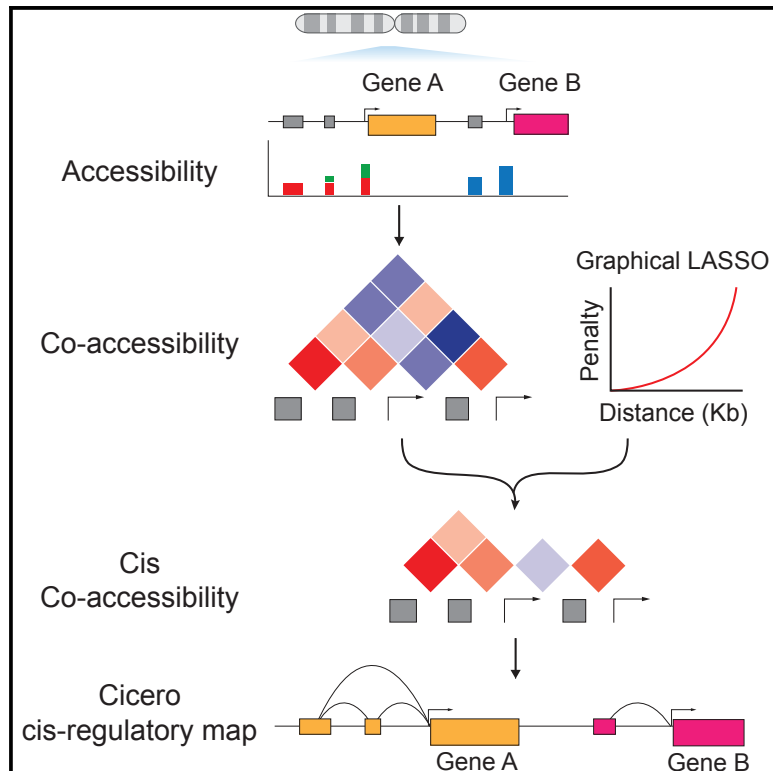


Molecular Cell

Cicero Predicts *cis*-Regulatory DNA Interactions from Single-Cell Chromatin Accessibility Data

Graphical Abstract



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In Brief

Pliner et al. introduce Cicero, a software program to connect distal regulatory elements with target genes using single-cell ATAC-seq data. They find evidence that groups of co-accessible elements form chromatin hubs and undergo coordinated changes in histone marks that are predictive of changes in gene expression in skeletal muscle development.

Highlights

- Cicero connects regulatory DNA elements to target genes
- Co-accessible elements form chromatin hubs
- Chromatin hubs are co-regulated during skeletal muscle development
- Cicero can help reveal the mechanisms of *cis*-regulation on a genome-wide scale

Cicero Predicts *cis*-Regulatory DNA Interactions from Single-Cell Chromatin Accessibility Data

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SUMMARY

Linking regulatory DNA elements to their target genes, which may be located hundreds of kilobases away, remains challenging. Here, we introduce Cicero, an algorithm that identifies co-accessible pairs of DNA elements using single-cell chromatin accessibility data and so connects regulatory elements to their putative target genes. We apply Cicero to investigate how dynamically accessible elements orchestrate gene regulation in differentiating myoblasts. Groups of Cicero-linked regulatory elements meet criteria of “chromatin hubs”—they are enriched for physical proximity, interact with a common set of transcription factors, and undergo coordinated changes in histone marks that are predictive of changes in gene expression. Pseudotemporal analysis revealed that most DNA elements remain in chromatin hubs throughout differentiation. A subset of elements bound by MYOD1 in myoblasts exhibit early opening in a PBX1- and MEIS1-dependent manner. Our strategy can be applied to dissect the architecture, sequence determinants, and mechanisms of *cis*-regulation on a genome-wide scale.

INTRODUCTION

Chromatin accessibility is a powerful marker of active regulatory DNA. In eukaryotes, chromatin accessibility at both promoters and distal elements delineates where transcription factors (TFs) are bound in place of nucleosomes (Felsenfeld et al., 1996). Genome-wide analyses of chromatin accessibility as measured by DNase hypersensitivity have found that the repertoire of accessible regulatory elements constitutes a highly specific molecular signature of cell lines and tissues (Thurman et al., 2012). Furthermore, genome-wide association studies (GWAS) show

that a substantial proportion of genetic risk for common disease falls within accessible regions in disease-relevant tissues or cell types (Gusev et al., 2014; Maurano et al., 2012).

