Kolmogorov complexity and information quantities

Andrei Romashchenko, LIP

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Outline

1. What is Kolmogorov complexity?
   - Definition of the plain Kolmogorov complexity
   - A few trivial properties
2. First funny applications
   - The Gödel Incompleteness Theorem
   - The set of all prime numbers is infinite
   - A $(k+1)$-heads automaton is more strong than a k-heads automaton
3. Important information quantities for a pair of words
   - The mutual information
   - Extracting a fingerprint
   - Complexity of a "two-ways" transformation
4. Almost practical applications of Kolmogorov complexity

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Definition

$K(x) =$ minimal length of a program that prints x

- Chose a description method

$$U : \{0,1\}^* \to \{0,1\}^*,$$

where U is a recursive function

- **Definition:** $K_U(x) = \min\{|p| : U(p) = x\}$
- U is *not worse* than V if $K_U(x) \leq K_V(x) + O(1)$
- **Theorem**[Kolmogorov] $\exists$ a description method U that is not worse than any other.

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- A description method

$$U : \{0,1\}^* \times \{0,1\}^* \to \{0,1\}^*,$$

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- **Definition:** $K_U(x|y) = \min\{|p| : U(p,y) = x\}$
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Definition $K(x|y) = K_{\text{Optimal Compiler}}(x|y)$

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- $K(x) = K(x|\Lambda) + O(1)$
- $K(x) \leq |x| + O(1)$
- The function $K(x)$ is semi-enumerable from above
- $\#\{x : K(x) \leq n\} \leq 2^n$

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- The statement $K(x) > n$ can be proven for only a finite set of numbers n
- **Theorem**[Chaitin] $\exists N\ \forall n > N\ PA \nvdash K(x) > n$
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- **Theorem** There exist infinitely many prime numbers p_i.
- Proof: Assume $p_1, \ldots, p_m$ is the set of *all* prime numbers.
  - $\forall x \in \mathbb{N}\ x = p_1^{m_1} \cdot \ldots \cdot p_m^{k_m}, \quad k_i \le \log_2 x$
  - $K(x) \le K(\langle k_1, \ldots, k_m \rangle) = O(\log \log x)$
  - But $K(x) \ge \lceil \log x \rceil$ for an incompressible x

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- **Theorem** There exist a language that can be recognized by an automaton with $(k+1)$ heads but cannot be recognized by any automaton with k heads.
- **Proof:** $L_m = \{w_1\#w_2\#\ldots\#w_m\#w_m\#w_{m-1}\#\ldots\#w_1\}$, where $w_i \in \{0,1\}^*$
- To recognize L_m, we need $m = 1+2+3+\ldots+(k-1) = \frac{k(k-1)}{2}$ heads!

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- **Definition** $I(x:y) = K(x) - K(x|y)$
- **Theorem**[Kolmogorov–Levin]
  $K(x,y) = K(x) + K(y|x) + O(\log(|x|+|y|))$
- **Corollary:** $I(x:y) \approx K(x) + K(y) - K(x,y) \approx I(x:y)$

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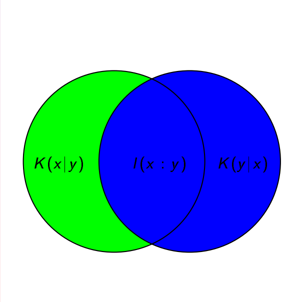

Conjecture For all x, y there exists a z such that

- $K(z|x) \approx 0$
- $K(z|y) \approx 0$
- $K(z) \approx I(x:y)$

Counter-example[An.Muchnik] Take a plane over $\mathbb{F}_{2^n}$. Let x be a line on the plane and y be a point at this line. Then

- $K(x) \approx K(y) \approx 2n$
- $I(x:y) \approx n$
- $\forall z K(z) \leq 2K(z|x) + 2K(z|y) + O(\log n)$

