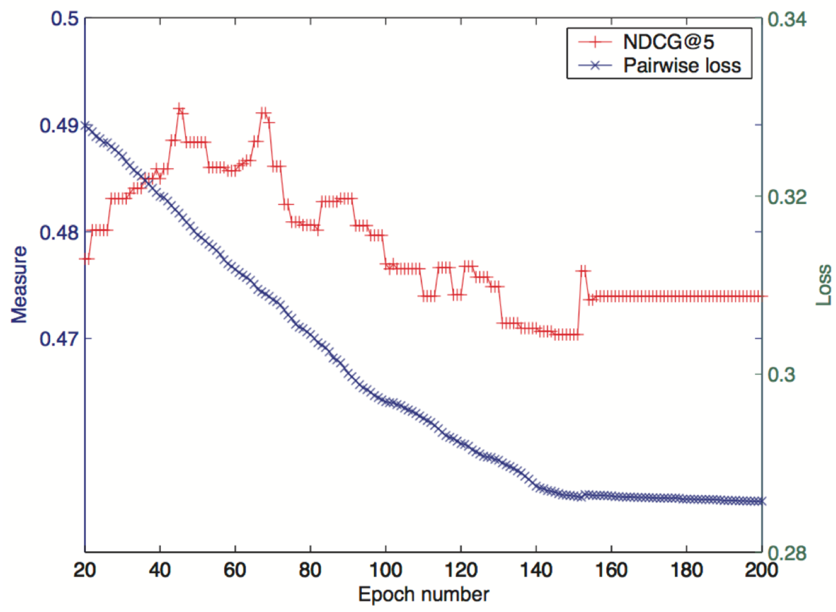


Figure 4. Pairwise loss v.s. NDCG@5 in RankNet

[CQL+07] Zhe Cao, Tao Qin, Tie-Yan Liu, Ming-Feng Tsai, and Hang Li. **Learning to rank: from pairwise approach to listwise approach**. In Proceedings of the 24th international conference on Machine learning, pages 129–136. ACM, 2007.

List-wise Algorithms: LambdaMart[Bur10]

Recall: ***GBRT requires a gradient*** g_i ***for every*** d_i

First: ***estimate the gradient comparing to*** d_j, with $y_i > y_j$:

derivative of the negative RankNet cost

Δ Quality after swapping d_i *with* d_j

$$\lambda_{ij} = \frac{1}{1 + e^{o_{ij}}} \, |\Delta NDCG| = -\lambda_{ji}$$

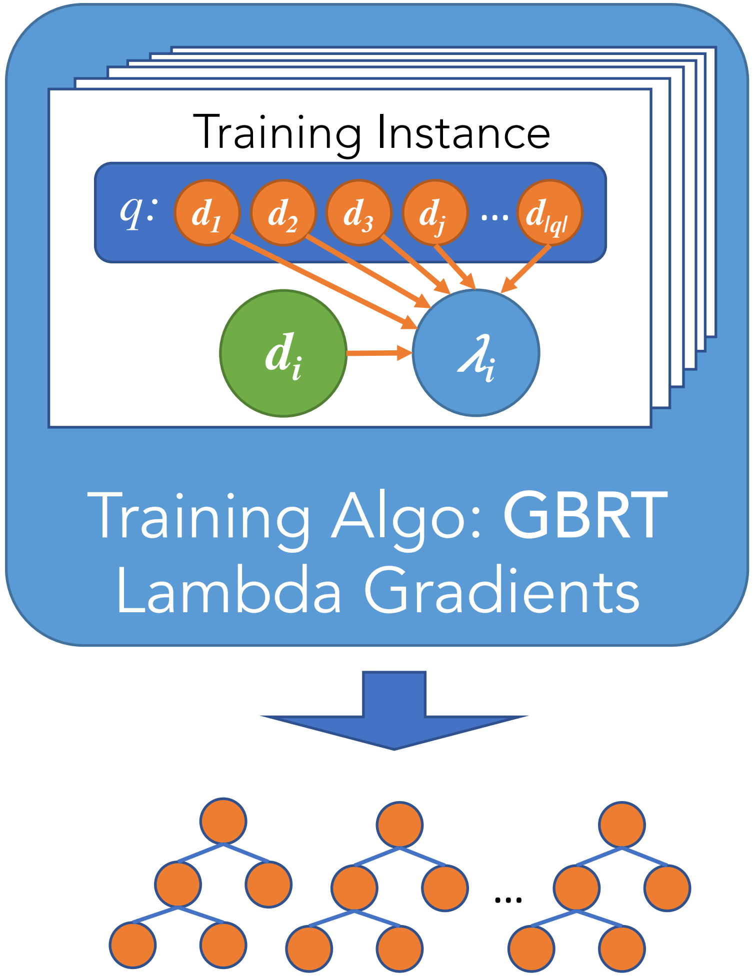
If $o_{ij} \to +\infty$
(i.e., correctly ordered)
$\lambda_{ij} \to 0$