Despite its importance, we continue to lack a quantitative understanding of how changes in chromatin accessibility relate to changes in the expression of nearby genes. A prerequisite for such an understanding is a map that links distal regulatory elements with their target genes. To this end, we developed Cicero, an algorithm that generates such linkages on a genome-wide basis based on patterns of co-accessibility in single-cell data.

We demonstrate Cicero’s capabilities through an analysis of skeletal myoblast differentiation, which remains one of the best characterized models of gene regulation in vertebrate development. Myoblast differentiation is orchestrated by a core set of TFs, including MYOD1 and MEF2 (Molkentin et al., 1995), which regulate the expression of thousands of genes as cells exit the cell cycle, align, and fuse to form myotubes. Here, we used single-cell combinatorial indexing ATAC-seq (sci-ATAC-seq) on 13,367 cells to identify 329,020 accessible elements in myoblasts, nearly 22,000 of which open or close during differentiation. When applied to these data, Cicero linked most dynamic sites to one or more putative target genes. From the resulting *cis*-regulatory map, we can predict changes in gene expression based on the chromatin accessibility dynamics of the linked distal elements.

Design

In contrast with previous approaches that rely on a large compendium of bulk chromatin accessibility data generated across many cell lines or tissues (Thurman et al., 2012; Budden et al., 2015), we sought a method that would work with single-cell chromatin accessibility data from a single experiment and that was robust to the sparsity of that data. Cicero uses sampling and aggregation of groups of similar cells to adjust for technical confounders and to quantify correlations between putative regulatory elements. Based on these correlations, Cicero links regulatory elements to target genes using unsupervised machine learning. The algorithm can be applied to any cell type and organism for which a sequenced genome and single-cell chromatin