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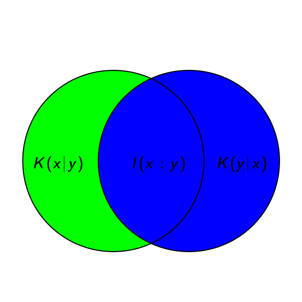
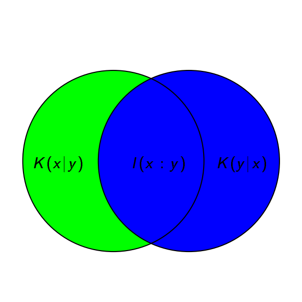


Theorem[An.Muchnuk] $\exists C\ \forall x, y\ \exists p$

- $K(p) = K(x|y)$
- $K(p|x) \le C \log K(x)$
- $K(x|y, p) \le C \log K(x)$

D.Musatov: We can let $p = Ext(x, *)$,
where *Ext* is an extractor!



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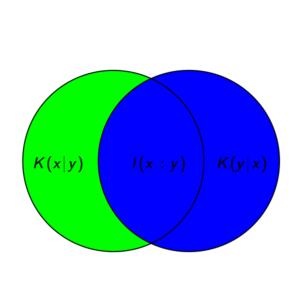

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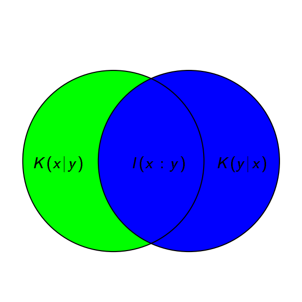

Definition
$K(x \leftrightarrow y) = \min\{|p| : U(p,x) = y \text{ and } U(p,y) = x\}$
Theorem[Gacs]
$K(x \leftrightarrow y) = \max\{K(x|y), K(y|x)\} + O(\log(K(x) + K(y)))$
Corollary: $\max\{K(x|y), K(y|x)\}$ is a distance
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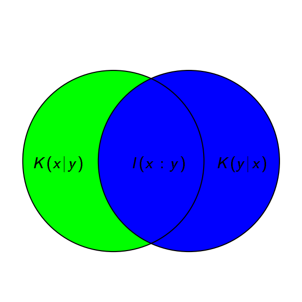

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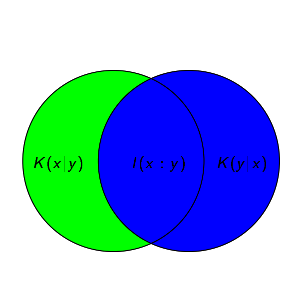

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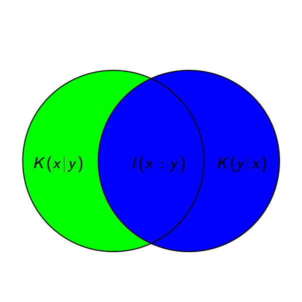

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Compressing le Petit Prince with ppmz:

	Sp. 1	Sp. 2	Sp. 3	Turq. 1	Turq. 2	Turq. 3	Serb. 1	Serb. 2	Serb. 3	Sp. and Turq.
Sp. 1:	9197	1129	1230	-641	-733	-714	-643	-640	-694	2794
Sp. 2:	1129	8079	1097	-712	-646	-663	-649	-558	-665	237
Sp. 3:	1230	1097	8848	-720	-721	-710	-711	-673	-700	309
Turq. 1:	-641	-712	-720	9170	1150	1253	-693	-659	-722	6430
Turq. 2:	-733	-646	-721	1150	8123	1158	-679	-590	-692	827
Turq. 3:	-714	-663	-710	1253	1158	8351	-674	-621	-687	913
Serb. 1:	-643	-649	-711	-793	-679	-674	8975	978	1027	-683
Serb. 2:	-640	-558	-673	-659	-590	-621	978	7806	899	-675
Serb. 3:	-694	-665	-700	-722	-692	-687	1027	899	8539	-715
Sp.,Turq.:	2794	237	309	6430	827	913	-683	-675	-715	9987