If $o_{ij} \to -\infty$
(i.e., mis-ordered)
$\lambda_{ij} \to |\Delta\, NDCG|$

Top documents are more relevant !

Then: ***estimate the gradient comparing to every other*** d_j ***for*** q

$$g_i = \lambda_i = \sum_{y_i > y_j} \lambda_{ij} - \sum_{y_i < y_j} \lambda_{ij}$$



[Bur10] Christopher J.C. Burges. **From ranknet to lambdarank to lambdamart: An overview**. Technical Report MSR-TR-2010-82, June 2010.

List-wise Algorithms: some results

- NDCG@10 on public LtR Datasets

Algorithm	MSN10K	Y!S1	Y!S2	Istella-S
RankingSVM	0.4012	0.7238	0.7306	N/A
GBRT	0.4602	**0.7555**	**0.7620**	0.7313
LambdaMART	**0.4618**	0.7529	0.7531	**0.7537**

Other approaches: ListNet/ListMLE[CQL+07], Approximate Rank[QLL10], SVM AP[YFRJ07], RankGP[YLKY07], others ...

[CQL+ 07] Zhe Cao, Tao Qin, Tie-Yan Liu, Ming-Feng Tsai, and Hang Li. **Learning to rank: from pairwise approach to listwise approach**. In Proceedings of the 24th international conference on Machine learning, pages 129–136. ACM, 2007.

[QLL10] Tao Qin, Tie-Yan Liu, and Hang Li. **A general approximation framework for direct optimization of information retrieval measures**. Information retrieval, 13(4):375–397, 2010.

[YFRJ08] Yisong Yue, Thomas Finley, Filip Radlinski, and Thorsten Joachims. **A support vector method for optimizing average precision**. In Proceedings of the 30th annual international ACM SIGIR conference on Research and development in information retrieval, pages 271– 278. ACM, 2007.

[YLKY07] Jen-Yuan Yeh, Jung-Yi Lin, Hao-Ren Ke, and Wei-Pang Yang. **Learning to rank for information retrieval using genetic programming**. In Proceedings of SIGIR 2007 Workshop on Learning to Rank for Information Retrieval (LR4IR 2007), 2007.