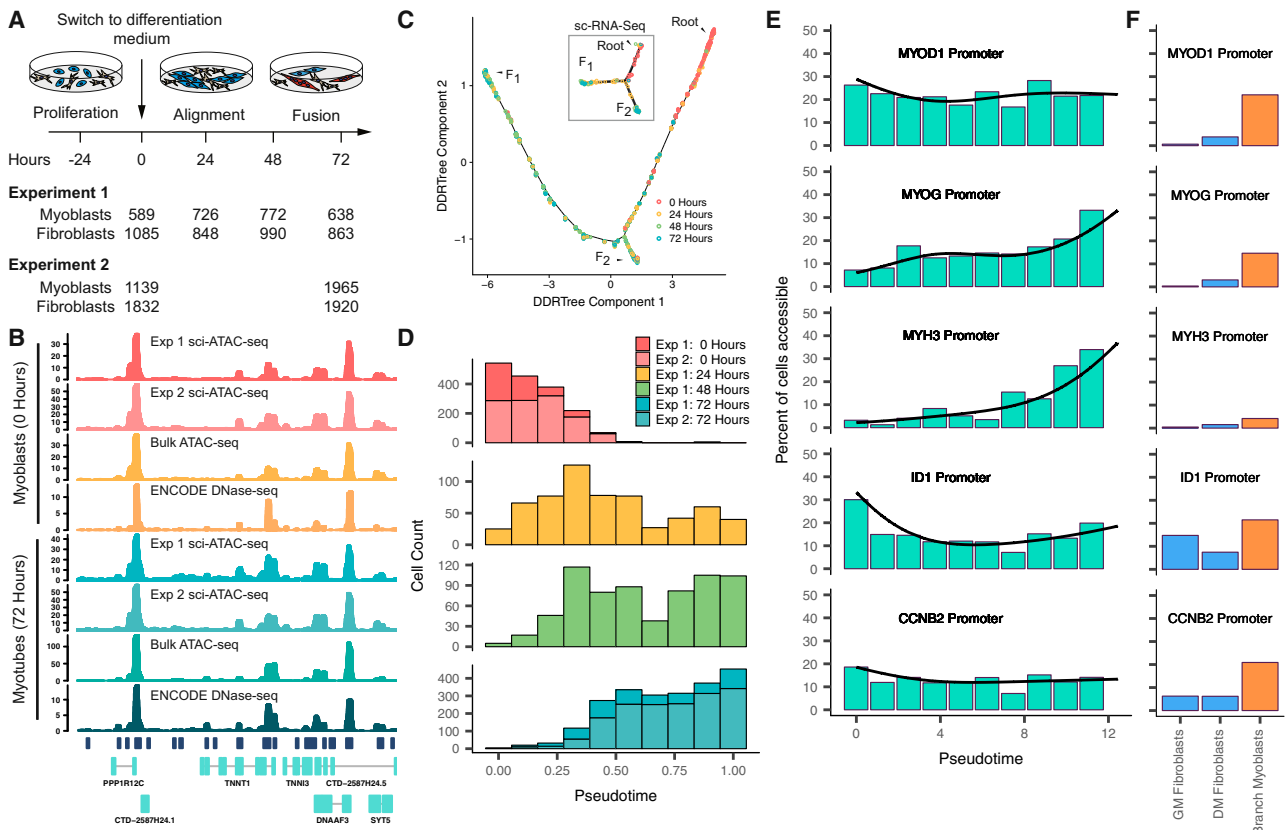


Figure 1. Differentiating Myoblasts Follow Similar Single-Cell Chromatin Accessibility and Gene Expression Trajectories

(A) Single-cell chromatin accessibility profiles for human skeletal muscle myoblasts (HSMM) were constructed with sci-ATAC-seq. Contaminating interstitial fibroblasts (common in HSMM cultures) were removed informatically prior to further analysis.

(B) Aggregated read coverage from sci-ATAC-seq experiments in the region surrounding *TNN1* and *TNN3* in myoblasts (0 hr) and myotubes (72 hr). Bulk ATAC-seq prepared from the same wells as experiment 2 are shown alongside DNase-seq from ENCODE for comparison (ENCODE experiments ENCSR000E00 and ENCSR000E0P) (ENCODE Project Consortium, 2012).

(C) The single-cell trajectory inferred from 2,725 myoblast sci-ATAC-seq profiles from experiment 1 by Monocle (see STAR Methods). In subsequent panels and throughout the paper, we exclude cells on the branch to outcome F₂ unless otherwise indicated. Inset: the sci-RNA-seq trajectory reported for HSMMs (reproduced from Figure 2 of Qiu et al., 2017a, cells were from the same lot and were cultured under identical conditions to those for sci-ATAC-seq).

(D) Distribution of cells in chromatin accessibility pseudotime from the root to trajectory outcome F₁.

(E) Percent of differentiating cells whose promoters for selected genes are accessible across pseudotime. Black line indicates the pseudotime-dependent average from a smoothed binomial regression.

(F) Percent of cells whose promoters for selected genes in (E) are accessible in fibroblasts collected in growth medium (GM) or differentiation medium (DM), as well as myoblasts localized to the branch to F₂.

See also Figure S1.

accessibility data are available. Because it accepts single-cell data as input, Cicero can in principle work on complex mixtures of different cell types as are found in tissues.

RESULTS

The Trajectories of Chromatin Accessibility and Gene Expression during Myoblast Differentiation Are Highly Similar

We performed a differentiation time course on human skeletal muscle myoblasts (HSMM), harvesting cells at 0, 24, 48, and 72 hr after the switch from growth media to differentiation media (Figure 1A). With optimized sci-ATAC-seq (Cusanovich et al.,

2018), we profiled chromatin accessibility in 13,367 cells across 2 independent experiments. Aggregated single-cell ATAC-seq data were highly concordant with both bulk ATAC-seq and published DNase hypersensitivity data from myoblasts and myotubes (Figures 1B and S1A) (ENCODE Project Consortium, 2012). To define accessible regions, we pooled reads from all cells from each experiment and called peaks with MACS 2 (Zhang et al., 2008). The vast majority of peaks were shared between experiments (Figure S1B), so we used a single merged set of peaks for all downstream analyses. After excluding 7,538 cells flagged as likely interstitial fibroblasts based on the absence of promoter accessibility in any of several known muscle markers (56%, a proportion similar to our estimate from single-cell

RNA-seq in this system) (Qiu et al., 2017a), we identified 329,020 sites accessible in muscle cells. Each cell had reads overlapping with an average of 3,466 promoter-proximal accessible sites and 9,055 distal accessible sites (Figure S1C).

We next sought to characterize changes in chromatin accessibility as myoblasts differentiated. However, analyzing differentiation from time series data is confounded by asynchronicity, i.e., Simpson's Paradox (Simpson, 1951). To overcome this, we recently developed the technique of "pseudotemporal reordering" (or "pseudotime") that uses machine learning to organize cells according to their progress through differentiation (Trapnell et al., 2014). Although our algorithm, Monocle 2, was designed for single-cell transcriptomes (Qiu et al., 2017a), we were able to adapt it to sci-ATAC-seq data with straightforward modifications (see STAR Methods).