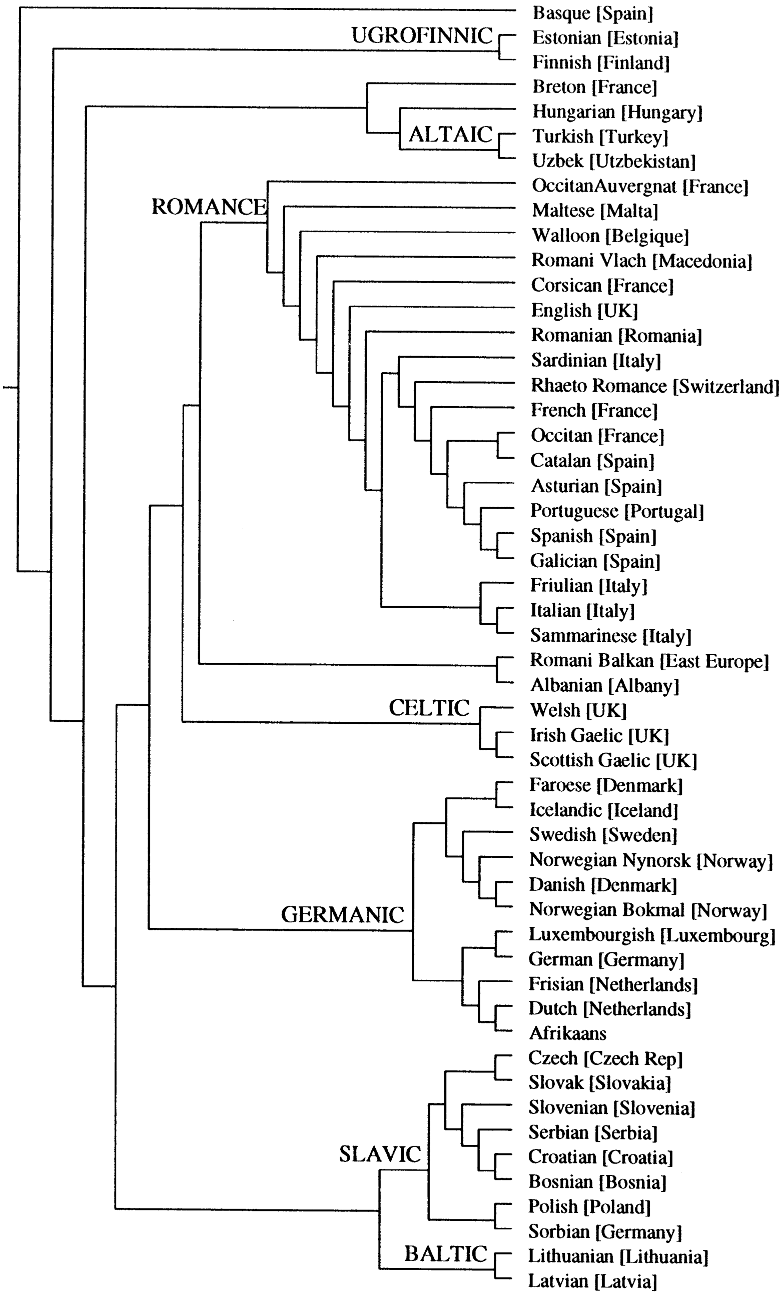

Fig. 4. The language tree using approximated normalized information distance, d_s-version (V.1), and neighbor joining.

resulting from our experiments (using Basque as the outgroup) seem more correct. We use Basque as the outgroup since linguists regard it as a language unconnected to other languages.

IX. Conclusion

We developed a mathematical theory of compression-based similarity distances and shown that there is a universal similarity metric: the normalized information distance. This distance uncovers all upper semi-computable similarities, and therefore estimates an evolutionary or relation-wise distance on strings. A practical version was exhibited based on standard compressors. Here it has been shown to be applicable to whole genomes, and to built a large language family tree from text corpora. References to applications in a plethora of other fields can be found in the Introduction. It is perhaps useful to point out that the results reported in the figures were obtained at the very first runs and have not been selected by appropriateness from several trials. From the theory point of view, we have obtained a general mathematical theory forming a solid framework spawning practical tools applicable in many fields. Based on the noncomputable notion of Kolmogorov complexity, the normalized information distance can only be approximated without convergence guarantees. Even so, the fundamental rightness of the approach is evidenced by the remarkable success (agreement with known phylogeny in biology) of the evolutionary trees obtained and the building of language trees. From the applied side of genomics, our work gives the first fully automatic generation of