Learning to Rank Algorithms

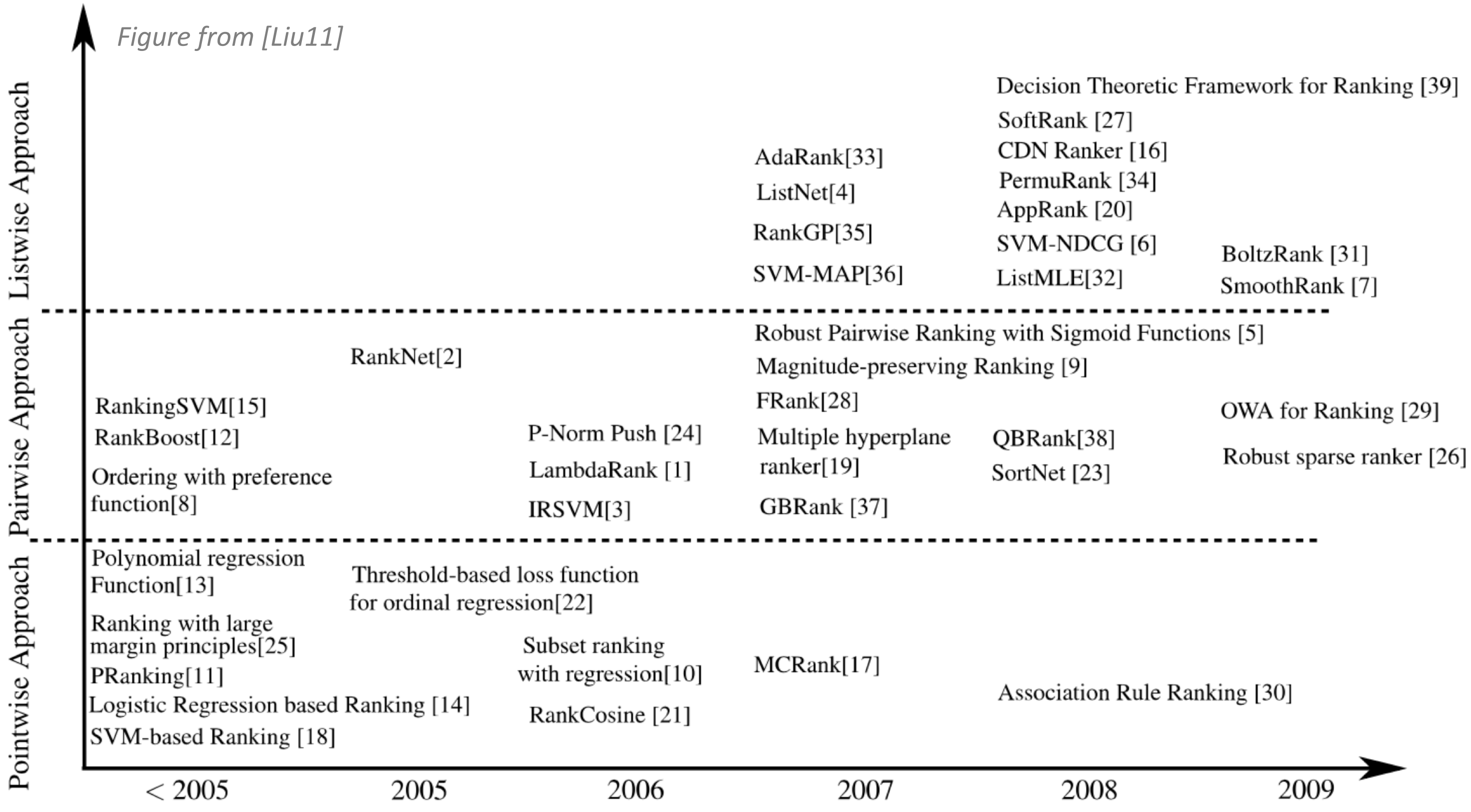


Figure from [Liu11]

- New approaches to **optimize IR measures:**
  - DirectRank[XLL+08], LambdaMart[Bur10], BLMart[GCL11], SSLambdaMART[SY11], CoList[GY14], LogisticRank[YHT+16], LambdaLoss[WGB+19] …
    See [Liu11][TBH15].
- **Deep Learning** to improve query-document matching:
  - Conv.DNN[SM15], DSSM[HHG+13], Dual-Embedding[MNCC16], Local and Distributed repr.[MDC17], Weak Supervision[DZS+17], Neural Click Model[BMdRS16], …
- **On-line learning**:
  - Multi-armed bandits [RKJ08], Dueling bandits [YJ09], K-armed dueling bandits[YBKJ12], online learning[HSWdR13][HWdR13], …

[Liu11] Tie-Yan Liu. **Learning to rank for information retrieval**, 2011. Springer.
[TBH15] Niek Tax, Sander Bockting, and Djoerd Hiemstra. **A cross-benchmark comparison of 87 learning to rank methods**. Information processing & management, 51(6):757–772, 2015.