Monocle independently placed the cells from each experiment along similar trajectories with two outcomes (denoted F_1 and F_2) (Figures 1C and S1D). These trajectories are similar to the trajectory constructed from single-cell transcriptomes in our previous work (Qiu et al., 2017a) (Figure 1C, inset). Cells harvested from growth media fell almost exclusively near the beginning of the trajectories, while cells from later time points were distributed over their length (Figure 1D). Over the path to F_1 , promoters for well-known myogenic regulators and structural components of muscle opened (became more accessible), whereas the promoter of *ID1*, a well-characterized repressor of myoblast differentiation (Benezra et al., 1990), closed (Figure 1E). Similar to the single-cell RNA sequencing (RNA-seq) trajectory (Qiu et al., 2017a), a number of cells were positioned on a branch leading to the alternative outcome F_2 . That these cells are accessible at the *MYOD1* promoter, but not the *MYH3* promoter, suggests they represent "reserve myoblasts" that did not fully differentiate (Yoshida et al., 1998) (Figure 1F). The similar trajectories constructed by Monocle from three independent experiments, as well as the close correspondence between the kinetics in expression and chromatin accessibility for key muscle genes, support the accuracy of Monocle's pseudotime ordering.

Distal DNA Elements Are Dynamically Accessible during Myoblast Differentiation

Differential analysis revealed significant pseudotime-dependent changes in accessibility at 21,678 of 329,020 (6.6%) sites during myoblast differentiation (Figures 2A and S2A). In addition, we conducted a similar differential analysis on previously published single-cell RNA-seq data from the same system (Trapnell et al., 2014). Of the "dynamic" accessible sites, only 1,324 (6.1%) were promoters (Figure 2B), of which 92 overlapped with 1,464 differentially expressed transcripts (false discovery rate [FDR] <5%) by single-cell RNA-seq. Of the 64 of promoters with non-transient changes in both accessibility and gene expression, 62 (97%) were directionally concordant. Of the 20,354 distal, dynamically accessible sites, 68% were annotated as enhancers in myoblasts or myotubes (Libbrecht et al., 2016), as compared with only 36% of all accessible sites (Figure 2B).

Using gene set enrichment analysis, we found that genes associated with contraction and other muscle-related functions were strongly enriched among genes with significantly opening

promoter regions. In contrast, promoters for genes associated with the cell cycle, which are downregulated early in differentiation, were only marginally enriched among the differentially accessible sites (Figure S2B). Most markers of actively proliferating cells did not show significant changes in promoter accessibility (Figure S2C).

Comparison to ChIP-seq data (Cao et al., 2010) revealed that 59% of opening sites and 34% of closing sites are bound by MYOD1 in myotubes and myoblasts, respectively (Figure 2C). In contrast, only 16% of static sites (those without significant changes in accessibility) were MYOD1-bound in either myoblasts or myotubes. Dynamically accessible distal elements and promoters were also strongly enriched for binding motifs for MYOD1, MYOG, and MEF2 family members and other TFs with central regulatory roles in myogenesis (Figure 2D).

Many TFs recruit enzymes that mark histones near regulatory DNA elements. For example, MYOD1 recruits p300, whose histone acetyltransferase activity is required for its role in activating gene expression (Dilworth et al., 2004; Puri et al., 1997; Sartorelli et al., 1997). A comparison with ENCODE data for myoblasts and myotubes showed overwhelming directional concordance between sites that were gaining or losing H3K27 acetylation (H3K27ac) versus sites that were opening or closing in chromatin accessibility, respectively (Figure 2E). However, most changes in histone marks during differentiation occurred at sites that did not undergo significant changes in chromatin accessibility (Figure S2D). Thus, myoblast differentiation is characterized by changes in H3K27ac at hundreds of thousands of sites, only a minority of which were accompanied by changes in their chromatin accessibility, at least to the extent that they are detectable by the methods employed here.

