

SEMITONES: Single-cell Marker Identification by Enrichment Scoring

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1 Abstract

2 Identification of markers is an essential step in single-cell analytic. Current
3 marker identification strategies typically rely on cluster assignments of cells.
4 Cluster assignment, in particular of development data, is non-trivial, potentially
5 arbitrary and commonly relies on prior knowledge. Yet, cluster uncertainty is
6 not commonly taken into account. In response, we present SEMITONES, a
7 principled method for cluster-free marker identification. We showcase its ap-
8 plication on healthy haematopoiesis data as 1) a robust alternative to highly
9 variable gene selection, 2) for marker gene and regulatory region identification,
10 and 3) for the construction of co-enrichment networks that reveal regulators of
11 cell identity.

12 **Background**

13 Since the inception of single-cell RNA sequencing (scRNA-seq) in 2009, single-
14 cell methods have become commonplace. scRNA-seq provides a snapshot of the
15 gene expression state of single cells and is a valuable resource to address ques-
16 tions on cell identity and cell lineage relationships. In recent years, single-cell
17 assays for transposase-accessible chromatin using sequencing methods (scATAC-
18 seq) have also become available. scATAC-seq provides a snapshot of the chro-
19 matin accessibility profile of single cells and can be used to identify putative
20 cell-type-specific *cis*-regulatory regions.

21 The appearance of these novel, sparse data types sparked the development
22 of specialized single-cell analysis methods that cover the entire single-cell data
23 analysis workflow. In both scRNA-seq and scATAC-seq pipelines, feature identi-
24 fication is an essential step which is commonly performed twice. First for feature
25 selection to reduce the number of genes or accessible regions in the data, and
26 later to identify markers of cell identity [1]. Feature selection for dimension-
27 ality reduction is most commonly performed by the identification of a certain
28 number of the most variable or most common features. The number of features
29 depends on the task complexity and influences clustering accuracy [1, 2]. If too
30 many features are chosen, spurious clusters of cells with no specific identity may
31 occur. Contrarily, if too few genes are selected, clusters of cells from distinct
32 biological origins may cluster together. This is especially problematic since the
33 ground truth of the cell types present in an experiment is commonly not avail-
34 able. Additionally, these effects are propagated into the downstream analyses
35 including marker identification, where commonly performed differential expres-
36 sion methods rely on the premise that the cell identities are known without
37 consideration for annotation uncertainty [3]. These observations illustrate the

38 interdependence between clustering accuracy and feature identification.

39 The aforementioned difficulties are aggravated when one considers develop-
40 mental data, like whole-organism development [4] or haematopoiesis [5] data.
41 In these datasets, cells are found along the full developmental axis, from omni-
42 and pluripotent stem cells to fully differentiated cells. Thus, clustering the cells
43 into distinct cell types becomes less meaningful. Pseudotime analysis is com-
44 mon for data of this nature. In these analyses, marker feature identification
45 is commonly performed by differential testing between branches, without con-
46 sidering the uncertainty in branching point determination. Thus, reservations
47 considering annotation accuracy persist.

48 Finally, genes and *cis*-regulatory elements act in interaction with one an-
49 other. It is the combination of expressed genes and/or open chromatin regions
50 which determine the transcriptomic or *cis*-regulatory state of an individual cell.
51 Thus, the identification of distinct regulatory (gene expression) networks is ex-
52 pected to provide a clearer picture of cell identity than individual markers.

53 To address the aforementioned challenges, we have developed SEMITONES
54 (Single-cEll Marker IdentificaTiON by Enrichment Scoring). SEMITONES is
55 a method for the identification of informative features and/or feature sets in
56 scRNA-seq and scATAC-seq data independent of data clustering. We illus-
57 trate the practical use of SEMITONES by application to published healthy
58 haematopoiesis scRNA-seq and scATAC-seq data [5]. We show its application
59 to feature selection for dimensionality reduction, marker gene and *cis*-regulatory
60 element identification, and signature gene set identification. In short, we present
61 a flexible method for the identification of signatures of cell identity in single-cell
62 omics data.

63 Results

64 SEMITONES identifies informative features in single-cell omics data. We con-
65 sider a feature as informative if it is only present or absent in similar cells since
66 both the presence and absence of a given feature are informative for cell identity.
67 The standard SEMITONES workflow consists of three steps. First, it selects
68 a set of diverse reference cells from the entire population of cells to serve as
69 a representation of the cell states present in the sample (Figure 1a). Next, it
70 calculates the enrichment score of each feature for the reference cell neighbour-
71 hood using a linear regression framework (Figure 1b). Lastly, to decide whether
72 a feature is informative or not, it performs statistical testing against a permu-
73 tation null distribution (Figure 1c). Besides single features, this procedure can
74 be followed for sets of features. The feature set enrichment scores can then be
75 used to construct co-enrichment graphs where vertices represent features and
76 the edges between them are weighted by enrichment scores (Figure 1d).

77 We evaluate the application of SEMITONES on published scRNA-seq and
78 scATAC-seq data of healthy haematopoiesis [5]. The primary objective of SEMI-
79 TONES, the clustering-free identification of markers of cell identity by enrich-
80 ment scoring, is explored for both scRNA-seq and scATAC-seq. Additionally,
81 we explore the selection of significantly enriched genes for feature selection as
82 an alternative to the selection of highly variable genes. Lastly, we show how
83 SEMITONES can be used to construct co-enrichment networks which reveal
84 regulators of cell identity.

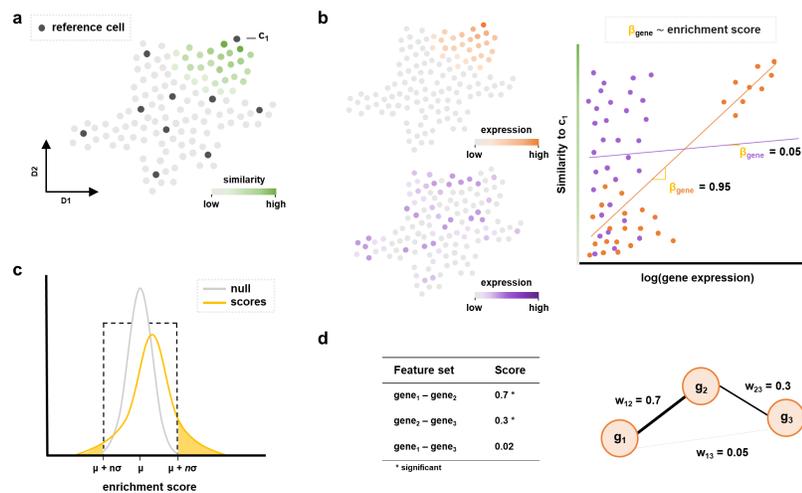


Figure 1: SEMITONES workflow. a) a two-dimensional embedding of all cells where dark grey dots are the selected reference cells. In the green gradient, we show the similarity to reference cell c_1 . b) Based on the assumption that informative genes are only expressed in the reference cell neighbourhood, we identify informative (orange) and uninformative (purple) genes in the reference cell (c_1) neighbourhood. The value of β is (proportional to) the enrichment score, so informative genes get high scores and vice versa. c) Scores in the shaded orange area are declared significant because they are more than n standard deviations away from the mean of the null-distribution. This null-distribution is the distribution of enrichment scores for the permuted feature vector of all features in the data. d) Given enrichment scores for sets of genes, we construct co-enrichment graphs where vertices are genes and the edges are weighted by the enrichment score of the gene set consisting of the genes connected by this edge.