In this session we focus on GBRTs

- facebook — ***Ads Click Prediction***: GBDT as a ***feature extractor***, then LogReg [HPJ+14]
- Microsoft — ***Ads Click Prediction***: refine/***boost NN*** output [LDG+17]
- amazon — ***Product Ranking***: 100 GBDTs with pairwise ranking [SCP16]
- YAHOO! — ***Document Ranking***: GBDT named LogisticRank [YHT+16]
- Yandex — ***Ranking, forecasting & recommendations***: ***Oblivious GBRT***

[HPJ+14] Xinran He, Junfeng Pan, Ou Jin, Tianbing Xu, Bo Liu, Tao Xu, Yanxin Shi, Antoine Atallah, Ralf Herbrich, Stuart Bowers, et al. **Practical lessons from predicting clicks on ads at facebook**. In Proceedings of the Eighth International Workshop on Data Mining for Online Advertising, pages 1–9. ACM, 2014.

[LDG+17] Xiaoliang Ling, Weiwei Deng, Chen Gu, Hucheng Zhou, Cui Li, and Feng Sun. **Model ensemble for click prediction in bing search ads**. In Proceedings of the 26th International Conference on World Wide Web Companion, pages 689–698. International World Wide Web Conferences Steering Committee, 2017.

[SCP16] Daria Sorokina and Erick Cantú-Paz. **Amazon search: The joy of ranking products**. In Proceedings of the 39th International ACM SIGIR conference on Research and Development in Information Retrieval, pages 459–460. ACM, 2016.

[YHT+16] Dawei Yin, Yuening Hu, Jiliang Tang, Tim Daly, Mianwei Zhou, Hua Ouyang, Jianhui Chen, Changsung Kang, Hongbo Deng, Chikashi Nobata, et al. **Ranking relevance in yahoo search**. In Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, pages 323–332. ACM, 2016.

In this session we focus on GBRTs

- Successful in several ***Data Challenges***:
  - Winner of the ***Yahoo! LtR Challenge***: combination of 12 ranking models, 8 of which were Lambda-MART models, each having up to 3,000 trees [CC11]
  - According to the 2015 statistics, GBRTs were adopted by the majority of the winning solutions among the ***Kaggle*** competitions, even more than the popular deep networks, and all the top-10 teams qualified in the ***KDDCup 2015*** used GBRT-based algorithms [CG16]

- New interesting ***open-source implementations***:
  - XGBoost, LightGBM by ***Microsoft***, CatBoost by ***Yandex***

- ***Pluggable*** within ***Apache Lucene/Solr***
  - https://www.techatbloomberg.com/blog/bloomberg-integrated-learning-rank-apache-solr/

[CC11] Olivier Chapelle and Yi Chang. **Yahoo! learning to rank challenge overview**. In Proceedings of the Learning to Rank Challenge, pages 1–24, 2011.

[CG16] Tianqi Chen and Carlos Guestrin. **Xgboost: A scalable tree boosting system**. In Proceedings of the 22Nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, KDD ’16, pages 785–794, New York, NY, USA, 2016. ACM.

Single-Stage Ranking

Requires to apply the learnt *model* to *every matching document*, and to generate the required *features*.

Not feasible!