Cicero Constructs Genome-wide *cis*-Regulatory Models from Sci-ATAC-Seq Data

We next sought to exploit patterns of co-accessibility between distal elements and promoters to build a genome-wide *cis*-regulatory map. This is challenging for several reasons. First, the raw correlations are driven in part by technical factors such as read depth per cell. Second, we have insufficient observations to accurately estimate correlations between billions of pairs of sites. Third, single-cell ATAC-seq data are very sparse. Finally, while the accessibility of distal elements might be correlated with their target promoters, very distant or interchromosomal pairs of sites, will also be correlated by virtue of being part of the same regulatory program.

To address these challenges, we developed a new algorithm, Cicero, that subtracts technical and genomic distance effects while constructing a global *cis*-regulatory map from single-cell chromatin accessibility profiles (Figure 3A). Briefly, the user provides Cicero with cells as input that have been clustered or pseudotemporally organized. The algorithm creates many groups of cells, each comprised of 50 cells similarly positioned in clustering or trajectory space. This helps to overcome the sparsity of the data while avoiding Simpson's paradox (Simpson, 1951; Trapnell, 2015). It then aggregates accessibility profiles for cells in each group to produce counts that can be readily adjusted to subtract the effects of technical variables. Finally, it computes the correlations in adjusted accessibilities

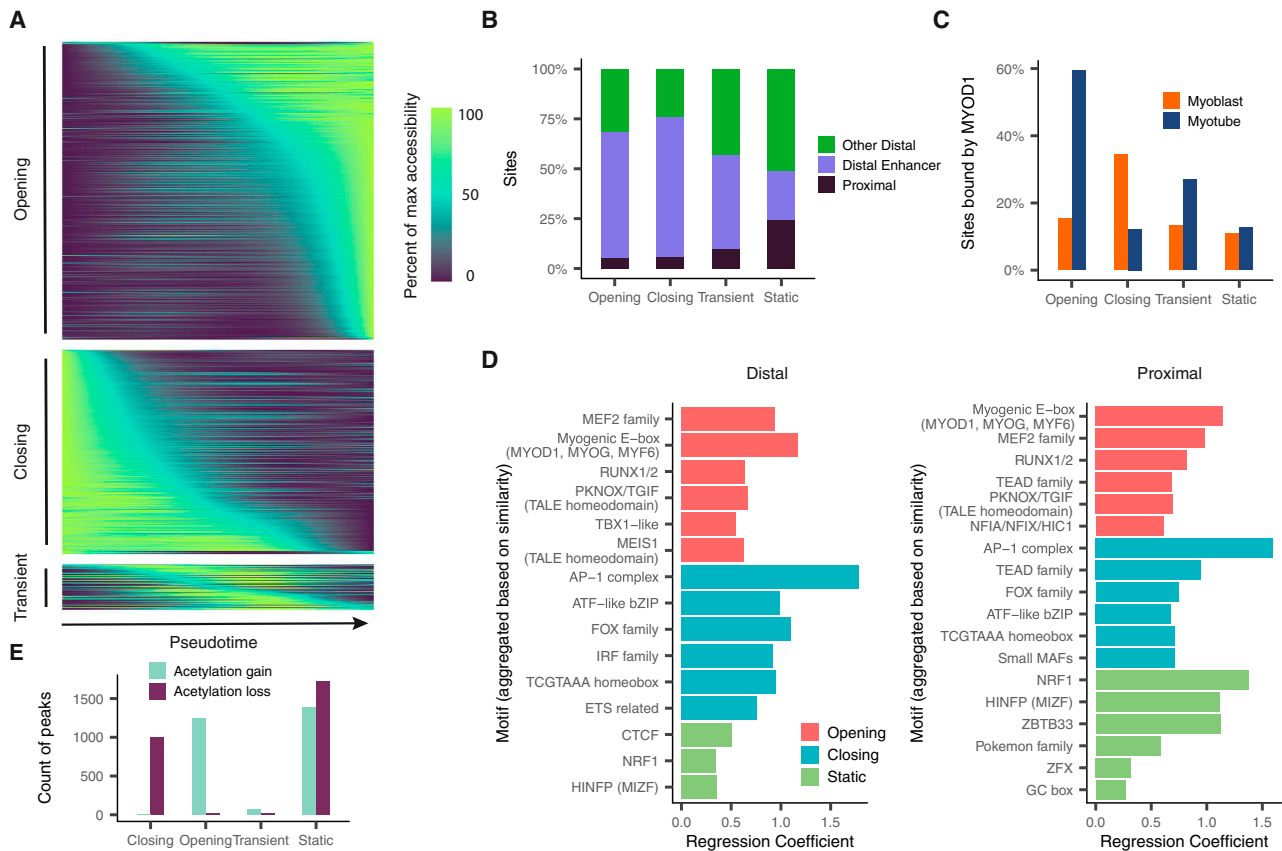


Figure 2. Thousands of DNA Elements Are Dynamically Accessible during Myoblast Differentiation

(A) Smoothed pseudotime-dependent accessibility curves, generated by a negative binomial regression and scaled as a percent of the maximum accessibility of each site. Curve regressions are the same as regression for differential accessibility (see STAR Methods). Each row indicates a different DNA element. Sites are sorted by the pseudotime at which they first reach half their maximum accessibility.