85 SEMITONES identifies marker genes

86 SEMITONES identifies known marker genes without preceding clustering (Fig-
87 ure 2). To illustrate, the top 3 most highly enriched genes include the erythro-
88 cyte markers *AHSP*, *HBB*, and *CA1* [6], the plasma cell markers *TNFRSF17*
89 [7] and *GPRC5D* [8], and the eosinophil/basophil/mast cell markers *HDC* and
90 *CLC* [9] (Figure 2a, see Supplementary Table 1, Additional File 2). This con-
91 firms that SEMITONES identifies markers of specialized cell types. In addi-
92 tion, SEMITONES identifies markers for stem- and progenitor cells, like the
93 haematopoietic stem cell (HSC) markers *AVP* [10] and *CRHBP* [11], the HSC
94 and multipotent progenitor (MPP) marker *SPINK2* [12], and the transcription
95 factor *GATA2* associated with erythroid-megakaryocyte lineage commitment
96 [6] (Figure 1b, see Supplementary Table 1, Additional File 2). SEMITONES
97 can also identify markers for specialized subpopulations of highly similar cells,
98 including the CD4⁺ T helper 17 (T_h17) cell marker *TNFRSF4* [9], the CD8⁺
99 mucosal associated invariant T (MAIT) cell marker *SLC4A10* [13], and the
100 transitional B cell specific *DTX1* (Figure 2b, see Supplementary Table 1, Addi-
101 tional File 2). These results illustrate that SEMITONES identifies markers of
102 cell identity-specific marker genes for fully differentiated, progenitor, and rare
103 cell populations.

104 SEMITONES is also suited to retrieve markers of specialized subpopulations
105 of highly similar cells, such as specific markers for different monocytic cell popu-
106 lations. To illustrate, SEMITONES identified relative enrichment markers that
107 distinguish immature classical monocytes, classical monocytes, and intermediate
108 monocytes (see supplementary Figure 1, Additional File 1, and Supplementary
109 Table 1, Additional File 2). Here, immature classical monocytes were identified
110 by top 4 enrichment of *S100A8*, *S100A9*, and *S100A12* and relatively lower
111 enrichment of the classical monocyte markers *CD14* and *VCAN*. The *S100A9*

112 and *S100A8* genes have previously been described to be highly expressed in the
113 early stages of monocytic differentiation [14, 15, 16]. Additionally, these *S100*
114 genes are also markers for human monocytic myeloid-derived suppressor cells
115 (MDSCs) that develop from immature myeloid cells in disease states like chronic
116 inflammation [17], further corroborating this annotation. Using SEMITONES
117 we identify *PLBD1*, *RBP7*, and *PADI4* as highly enriched in immature classical
118 monocytes (Figure 1c, see Supplementary Table 1, Additional File 2). These
119 three genes are not within the top 10 most highly enriched genes for other mono-
120 cytic subpopulations, and the co-expression of *RBP7* and *PADI4* appears to be
121 specific to immature classical monocytes (Figure 2b). Similarly, we identify
122 reference cells with high enrichment for *LGALS2* in absence of top 10 enrich-
123 ment of the classical monocyte marker *VCAN* [9]. In line with observations
124 of higher relative expression of *LGALS2* in intermediate monocytes compared
125 to non-classical monocytes [18], we suggest that this identifies a population of
126 intermediate monocytes.

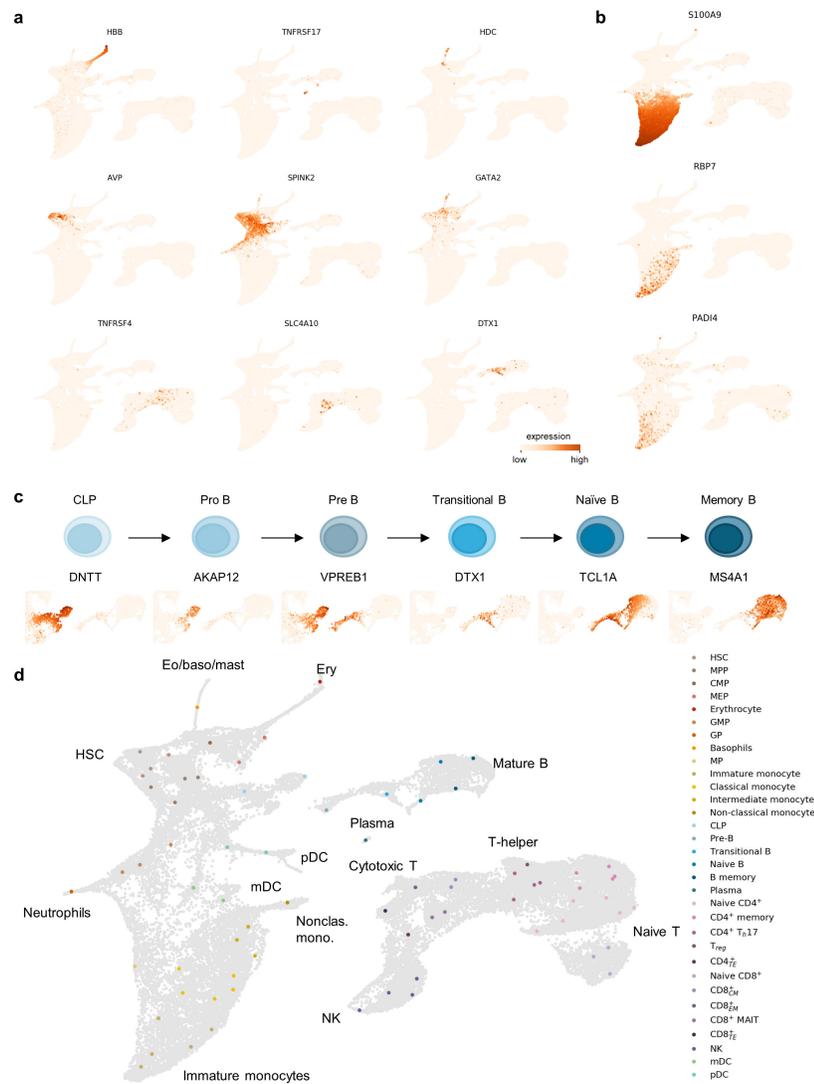


Figure 2: Application of SEMITONES for marker gene identification in scRNA-seq data. a) Highly specific markers of well-characterized cell types (top row: erythrocytes, plasma cells, eosinophil/basophil/mast cell lineage), progenitor cells (middle row: haematopoietic stem cells, haematopoietic stem- and progenitor cells, myeloid progenitors), and specific subpopulations (bottom row: T_{reg}, CD8⁺ MAIT, and transitional B cells). b) The expression profile of the known immature monocyte marker *S100A9* and the newly proposed immature classical monocyte markers *RBP7* and *PADI4*. c) The expression of markers along the B cell developmental trajectory. d) Reference cell annotations based on the marker genes identified by SEMITONES.