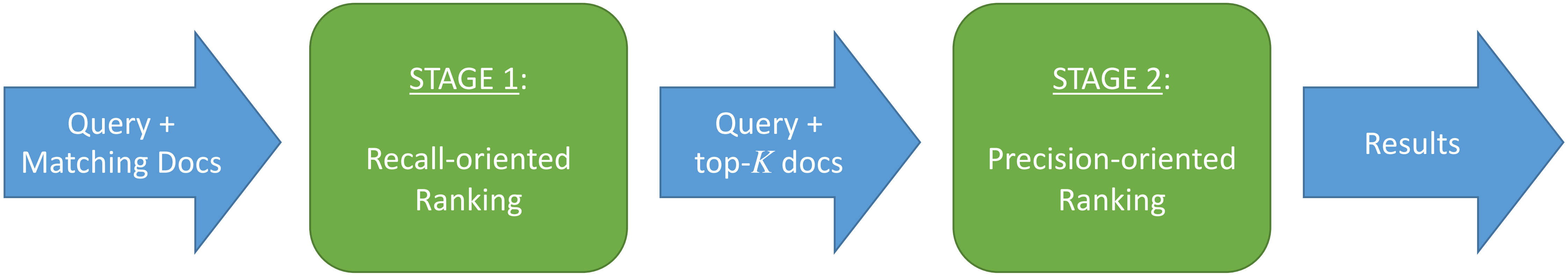
We have at least ***3*** ***efficiency vs. effectiveness trade-offs***.

Single-Stage Ranking

① ***Feature Computation Trade-off***

- Computationally ***Expensive*** & ***highly discriminative*** features vs. computationally ***Cheap*** & ***slightly discriminative*** features

Two-Stage Ranking



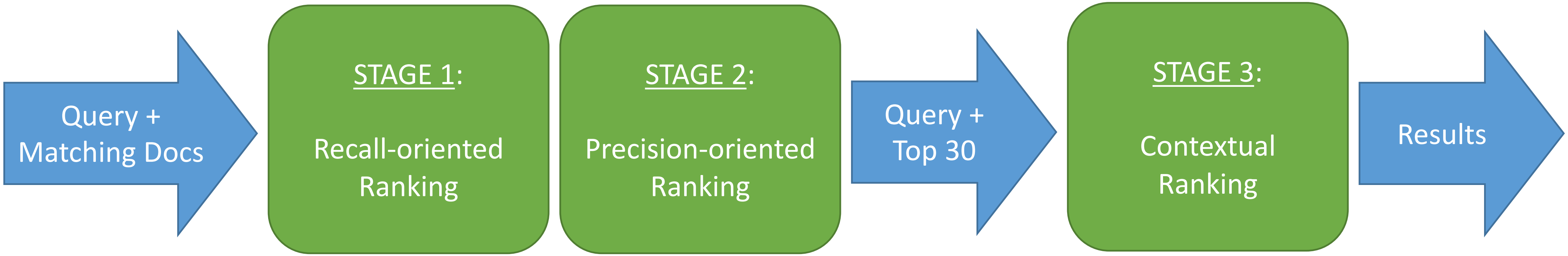
Expensive features are computed only for the *top-K candidate documents* passing the first stage.
How to chose K?

② ***Number of Matching Candidates Trade-off*** :

- a ***Large set*** of candidates is ***Expensive*** and produces ***high-quality*** results vs.
  a ***Small set*** of candidates is ***Cheap*** and produces ***low-quality*** results
  - 1000 documents [DBC13] (Gov2, ClueWeb09-B collections)
  - 1500-2000 documents [MSO13] (ClueWeb09-B)
  - “hundreds of thousands” (over “hundreds of machines”) [YHT+16a]

[DBC13] Van Dang, Michael Bendersky, and W Bruce Croft. **Two-stage learning to rank for information retrieval**. In Advances in Information Retrieval, pages 423–434. Springer, 2013.
[MSO13] Craig Macdonald, Rodrygo LT Santos, and Iadh Ounis. **The whens and hows of learning to rank for web search**. Information Retrieval, 16(5):584–628, 2013.
[YHT+16] Dawei Yin, Yuening Hu, Jiliang Tang, Tim Daly, Mianwei Zhou, Hua Ouyang, Jianhui Chen, Changsung Kang, Hongbo Deng, Chikashi Nobata, et al. **Ranking relevance in yahoo search**. In Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, pages 323–332. ACM, 2016.