CompLearn Online Demo

- New experiment
- Random experiment
- All experiments
- CompLearn Home

Results for experiment , 1164628608

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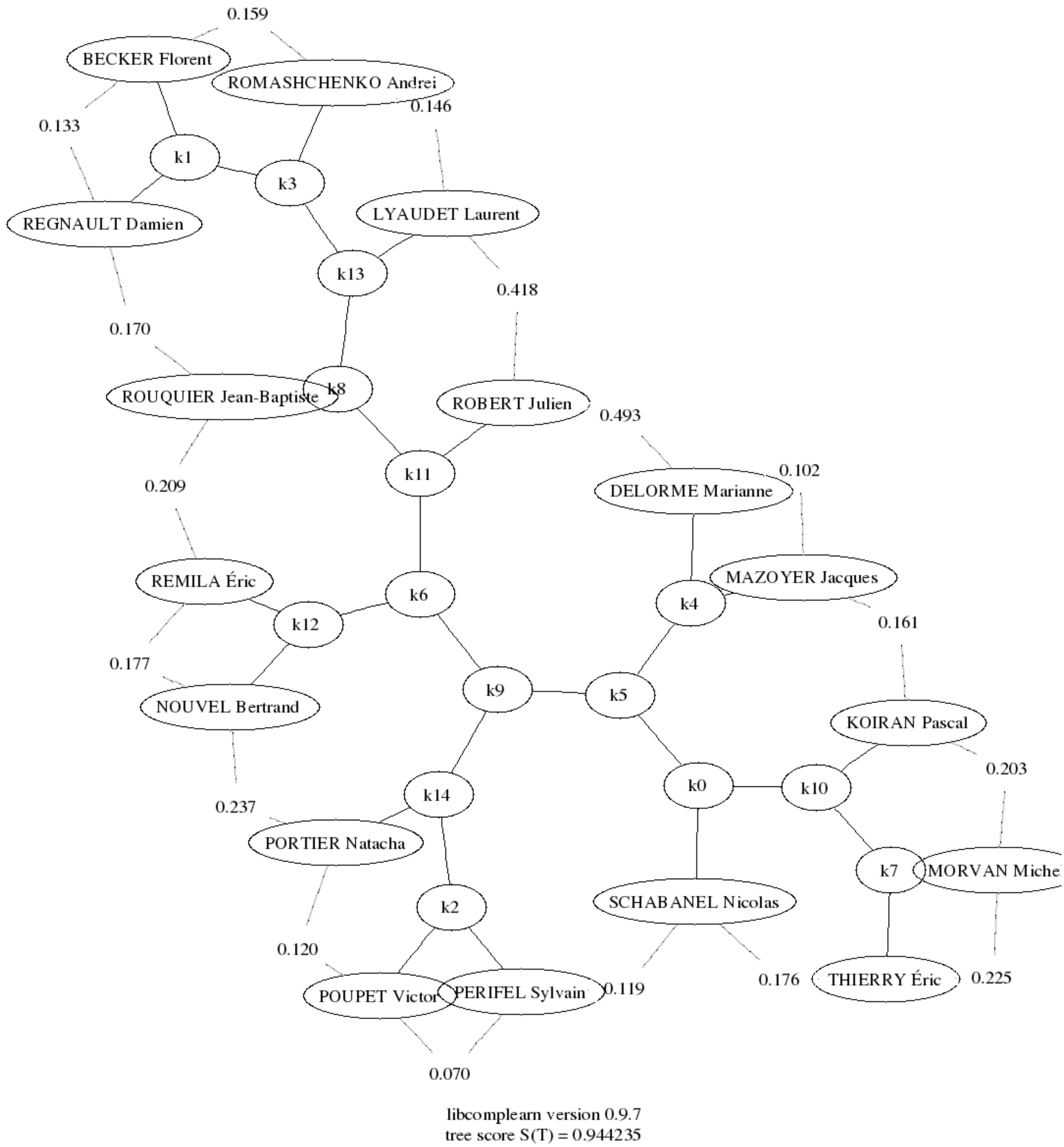
error:_soap_client_build_result():HTTP code is not OK (502) [1400] *WARN*:(1085884736) [hsocket_read] hssl_read failed (recv failed (Connection timed out)) *ERROR*:(1085884736) [hresponse_new_from_socket] Socket read error error:hssl_read():recv failed (Connection timed out) [1005] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (500) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] *WARN*:(1085884736) [hsocket_read] hssl_read failed (recv failed (Connection timed out)) *ERROR*:(1085884736) [hresponse_new_from_socket] Socket read error error:hssl_read():recv failed (Connection timed out) [1005] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400] error:_soap_client_build_result():HTTP code is not OK (502) [1400]