127 Similarly, SEMITONES identifies markers of developmental stages along the
128 haematopoiesis axis, as we illustrate using the example of B-cell maturation
129 (Figure 2c). Here, as the top-scoring gene in one reference cell, we identify
130 the *DNTT* gene which codes for the recombination substrate terminal deoxynu-
131 cleotidyl transferase that is involved in immunoglobulin (Ig) and T-cell receptor
132 (TCR) recombination [19]. This gene is expressed in the lymphoid-primed pro-
133 genitor (LMPP) stage and upregulated in the common lymphoid progenitor
134 (CLP) stage [20]. Therefore, we can identify this cell as a CLP. In another
135 cell for which high *DNTT* enrichment is found, the top-scoring enrichment is
136 found for *AKAP12* (see Supplementary Table 1, Additional File 2), which is
137 expressed exclusively in pro-, pre-, and immature B lymphocytes [21]. Given
138 the combined enrichment of *DNTT* and *AKAP12*, we identify this cell as a
139 pro-B cell. Both these cells also show enrichment for the *VPREB1* gene, which
140 encodes the ι polypeptide chain that is part of the pre-B cell receptor [22]. This
141 gene is lowly expressed in CLPs and highly expressed in pro-B and pre-B cells
142 [23], further confirming our annotations. Interestingly, the identification of a
143 cell stage with a strong cell cycle signature which includes the *TOP2A*, *KIFC1*,
144 and *NUSAP1* genes, alongside *VPREB1* as the 19th most enriched gene, allows
145 for the identification of large-pre B cells, a highly proliferative cell state in B
146 cell development [24]. Furthermore, we find high *DTX1* and *BMP3* enrichment
147 for a cell that can now be annotated as a transitional B lymphocyte, the next
148 step in B lymphocyte development [25, 26]. Next, selective top 10 enrichment
149 of *TCL1A*, which is not expressed in memory B cells [27], and *FCER2*, which
150 is involved in B cell differentiation and regulates IgE production [22], indicates
151 cells that are immature B lymphocytes [9]. Lastly, top enrichment for *MS4A1*,
152 coding for the B-lymphocyte antigen CD20 which promotes calcium influx after
153 activation by the BCR [28], and *FCER2* in the absence of *TCL1A* can be used

154 to identify mature B cells [9, 27]. To conclude, SEMITONES identifies markers
155 of many cell identities along the developmental axis without the need to enforce
156 (arbitrary) cell identity boundaries.

157 After confirming that SEMITONES identifies markers of cell identity, we
158 use the top 10 most highly enriched genes to annotate all reference cells (Figure
159 2d). To evaluate the cell-type retrieval of our data-driven selection approach,
160 we compare those annotations to the published cluster annotations from [5].
161 This comparison reveals that one cell of every annotation is present in our set of
162 75 reference cells (see supplementary Figure 2, Additional File 1), i.e., our sim-
163 ple data-driven selection procedure manages to include all cell types of interest
164 by selecting just 0.2% of the total number of cells as reference cells. Besides,
165 we identify additional cell types based on SEMITONES reference cell selection
166 and enrichment scores, including intermediate monocytes, and several B- and
167 T-lymphocyte subsets. Further comparisons were made to a set of 75 man-
168 ually selected reference cells (see supplementary Figure 3, Additional File 1),
169 annotated based on SEMITONES enrichment scores. One of these manually
170 selected reference cells was identified to be a plasmablast, a cell type that is not
171 part of the cluster-based or algorithmically selected reference cell annotations.
172 We note that the data-driven reference cell selection depends on the dissimilar-
173 ity metric and the embedding over which the dissimilarity is determined (see
174 supplementary Figure 4, Additional File 1). In general, given a descriptive sim-
175 ilarity metric, the data-driven selection of reference cells will provide a sample
176 of cells that is representative of the population.

177 The results described above relate to enrichment scores obtained using an
178 RBF-kernel with $\gamma = 8 \times 10^{-1}$ to represent the pairwise cell similarities be-
179 cause this parameterization allows for the identification of selective cell identity
180 markers. However, by decreasing the value of γ , one can also identify more glob-

181 ally enriched genes (see supplementary Figure 5, Additional File 1). Namely,
182 γ is the inverse of the radius of influence, which is proportional to the size of
183 the cell neighbourhood for which we want to retrieve marker genes. This illus-
184 trates how SEMITONES can flexibly infer highly specific or global cell identity
185 markers without relying on hard cluster boundaries.

186 **SEMITONES identifies transcriptional regulators**

187 To reveal co-enrichment relationships of genes in a given cell neighbourhood, we
188 construct co-enrichment graphs using SEMITONES co-enrichment scores. Since
189 $\sim 143 \times 10^6$ possible pairwise gene sets of 16,900 expressed genes exist, we com-
190 pute pairwise enrichment scores for gene sets of significantly enriched genes in a
191 subset of reference cells. This subset of reference cells contains one cell of each
192 annotation, where we select the cell with the enrichment score for the primary
193 annotation marker (see Supplementary Table 2, Additional File 3). Given this
194 subset, we obtain 333974 possible pairwise sets of significantly enriched genes
195 ($n_\sigma = 25$) per cell in the subset. Next, we perform enrichment scoring for all
196 gene sets for each reference cell in the subset (see Methods). We then construct
197 co-enrichment graphs containing all gene sets that are significantly, positively
198 co-enriched ($n_\sigma = 30$) in some reference cell. To unveil the crucial connections
199 in each co-enrichment graph, we evaluate the maximum spanning tree (MST)
200 of each graph.

201 The co-enrichment graphs contain paths that link together genes that inter-
202 act in specific stages of haematopoietic development. To illustrate, in the in-
203 teraction co-enrichment graph of the transitional B cell neighbourhood we find
204 that *IGLL5* is highly connected to its predicted interaction partner *CD79B* (see
205 supplementary Figure 6, Additional File 1, [29]). These genes encode proteins
206 ($\text{Ig}\beta$, and $\text{Ig}\lambda$, respectively) that are involved in pre-B cell receptor signalling,

221plementary Figure 7, Additional File 1), whilst the *S100A9* gene was found to
222be more highly enriched in immature classical monocytes. Differences between
223monocytic cell populations are also found regarding which other genes a highly
224connected gene connects to. To illustrate, *NEAT1* is a highly central node in
225classical and intermediate monocytes but connects to different genes in each
226subset (see supplementary Figure 7, Additional File 1). In classical monocytes,
227*NEAT1* is highly connected to *S100A9* and *S100A8*, but in intermediate mono-
228cytes it is highly connected to *LGALS2*, *HLA-DRB1*, and *HLA-DRA*. These
229interactions are plausible based on higher expression of *S100A8* and *S100A9*
230in classical monocytes and *HLA-DRA* in intermediate monocytes compared to
231other monocyte populations [32]. Descriptions of gene interactions in monocytic
232subpopulations are only sparingly available in the literature, and we did not find
233any mechanistic evidence for the interactions described above. In general, how-
234ever, these results confirm that SEMITONES uncovers subtle differences in the
235co-enrichment networks of highly similar cell populations. Based on the evidence
236described for transitional B lymphocytes and naive CD8⁺ cells, we suggest that
237these represent putative mechanistic distinctions.

238To identify central genes in the co-enrichment networks, we calculate the
239current flow betweenness centrality of the vertices in the MST (see Supplemen-
240tary Table 3, Additional File 4). Inspection of the top 10 most central genes
241reveals known regulators of cell identities. For example, the known regulators
242of erythropoiesis *GFI1B* and *HES6* are in the most central vertices of all ery-
243throcyte co-enrichment graphs [33, 34]. Interestingly, these genes are ranked
244only 31st and 46th most enriched in the erythrocyte neighbourhood. Similarly,
245*S100A4* is a highly central node in all T_h17 co-enrichment graphs (Figure 3b,
246see Supplementary Table 3, Additional File 4), but is only the 52nd most en-
247riched gene in the T_h17 neighbourhood. This rank is intuitively coherent with

248 the global expression profile of this gene, with high expression observed in all
249 monocyte, monocytic dendritic cells (mDC), natural killer (NK) cell, and ma-
250 ture T lymphocyte populations (Figure 3b). *S100A4* is suggested as a regulator
251 of T_H17 differentiation, albeit in Rheumatoid Arthritis mouse models [35]. An-
252 other *S100* gene, *S100A11*, was found as a highly central node in minimum
253 expression-based co-enrichment graphs of T_H17 and T_{reg} neighbourhoods (see
254 Supplementary Table 3, Additional File 4), whilst ranking as 546th and 790th
255 most enriched, respectively. This gene has been implicated as a regulator of T_{reg}
256 development [36]. Based on these results, SEMITONES co-enrichment analysis
257 enables the identification of putative regulators of cell-type specialization, also
258 in cases where these regulators are not restrictively expressed in a specific cell
259 neighbourhood.