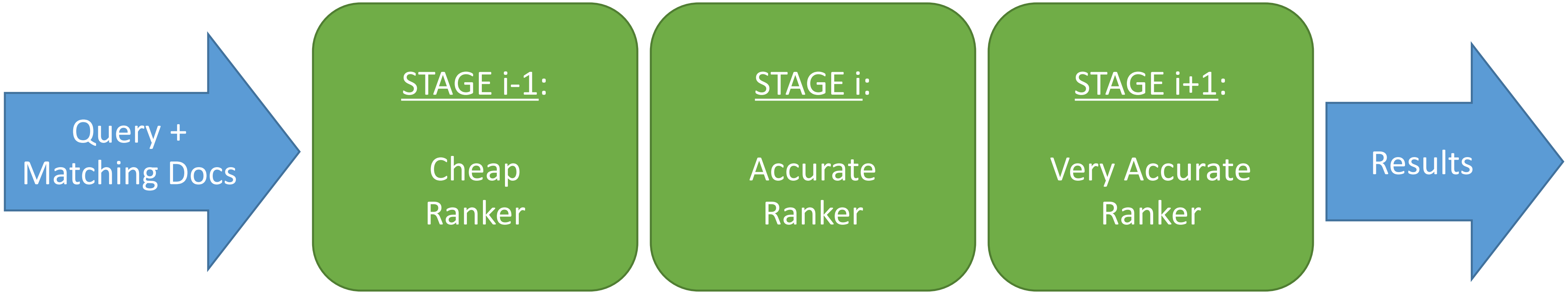
Multi-Stage Ranking



- 3 stages [YHT+16]: ***Contextual features*** are considered in the 3rd stage
  - Contextual => ***about the current result set***
  - Rank based on specific features, Mean, Variance, Standardized features (see also [LNO+15a]), topic model similarity
  - First two stages are executed at each serving node
- *N* stages [CGBC17]: Which ***model*** in each stage? Which ***features***? How many ***documents***?
  - About ***200 configurations tested,*** best results with N=3 stages, 2500 and 700 docs between stages
- Predict the best *k* for STAGE 1 [CCL16], the best processing pipeline [MCB+18], learn the pipeline at training time [CGBC19]

[YHT+16] Dawei Yin, Yuening Hu, Jiliang Tang et al. **Ranking relevance in yahoo search**. In Proceedings of the 22nd ACM SIGKDD. ACM, 2016.
[CGBC17] Ruey-Cheng Chen, Luke Gallagher, Roi Blanco, and J. Shane Culpepper. **Efficient cost-aware cascade ranking in multi-stage retrieval**. In Proceedings of ACM SIGIR ACM, 2017.
[MCB+18] Mackenzie, J., Culpepper, J. S., Blanco, R., et al. **Query Driven Algorithm Selection in Early Stage Retrieval**. In Proceedings of WSDM. ACM, 2018.
[CCL16] Culpepper, J. S., Clarke, C. L., & Lin, J. **Dynamic cutoff prediction in multi-stage retrieval systems**. In Proceedings of the 21st Australasian Document Computing Symposium. ACM, 2016.
[CGBC19] L. Gallagher, R. Chen, R. Blanco, J. S. Culpepper, **Joint Optimization of Cascade Ranking Models**. In Proc. ACM WSDM 2019.