(B) Proportions of dynamic and static sites by site type. Color indicates whether a site is promoter-proximal (see STAR Methods), a distal enhancer (defined as peaks that are not promoter-proximal, and are annotated by Segway as enhancers in either myoblasts or myotubes), or other distal (remaining sites).

(C) Percent of sites reported as bound by MYOD1 in either myoblasts or myotubes by Cao et al. (2010).

(D) Motif enrichments in accessible sites. *p* values result from logistic regression models that use the presence or absence of a given motif in each site to predict whether the site has a given accessibility trend (opening/closing/static). Plots show up to the top 6 Bonferroni-significant motifs by *p* value.

(E) Counts of sites undergoing significant changes in H3K27 acetylation as measured by chromatin immunoprecipitation sequencing (ChIP-seq) (Tang et al., 2015). See also Figure S2.

between all pairs of sites within 500 kb. To calculate robust correlations, we use Graphical LASSO (Friedman et al., 2008), which estimates regularized correlation matrices. Cicero penalizes correlations in a distant-dependent manner, preserving local patterns at the expense of very long-range ones. The output of Cicero consists of the co-accessibility scores for all pairs of sites within 500 kb of one another. Full details are provided in the STAR Methods.

We applied Cicero to generate a genome-wide *cis*-regulatory map from our myoblast sci-ATAC-seq data. As the first step, for example in experiment 1, Cicero aggregated differentiating myoblasts into 277 groups and identified 6.5 M pairs of sites with positive co-accessibility scores, including 1.8 M comprising a distal element and promoter. As the co-accessibility threshold is raised, promoters are connected to fewer regulatory elements with higher confidence. For example, at

a cutoff of 0.25, promoters were connected to a median of 2 distal elements in experiment 1 (Figure S3A). Distal sites that were highly co-accessible with promoters were more conserved across vertebrates (Figure 3B). This trend was more pronounced for sites linked to highly conserved genes, which tended to be co-accessible with more conserved distal elements (Figure 3C). To verify that co-accessibility between sites was not confined to our specific primary myoblast culture, we performed bulk ATAC-seq in myoblasts from another donor (“54-1”), before and after differentiation. Reassuringly, highly co-accessible sites were 2.2-fold more likely than unlinked sites to be undergoing directionally concordant changes in accessibility across differentiation in the 54-1 cells (Figure 3D). To explore how accessibility corresponded with gene regulation during differentiation, we devised a composite “gene activity score” of accessibility at both promoters and