260 Lastly, we qualitatively assess the robustness of biologically meaningful co-
261 enrichment identification when using different approaches for gene set expres-
262 sion vectors. We find that some, but not all, connections are shared between
263 all graphs for a given cell neighbourhood. For example, *AHSP* and *GFI1B* are
264 found to be highly connected in all erythrocyte co-enrichment graphs (see sup-
265plementary Figure 8, Additional File 1abcd), whilst the connections of *AHSP*,
266 *HBB*, and *HBB* are only found for interaction, maximum value-, and median
267 value-based co-enrichment graphs (see supplementary Figure 8, Additional File
268 1abc). Similarly, the interactions between *ASHP*, *KLF1*, *HBA1* and *HBA2*
269 are only found in the minimum-value based graphs (see supplementary Fig-
270ure 8, Additional File 1d). All these connections can be traced back to the
271 biology of erythrocyte development and function. Namely, both *AHSP* and
272 *GFI1B* are essential for erythrocyte development and function [33, 37], *AHSP*
273 is a haemoglobin stabilizing protein and a chaperone of *HBA1* and *HBA2*, and
274 *KLF1* binds to the promoters of *HBA1* and *HBA2* [38]. Additionally, high

275 confidence interactions from experiments and curated databases were found be-
276 tween *AHSP*, *HBA1*, *HBA2*, *HBB*, and *HBD* in STRING [29]. Overall, these
277 results suggest that interaction, maximum value, and medium value-based co-
278 enrichment are more similar to each other than the minimum expression-based
279 co-enrichment graphs. This is readily explained by the relative focus on more
280 lowly expressed genes for the minimum value-based co-enrichment graphs, with
281 its stronger emphasis on lowly expressed genes. Importantly, independent of
282 the method of gene set expression vector construction, biological proof of the
283 co-enrichment identified SEMITONES can be found in curated databases and
284 the scientific literature [29].

285 **SEMITONES for feature selection**

286 SEMITONES is also a highly effective approach for feature selection. Feature
287 selection typically takes place at the beginning of the preprocessing, when little
288 information is available to aid the selection of a suitable similarity metric. We
289 therefore choose the standard cosine similarity to characterize the similarity be-
290 tween cells. Additionally, we compute the similarity over the top 50 principal
291 components instead of an optimized multi-dimensional UMAP. On the same
292 grounds, we use the manually curated reference for feature selection. These
293 reference cells were annotated when assessing the cell type retrieval in the data-
294 driven reference cell selection, and we will use the same annotations in this
295 section. We use SEMITONES to select 4000, 2000, 1000 and 500 significantly
296 enriched genes by adjusting the number of standard deviations away from the
297 null-distribution mean at which we declare significance. This approach is com-
298 pared to selecting the same numbers of highly variable genes (HVGs) with the
299 “Seurat-flavoured” HVG selection from Scanpy [39]. For each set of selected
300 features, we perform LSI and construct a 2D UMAP using 35 nearest neigh-

301 bours with a minimum Euclidean distance of 0.3. The methods are evaluated
302 based on the cell identity separation and marker gene localization in the UMAP
303 space.

304 The separation of cell identities in the UMAP space is less affected by se-
305 lecting a lower number of SEMITONES enriched genes than to selecting a lower
306 number of HVGs (see supplementary Figure 9, Additional File 1). To illustrate,
307 when selecting 4000 genes, the only difference is the reduced separation of ery-
308 throcytes and megakaryocyte-erythrocyte progenitor (MEP) cells when using
309 HVGs. However, the discrepancies increase as we lower the number of genes we
310 select. For example, when using the top 2000 HVGs, plasmablasts and plasma
311 cells cluster together, and one $CD8^+_{CM}$ is found within the naive $CD8^+$ cell
312 neighbourhood. There is no decreased separation when using 2000 most en-
313 riched genes, and even lowering the number of genes to the 1000 most enriched
314 genes does not impact the separation of cell identity in the 2D UMAP space.
315 In contrast, when using the 1000 most variable genes, one B cell is found in the
316 NK-cell neighbourhood, and one NK cell is found in the $CD4^+$ neighbourhood.
317 Additionally, granulocytes, plasmacytoid dendritic cells (pDCs), and granulo-
318 cyte and monocyte progenitors (GMP) are no longer as distinctly separated, and
319 neither are the different monocyte subpopulations (Figure 4). Lastly, and per-
320 haps most apparent, the erythrocyte and eosinophil/basophil/mast cell popula-
321 tions are not resolved. Strikingly, these erythrocyte, eosinophil/basophil/mast
322 cell and the granulocyte progenitor (moving towards neutrophils) branches that
323 contain only a few cells, are still resolved when using just the 500 most highly
324 enriched genes, but we observe the first loss of resolution, with the naive $CD8^+$
325 cells merging with the $CD4^+$ and T_H17 cell neighbourhoods. The naive $CD8^+$
326 population remains well separated when using the top 500 HVGs but at the cost
327 of a further decrease in the separation of additional T cell subsets and mono-

328 cyte subpopulations. Overall, these results demonstrate that a smaller number
 329 of SEMITONES selected features explains the same amount of biological vari-
 330 ation as a larger set of HVGs.

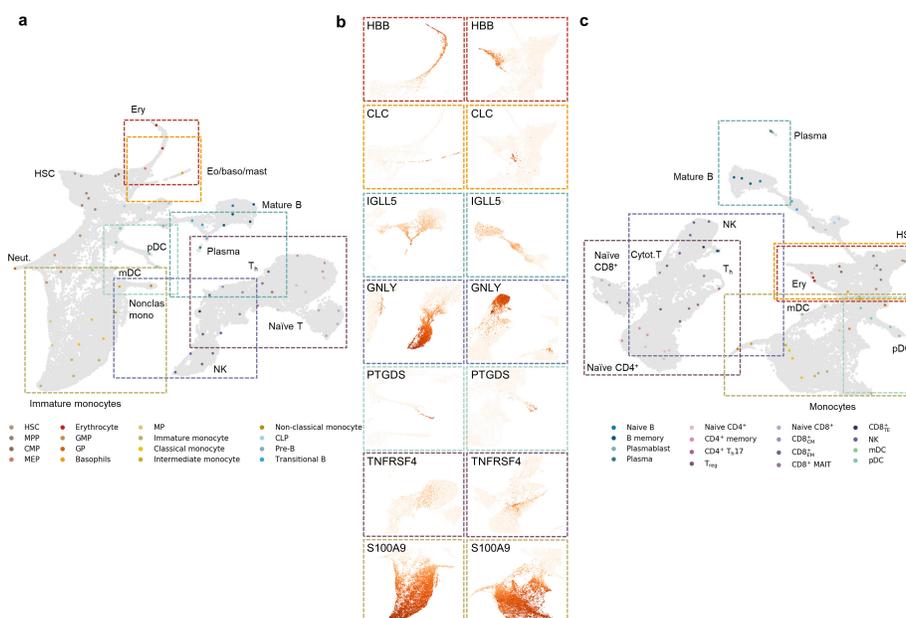


Figure 4: SEMITONES is a more sensitive alternative to highly variable gene selection. a) UMAP embedding of the scRNA-seq data based on the top 1000 most enriched genes. b) Marker gene expression visualized on the top enriched gene UMAP (left column, panel a) and the highly variable gene UMAP (right column, panel c). The border colours correspond to the annotation label colours of the label for which this gene is a marker. c) UMAP embedding of the scRNA-seq data based on the top 1000 most variable genes.