Multi-Stage Ranking



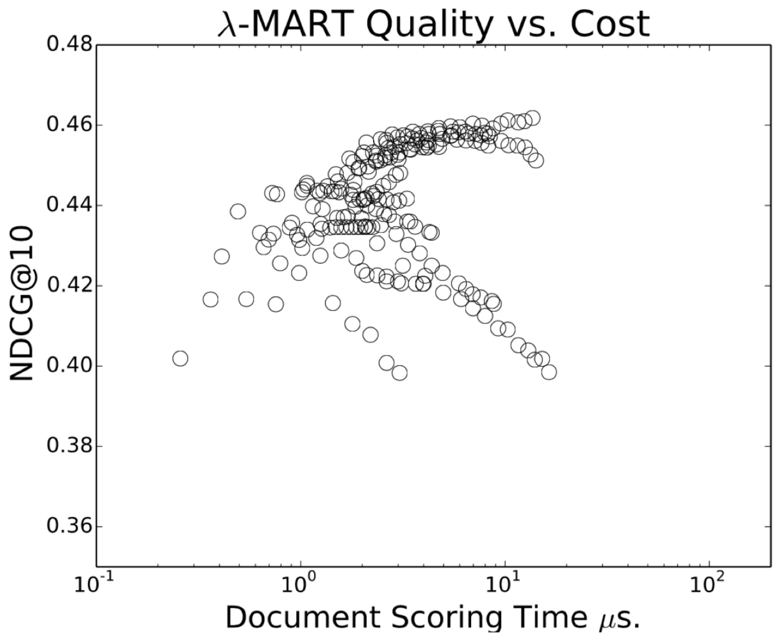
③ ***Model Complexity Trade-off*** :

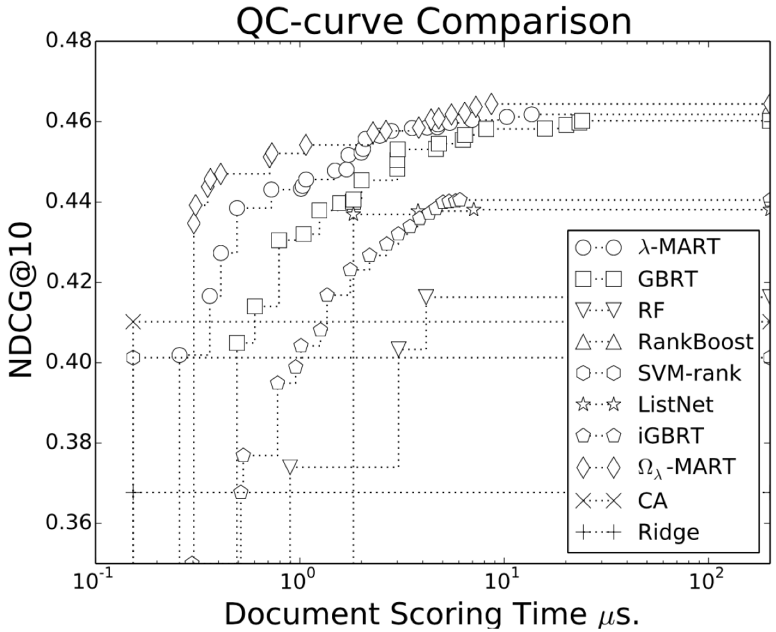
- ***Complex*** & ***Slow*** ***high-quality*** vs. ***Simple*** & ***Fast*** ***low-quality*** models:
  - ***Complex*** as: Random Forest, GBRT, Initialized GBRT, Lambda-MART,
  - ***Simple*** as: Coordinate Ascent, Ridge Regression, SVM-Rank, RankBoost
  - ***In-between*** as: Oblivious Lambda-Mart, ListNet

Model Complexity Trade-off

- Comparison on varying training parameters [CLN+16]:
  - #trees, #leaves, learning rate, etc.
- ***Complex models*** achieve significantly ***higher quality***
- Best model depends on ***time budget***

- ***Today is about Model Complexity Trade-off!***





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Next …

Efficiency/Effectiveness trade-offs in:

- Feature Selection
- Enhanced Learning Algorithms
- Approximate scoring
- Fast Scoring

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