BECKER Florent	0.000	0.270	0.332	0.152	0.314	0.362	0.257	0.260	0.257	0.235	0.133	0.235	0.438	0.159	0.225	0.280	0.379
DELORME Marianne	0.270	0.000	0.190	0.234	0.102	0.253	0.272	0.176	0.167	0.265	0.267	0.265	0.492	0.243	0.270	0.156	0.233
KOIRAN Pascal	0.332	0.190	0.000	0.316	0.160	0.202	0.339	0.117	0.097	0.178	0.302	0.274	0.528	0.286	0.365	0.138	0.216
LYAUDET Laurent	0.152	0.234	0.316	0.000	0.275	0.345	0.245	0.248	0.214	0.224	0.140	0.224	0.417	0.145	0.215	0.212	0.337
MAZOYER Jacques	0.314	0.102	0.160	0.275	0.000	0.184	0.319	0.213	0.219	0.312	0.309	0.230	0.517	0.286	0.317	0.193	0.236
MORVAN Michel	0.362	0.253	0.202	0.345	0.184	0.000	0.353	0.227	0.235	0.290	0.357	0.307	0.549	0.359	0.281	0.181	0.224
NOUVEL Bertrand	0.257	0.272	0.339	0.245	0.319	0.353	0.000	0.288	0.236	0.278	0.253	0.176	0.485	0.255	0.283	0.262	0.420
PERIFEL Sylvain	0.260	0.176	0.117	0.248	0.213	0.227	0.288	0.000	0.115	0.069	0.231	0.281	0.486	0.258	0.258	0.118	0.286
PORTIER Natacha	0.257	0.167	0.097	0.214	0.219	0.235	0.236	0.115	0.000	0.120	0.278	0.278	0.499	0.280	0.282	0.154	0.232
POUPET Victor	0.235	0.265	0.178	0.224	0.312	0.290	0.278	0.069	0.120	0.000	0.232	0.254	0.473	0.233	0.271	0.166	0.382
REGNAULT Damien	0.133	0.267	0.302	0.140	0.309	0.357	0.253	0.231	0.278	0.232	0.000	0.147	0.407	0.150	0.170	0.208	0.306
REMILA Éric	0.235	0.265	0.274	0.224	0.230	0.307	0.176	0.281	0.278	0.254	0.147	0.000	0.473	0.233	0.209	0.256	0.363
ROBERT Julien	0.438	0.492	0.528	0.417	0.517	0.549	0.485	0.486	0.499	0.473	0.407	0.473	-0.000	0.434	0.481	0.448	0.487
ROMASHCHENKO Andrei	0.159	0.243	0.286	0.145	0.286	0.359	0.255	0.258	0.280	0.233	0.150	0.233	0.434	0.000	0.249	0.277	0.376
ROUQUIER Jean-Baptiste	0.225	0.270	0.365	0.215	0.317	0.281	0.283	0.258	0.282	0.271	0.170	0.209	0.481	0.249	0.000	0.260	0.417
SCHABANEL Nicolas	0.280	0.156	0.138	0.212	0.193	0.181	0.262	0.118	0.154	0.166	0.208	0.256	0.448	0.277	0.260	0.000	0.175
THIERRY Éric	0.379	0.233	0.216	0.337	0.236	0.224	0.420	0.286	0.232	0.382	0.306	0.363	0.487	0.376	0.417	0.175	-0.000



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