331 The decreased separation of cell identities when using HVGs compared to
 332 highly enriched genes can be linked to the absence of marker genes in the HVG
 333 sets: the erythrocyte markers *AHSP* and *HBB* are absent from the top 4000
 334 HVGs onward, and the plasmablast marker *IGLL5* and the CD8⁺_M and NK-cell
 335 expressed *CCL5* are absent from the top 2000 HVGs. Additionally, differences
 336 in the separation of cell identity can be linked to differences in marker gene
 337 localization in the UMAP space as illustrated in Figure 4 for 1000 enriched

338 versus 1000 HVG genes. There are also genes that are more localized in UMAPs
339 constructed using the top HVGs, e.g. the T_h17 marker *TNFRSF4* when using
340 1000 (Figure 4) or 500 (see supplementary Figure 10, Additional File 1) genes. In
341 general, however, gene expression appears more localized in UMAPs constructed
342 using the top SEMITONES enriched genes. Overall, these results suggest that
343 SEMITONES feature selection reduces the gene space to a small set of highly
344 informative genes.

345 **SEMITONES identifies cell-specific cis-regulatory elements**

346 Since SEMITONES is readily compatible with the scATAC-seq input matrices,
347 we also explore its application for the identification of enriched ATAC peaks for
348 75 algorithmically selected reference cells. Visual inspection of top and bottom
349 scoring regions reveals that SEMITONES accurately identifies peaks that are
350 specifically present or absent in specific cell neighbourhoods (Figure 5a). Rarely,
351 these significantly enriched peaks correspond to known *cis*-regulatory regions,
352 like the PID1-DNER Intergenic CAGE-Defined Monocyte Enhancer (chromo-
353 some 2, 230147763-230148263bp, Figure 5a). Therefore, we use GREAT (v4.0.4)
354 [40] to identify associated genes and enriched GO terms for the significantly
355 enriched peaks ($n_{\sigma} = 20$). Based on this, we confirm that the peaks are in
356 regions responsible for haematopoietic (e.g. HSC differentiation) and immune
357 (e.g. leukocyte degranulation) processes. Many of these terms were cell type-
358 specific and enabled us to directly annotate 74 out of 75 reference cells based
359 on the GO terms and their associated genes (Figure 5b), without having to fall
360 back on complementary data such as from scRNA-seq. Most of the annotations
361 are concordant with the annotations in [5], which were obtained using Seurat's
362 canonical correlation analysis with scRNA-seq based annotations, with the ex-
363 ception of resolving all monocyte and T lymphocyte subpopulations. However,

364 in turn, we reveal additional signatures, including a Notch signalling signature
365 indicative of a pre-T lymphocyte fate in a CLP and a dendritic signature in
366 a subset of reference cells. These observations may be related to the selection
367 and representation of the reference cells and their neighbourhoods, and they
368 support the notion that early *cis*-regulatory signatures reveal lineage commit-
369 ments before they can be identified on the RNA level. Separate inference on the
370 chromatin level is thus essential to gain novel insights from scATAC-seq data.

371 Significantly enriched peaks are enriched for the transcription factor binding
372 motifs that one would expect to find in the annotated cell types. For example,
373 HOX motifs are enriched in stem and progenitor cells, GATA motifs are enriched
374 in the myeloid lineage, and PRDM1 and IRF4 motifs are enriched in the B
375 cell lineages. We also identify cell type-specific motifs. For example, we find
376 enrichment for motifs of the known regulators of B cell differentiation E2A,
377 EBF, PAX5, PU.1 and IRF8 [41] in pre-B and transitional B cells (Figure 5c),
378 and for GATA3, which is indispensable for T helper 2 (T_H2) cell differentiation
379 [42], in the CD4⁺ memory cell neighbourhood. These results further suggest
380 that SEMITONES identifies distinct and import features (i.e. open chromatin
381 regions) of cell identity.

382 Finally, we evaluate whether certain *cis*-regulatory elements are overrepre-
383 sented in the significantly enriched peaks. Selectively inaccessible regions are
384 more often promoter regions than any other *cis*-regulatory regions (Figure 5d).
385 In the same vein, peaks with a positive enrichment score are, on average, most
386 likely to fall in enhancer regions. Both these trends fit prior analyses that
387 showed that in general, promoters per default are open across conditions, while
388 many distal regulatory regions are specifically opened [43]. Lastly, we identify a
389 relative overrepresentation of enhancer regions in monocytes and T lymphocytes
390 (see supplementary Figure 11, Additional File 1), although this might be related

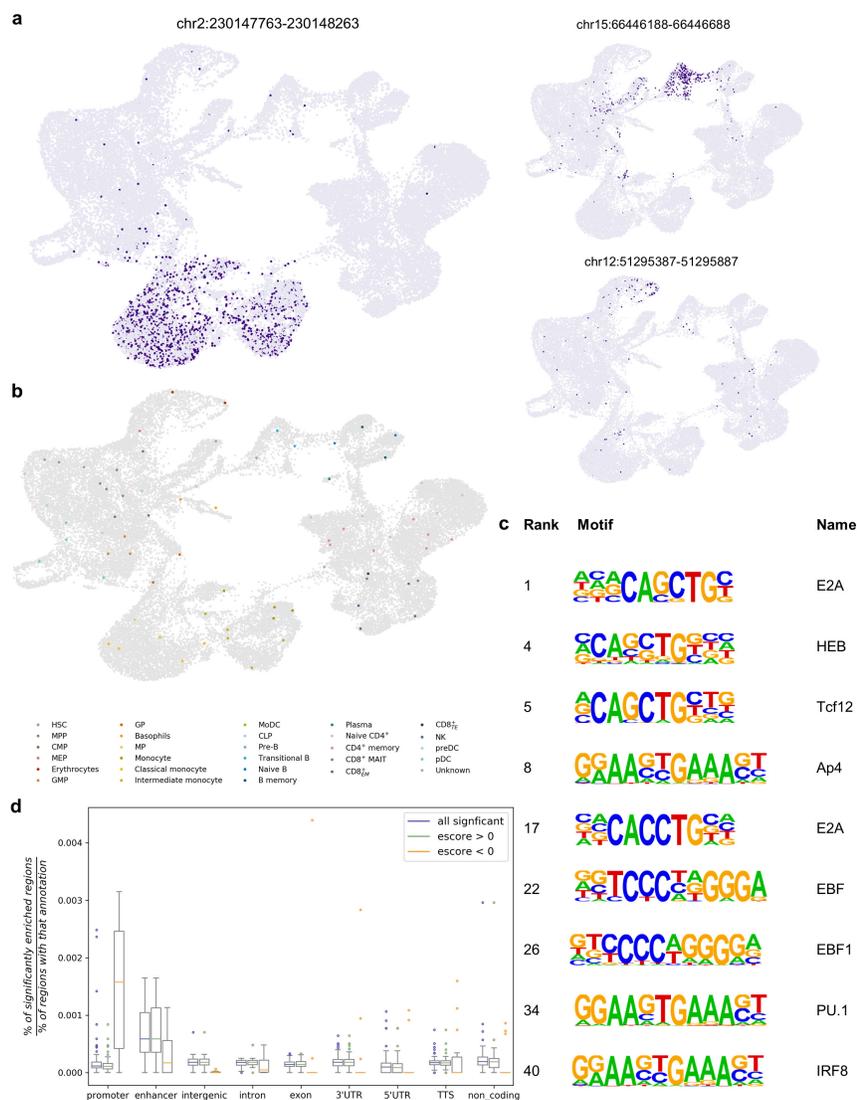


Figure 5: Application of SEMITONES for marker region identification in scATAC-seq data. a) The accessibility profile of several highly enriched regions visualized in a UMAP embedding. Region chr2:230147763-230148263 contains the PID1-DNER Intergenic CAGE-Defined Monocyte Enhancer. b) Reference cell annotations based on enriched GO-terms and associated genes, identified by HOMER, in significantly enriched marker regions identified by SEMITONES. c) Motifs that were found to be enriched in regions that SEMITONES identified as significantly enriched in transitional B cells. d) The normalized percentage of significantly enriched regions that have a certain annotation in HOMER or FANTOM5.

391 to a relative overrepresentation of certain cell types in the FANTOM5 data.
392 Overall, these results illustrate how the identification of cell type-specific open
393 chromatin regions is invaluable to the elucidation of the role of *cis*-regulatory
394 element accessibility in the acquisition and maintenance of cell identity.

395 Scalability of SEMITONES

396 SEMITONES calculates enrichment scores of 30,000 features for a single refer-
397 ence cells in just a few minutes when the number of non-zero values is representa-
398 tive of scRNA-seq ($\sim 10\%$ non-zero values) or scATAC-seq ($\sim 2\%$ non-zero val-
399 ues, Figure 6bc). When applying SEMITONES to large and sparse data with a
400 density representative of scATAC-seq data, parallel processing is needed to limit
401 runtime (Figure 6d). Runtime increases decidedly when applying SEMITONES
402 to larger numbers of features and reference cells, or combinations thereof (see
403 supplementary Figure 12, Additional File 1). Currently, the main bottleneck
404 lies in the memory demand for large numbers of reference cells, because the sim-
405 ilarity matrix is dense and of the dimension $|\text{cells}| \times |\text{reference cells}|$. Therefore,
406 it is advisable to use multiple cores when using a large number of features for
407 very sparse data, and submitting individual jobs for subsets of reference cells
408 when applying semitones to large numbers of reference cells.

409 Discussion

410 We present SEMITONES; a tool for the *de novo* identification of informative
411 features in single-cell omics data. We illustrate that SEMITONES identifies
412 marker genes and regulators of cell identity without first clustering the cells.
413 This way, we aim to mitigate the propagation of errors or biases from cluster
414 assignments. Additionally, we show that SEMITONES is an effective alterna-
415 tive to highly variable genes for feature selection in scRNA-seq preprocessing.

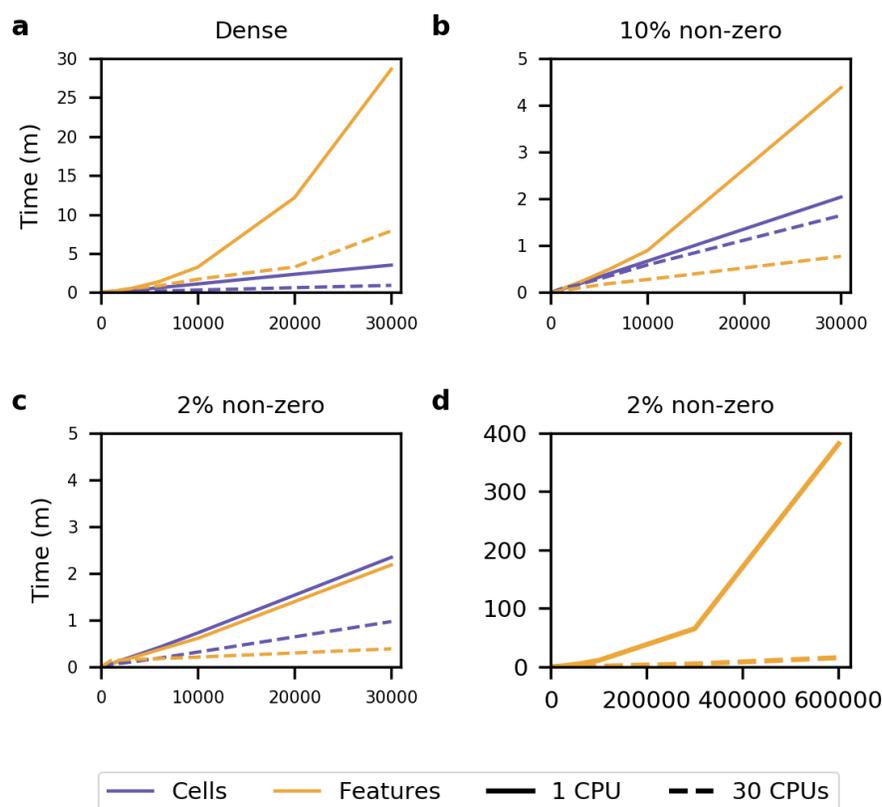


Figure 6: Runtime scalability of SEMITONES. The runtime of SEMITONES when applied to a) data with all non-zero values, b) data with a density representative of scRNA-seq data (10% non-zero values), and c) a data density representative of scATAC-seq data (2% non-zero values) for a maximum of 30,000 features. d) The runtime of SEMITONES when applied to data with 2% non-zero values with a maximum of 600,000 features, which is representative for a large scATAC-seq data set that was not filtered for highly variably/commonly accessible regions. The purple lines show the runtime with respect to the number of reference cells and the orange lines show the runtime with respect to the number of features. The dotted lines represent the runtime when parallelizing over 30 CPUs and the solid lines show the runtime when using 1 CPU. All results were obtained for a dataset containing 100,000 rows, simulating a data set of 100,000 cells in total.

416 Here, SEMITONES identifies a smaller number of genes that captures the same
417 biological diversity as a larger number of HVGs. Lastly, we show that SEMI-
418 TONES can also be readily applied to the identification of relevant peaks from
419 scATAC-seq data. In short, SEMITONES is a flexible tool aiding the identifi-
420 cation of biologically relevant features from single-cell omics data.

421 SEMITONES accurately retrieves marker genes of cell identity. Since refer-
422 ence cell annotations based on these markers largely overlap with the published
423 annotations [5], we conclude that SEMITONES accurately retrieves cell identity
424 specific markers, and propose highly enriched genes for which we did not find
425 literature evidence, like *PADI4* in immature classical monocytes, as putative
426 novel markers. These highly specific marker genes also annotated subpopula-
427 tions of cells that are otherwise highly similar, like monocytes and T cells. The
428 use of an RBF-kernel to describe cell similarities enables the identification across
429 a broad range of specificity because we can use the parameter γ to define the cell
430 neighbourhood range for which we identify informative genes (see supplemen-
431 tary Figure 5, Additional File 1). By performing regression to these similarities,
432 we remove the need to assign cells to groups of the same identity but instead
433 allow cells to be part of multiple cell neighbourhoods. This way, we identify
434 marker genes along the haematopoietic axis, as was illustrated for the B cell
435 lineage. On the other hand, the dependence on the similarity metric is a poten-
436 tial limitation of SEMITONES, especially when no prior knowledge is available
437 to evaluate the adequacy of the similarity metric. Importantly, an adequate
438 similarity metric is essential for the data-driven selection of a set of reference
439 cells that is representative of the biological cell diversity. Ultimately, given an
440 accurate similarity metric, SEMITONES identifies highly specific markers of
441 cell identity, illustrated here for the haematopoietic axis. We also explore using
442 highly enriched genes, identified by SEMITONES, as an alternative to using

443 HVGs. Cell identity separation and localization of marker gene expression in
444 the 2D UMAP space improves when using highly enriched genes compared to
445 HVGs. Thus, we conclude that n highly enriched genes capture more biolog-
446 ical variability than n HVGs. This is of particular interest in light of recent
447 developments in targeted scRNA-seq, for which the need to select a set of a few
448 hundred genes arises that contain sufficient transcriptomic information regard-
449 ing the biological system. The adequate performance while using the cosine
450 similarity over the top 50 principal components instead of an RBF-kernel over
451 25 UMAP dimensions illustrates that SEMITONES also identifies informative
452 genes when using a non-specialized similarity metric. However, the performance
453 of SEMITONES will depend on the provided reference cells since SEMITONES
454 only identifies highly enriched genes in reference-cell neighbourhoods. From
455 simulations (see supplementary Figure 4, Additional File 1) we conclude that
456 reference cell sets obtained using suboptimal similarity metric-embedding com-
457 binations do not represent all cell identities. In this case, the highly enriched
458 genes will only capture the variability for cell identities present in the reference
459 cells. Based on the same simulations, we recommend using the Euclidean dis-
460 tance over a reasonable number (e.g. 50) of principal components if using the
461 SEMITONES data-driven reference cell selection. Besides marker gene identi-
462 fication, SEMITONES can be used to construct co-enrichment graphs. These
463 co-enrichment graphs revealed several interactions indicative of mechanistic as-
464 pects of gene regulation and cellular function. For example, high co-enrichment
465 of *CD8A*, *CD3E*, and *CD3D* in $CD8^+$ T lymphocytes is substantiated by the
466 role of *CD8A* as a chaperone to the CD3-complex (Figure 3a). Highly central
467 nodes (i.e. genes) in these networks represent putative regulators of cell identity,
468 even if they are not individually enriched in a cell neighbourhood, as seen for
469 *S100A4* gene in T_H17 cells (Figure 3b, [35]).

470 The SEMITONES workflow is readily transferable to the identification of
471 marker peaks from scATAC-seq [peak x cell] matrices. Based on GO term
472 enrichment of associated genes and enrichment for known transcription factor
473 binding motifs, we conclude that SEMITONES retrieves biologically relevant
474 peaks. Additionally, we identify biological signatures that we did not unveil in
475 the marker genes. This illustrates the benefit of analysing scATAC-seq data
476 independently of scRNA-seq data, although we cautiously note that this obser-
477 vation may be a result of differences in the cell identities represented by the
478 reference cells. Besides using the enriched peaks to annotate cell identities, we
479 also use significantly enriched peaks to identify global patterns of chromatin
480 accessibility and *cis*-regulatory regions. Most notably, we find that selectively
481 inaccessible regions are most likely promoters and selectively accessible regions
482 are most likely enhancers, once more indicating the higher cell type-specificity
483 of enhancers. However, these results are limited to a small number of reference
484 cells and were not subjected to rigorous statistical analysis.

485 Conclusion

486 SEMITONES is a diverse and flexible tool for the identification of informa-
487 tive features from single-cell omics data, readily applicable to expression and
488 chromatin-related data. Its possible limitations include the need for an ade-
489 quate cell similarity metric and a set of reference cells that is representative of
490 the cell population. Therefore, in future research, we will explore deterministic
491 approaches and the use of geometric sketching [44] to select an optimal set of
492 reference cells. Additionally, we aim to improve the run time for many features
493 and the memory demand for large numbers of reference cells. Namely, the appli-
494 cation of SEMITONES to large numbers of reference cells currently requires the
495 user to perform computations for subsets of reference cells due to limitations in

496 the multiprocessing setup. On a biological level, we will explore the integration
497 of scRNA-seq and scATAC-seq data on the cell level. As such, we aim to keep
498 SEMITONES up to date as single-cell data grows and diversifies, to aid the
499 elucidation of regulatory mechanisms underlying the acquisition of cell identity
500 in health and disease.

501 Methods

502 Reference cell selection

503 In this article, we use two reference cell selection methods: an automated data-
504 driven cell selection method, and manual selection of a set of reference cells from
505 a 2D cell embedding. For the manual selection of cells from any 2D embed-
506 ding, we provide a figure widget implementation. The data-driven cell selection
507 method is presented in Algorithm 1 and described below.

Algorithm 1 Data-driven iterative selection of dissimilar cells.

```
s ← [i]
e ← [i]
k ← ⌈ $\frac{N-n}{n}$ ⌉
di ← distances(X, xi)
append k - NN of i to e
append argmax(di) to e and s
while k - NN < n - |e| do
    ds[-1] ← distances(X, xs[-1])
    append k - NN of s[-1] to e
    append argmax(ds[-1]) to e and s
end while
```

508 In addition to the methods applied in this study, we provide the options
509 to use the sklearn k-means++ implementation and a fixed-grid search. In the
510 fixed-grid search, a lattice graph of a user-defined size $n \times n$ is placed over the
511 2D embedding of single cells, as illustrated in Supplementary Figure 13, Addi-

512 tional File 1. Then, the cells closest to the intersections of the horizontal and
513 vertical grid lines are selected. The method avoids selecting a disproportionate
514 number of cells at the edge of the 2D-embedding by putting a constraint on the
515 minimum distance between each pair of selected cells. The implementations of
516 these methods can be found in the cell selection module of SEMITONES.

517 **Enrichment scoring**

518 Given a set of reference cells (Figure 1a), we identify informative features in
519 these cells. From the idea of an informative feature as being only expressed
520 or absent in similar cells, we can derive the formal definition that informative
521 features harbour a strong linear relationship with the similarity to the reference
522 cell (Figure 1b).

523 In SEMITONES, we infer informative features using a simple linear regres-
524 sion framework (Equation 1). Here, y_c is a vector representing each cell by its
525 similarity to some reference cell c using any suitable metric. As example, we use
526 an RBF-kernel with $\gamma = 8 \times 10^{-1}$ over a multidimensional UMAP embedding
527 in applications for marker selection. For applications to feature selection, we
528 use the cosine similarity over the top n principal components. The vector x_f
529 represents the value of the feature g in each cell. When applying the method
530 to scRNA-seq data, this feature vector x_f contains the gene expression level in
531 each cell. For applications to scATAC-seq data, x_f is a binary feature vector
532 indicating whether the chromatin at a certain location in a cell is accessible (1)
533 or not (0). The regression coefficient $\beta_{c,f}$, which is estimated using the ordinary
534 least squares method, describes the strength of the linear relationship between
535 y_c and x_f . Thus, the value of $\beta_{c,f}$ can be interpreted as a score of the enrichment
536 of some feature f in some reference cell c . High positive enrichment scores will
537 be obtained for features which are only observed in cells similar to some cell c

538 (Figure 1b). Inversely, low negative scores will be obtained for features which
539 are only observed in cells which are dissimilar to some cell c (Figure 1b).

$$y_c = x_{cf} \times \beta_f + \varepsilon_c, \quad \varepsilon_c \sim \mathcal{N}(0, \sigma^2) \quad (1)$$

540 In addition to single feature enrichment scores, one can also opt to calculate
541 enrichment scores for sets of features. In this case, x_f is a vector representing
542 the combined values of all features in the set. In the case of continuous feature
543 values, like in gene expression values in scRNA-seq, we provide four different
544 approaches to representing a set of features in a single vector. The first ap-
545 proach is the multiplication of the vectors, like an interaction term in multiple
546 regression. The second and third approaches are to select the lowest or highest
547 expression value of the features in a set as the representative expression value,
548 respectively. Lastly, the fourth approach is to take the median expression of the
549 features in the set as the representative value. For binary feature vectors, like
550 in scATAC-seq, we can also readily take the median feature values to present
551 the feature set expression vector. Additionally, we implement the strategy of
552 annotation a feature set as present (1) if one or all of the features in a set are
553 present and absent (0) if none of the features is present.

554 The pairwise feature set enrichment scores can be used to construct co-
555 enrichment graphs, where vertices (i.e. features) are connected by edges that
556 are weighted by the feature set enrichment scores (Figure 1d). To improve
557 interpretability we then infer the maximum spanning tree of these graphs, in
558 which all vertices are connected using the least number of edges with a maximum
559 total weight, using networkx (v2.4) [45]. The current flow betweenness centrality
560 measure is used as a measure of the importance of a feature in the co-enrichment
561 network. Visualization of graphs is performed in Netwulf [46].

562 **Significance testing**

563 The null distribution for significance testing is obtained by repeating the scoring
564 procedure using n times permuted feature vectors. Due to the permutation of
565 the feature vectors, the feature values are randomized while still resembling the
566 original data. Significance is declared at a user-defined number of standard
567 deviations ($n\sigma$) away from the mean of this null distribution (Figure 1c). Here,
568 we always use $n = 256$.

569 **Data processing**

570 The practical use of SEMITONES is illustrated by its application to healthy
571 haematopoiesis scRNA-seq and scATAC-seq data published by [5]. The scRNA-
572 seq count matrices were obtained from the GEO database (GSE139369, accessed
573 February 28 2020). The scATAC-seq count matrix was downloaded from the
574 GitHub page linked to the original data publication ([47], accessed on 3 March
575 2020).

576 The scRNA-seq data covers a total of 35582 cells obtained from six different
577 samples, including two samples of CD34⁺ enriched BMMCs, two samples of
578 non-enriched BMMCs and two samples of PBMCs. First, we removed any cells
579 for which the ratio between the number of genes expressed over the count-depth
580 is greater than or equal to 0.3. Next, we performed scran deconvolution nor-
581 malization using the computeSumFactors function using clusters obtained from
582 the quickCluster function [48, 49]. The normalized counts were log-transformed
583 using an alternative pseudo-count as proposed by Lun et al. (2018) [50]. Inspec-
584 tion of the count depth of cells in a 2D UMAP embedding (computed over the
585 top 10 principal components) revealed a cluster of cells with low count depth
586 in one of the CD34⁺ samples, which was removed. This leaves a total of 35156
587 cells.

588 The (non-normalized) count data from all cells that passed quality control
589 were combined, and scan deconvolution normalization was performed on the
590 combined data. The data were log-transformed using an alternative pseudo-
591 count [50] for use in enrichment scoring. We then performed latent semantic
592 indexing for the reduction of the normalized count data to a 50-dimensional
593 embedding. A 2D and 25D uniform manifold approximation and projection
594 (UMAP, 30 neighbours and a minimum distance of 0.3) over the LSI space were
595 computed for visualization and similarity calculations, respectively.

596 The scATAC-seq data contains a total of 35038 DC34⁺ enriched BMMC,
597 non-enriched BMMC, and PBMC cells. We performed quality control on the
598 combined data as follows. Cells were removed if their peak depth exceeds
599 200,000 or more than 60,000 peaks were called in this cell, and peaks were
600 removed if their count exceeds 40,000, leaving 35022 cells. Next, we binarized
601 the peak by cell-matrix and perform LSI to reduce the feature space to 50 dimen-
602 sions. We computed a 2D and 35D UMAP (50 neighbours, minimum distance of
603 0.5) over the 50-dimensional space for visualization and similarity calculations,
604 respectively.

605 **Evaluation references**

606 For the annotation of the scRNA-seq reference cells we look at the top 10 most
607 highly enriched genes (according to SEMITONES). The Human Blood Atlas
608 [9], with a special focus on the Monaco scaled dataset [51], served as a primary
609 reference. Additional markers were obtained from the literature (see Supple-
610 mentary Table 2, Additional File 3). The STRING (v11.0) database ([29], [52])
611 was used for qualitative evaluation of co-enrichment graphs. The assessment of
612 SEMITONES as a method for feature selection in scRNA-seq was performed in
613 comparison to the retrieval of highly variable genes as implemented in Scanpy

614 (v1.4.5) [39]. For the annotation of scATAC-seq reference cells, we obtain GO-
615 term enrichments and associated genes for significantly enriched peaks using
616 GREAT (v4.0.4) [40]. We provide all peaks in the clean scATAC-seq data as a
617 background set and select the “basal plus extension” association rule to charac-
618 terize the regulatory domain. According to this association rule, the proximal
619 domain is 5 kilobases upstream and 1 kilobase downstream of the transcrip-
620 tion start site (TSS), and the distal domain is defined as up to 1000 kilobases
621 from the TSS. *cis*-Regulatory element annotations were obtained from HOMER
622 (v10.4) (promoter, exon, 5’ UTR, 3’ UTR, intronic, intergenic, transcription ter-
623 mination site) and the permissive enhancer annotations in FANTOM 5 phase
624 2.6. In HOMER (v10.4), a region is annotated as a promoter if it lies within
625 -1000 and +100 base pairs from the TSS as annotated in RefSeq. Motif enrich-
626 ment of known transcript factor (TF) binding motifs was performed using the
627 findMotifsGenome function from HOMER (v10.4). We consider motifs enriched
628 if their (Benjamini) q-value < 0.01 .

629 **Scalability of run time**

630 The run time scalability was assessed for different numbers of cells, numbers
631 of features, data densities, and the number of core processing units (CPUs).
632 Random data sets with 100%, 10%, or 2% nonzero values were constructed. The
633 decision for 10% and 2% nonzero values were based on the sparsity character of
634 the data used in the application example. In all experiments, the total number
635 of cells was set to be 100,000. Run time was compared between computations
636 using one CPU and 30 CPUs. Parallelization over rows or columns was selected
637 based on whether the number of rows or columns was greater, respectively.

638 **Availability of data and materials**

639 The datasets supporting the conclusions of this article are available from public
640 sources. The healthy haematopoiesis scRNA-seq dataset was downloaded from
641 the Gene Expression Omnibus (GSE139369). The healthy scATAC-seq dataset
642 was downloaded from GitHub, accessed on 3 March 2020 [47, 5]. The SEMI-
643 TONES software is freely available from GitHub [53] under the GPL-3.0 license.
644 The scripts and notebooks used for data processing and analyses are published
645 on GitHub [54].

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649 **Author's contributions**

650 AHCV, SM, and UO conceived the project. AHCV implemented and evaluated
651 the method. UO and SM guided the implementation of the method. UO guided
652 the evaluation of the method. AHCV wrote the draft manuscript and UO and
653 SM suggested revisions. All authors approved the final manuscript.

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819 **Additional Files**

820 **Additional file 1 — Supplemental Figures**

821 This file (.pdf) contains all supplemental figures that were referenced within the
822 main text.

823 **Additional file 2 — Table S1**

824 Table S1 (.csv) lists the top 10 most highly enriched genes for all data-driven selected
825 reference cells.

826 **Additional file 3 — Table S2**

827 Table S2 (.csv) lists the marker genes used for the annotation of reference cells
828 based on the top 10 most highly enriched genes.

829 **Additional file 4 — Table S3**

830 Table S3 (.csv) lists the most central nodes in the co-enrichment graphs constructed
831 using enrichment scores for interaction vectors, maximum-value vectors, median-
832 value vectors, minimum-value vectors.