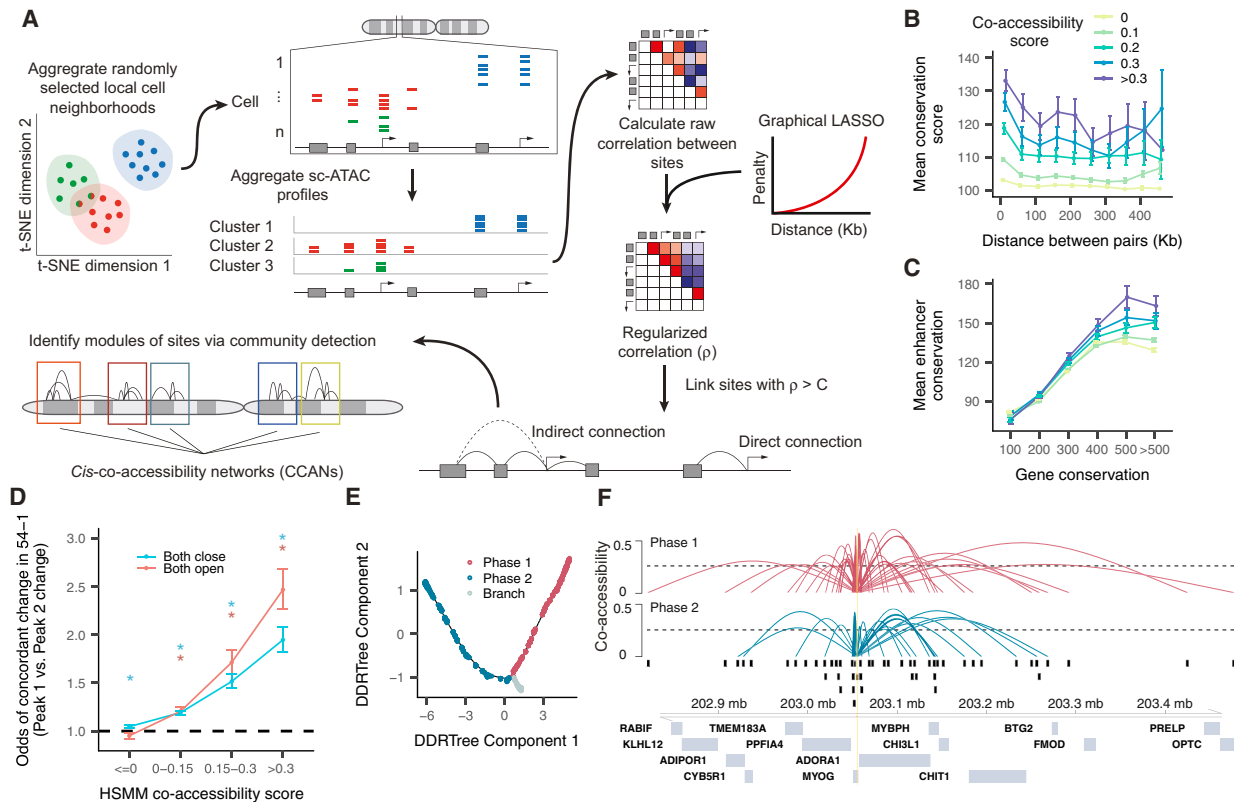


Figure 3. Cicero Constructs *cis*-Regulatory Models Genome-wide from Sci-ATAC-Seq Data

(A) An overview of the Cicero algorithm (see STAR Methods for details).

(B) Mean phastCons 46-way placental conservation scores of distal peaks connected to promoters. Peaks were stratified by distance from the promoter and co-accessibility score between the promoter and the distal peak.

(C) Mean distal site conservation score versus connected gene conservation score stratified by co-accessibility score.

(D) Odds ratios of concordant accessibility dynamics across differentiation in 54-1 myoblasts between pairs of sites that are co-accessible in HSM. For each bin of co-accessibility in HSM, pairs of peaks that overlapped peaks in 54-1 non-targeting controls were assessed for concordant dynamics (>2 log₂ fold change in both peaks or <-2 log₂ fold change in both peaks). Error bars indicate 95% confidence intervals calculated using Fisher's exact test. Asterisks represent estimates significantly different than 1 (p values < 0.05 by Fisher's exact test).

(E) Two "phases" of myoblast differentiation illustrated.

(F) A summary of the Cicero co-accessibility links between the MYOG promoter and distal sites in the surrounding region. The height of connections indicates the magnitude of the Cicero co-accessibility score between the connected peaks. The top set of (red) links were constructed from cells in phase 1, while the bottom (in blue) were built from phase 2.

See also Figures S3 and S4.

linked distal sites (STAR Methods). Accessibility-based gene activity scores were positively correlated with expression (Figures S3B–S3D).

As co-accessible elements tended to cluster, we post-processed Cicero's output with a community detection algorithm to identify "*cis*-co-accessibility networks" (CCANs): modules of sites that are highly co-accessible with one another. The majority of dynamically accessible sites were included in CCANs even using a high co-accessibility threshold (Figures S4A–S4E).

To assess the reproducibility of Cicero maps, we adapted a maximum weighted bipartite matching method to identify pairs of CCANs from the two experiments that share DNA elements in common (STAR Methods). This algorithm matched 1,868 of the CCANs between the experiments, accounting for 84% and 91% of the sites in CCANs in experiments 1 and 2, respectively

(Figure S4F). Most pairs of sites linked in one experiment were also linked in the other (score >0.25; 81% of experiment 1 sites also linked in experiment 2; 64% of experiment 2 sites also linked in experiment 1; Figures S4G and S4H).

To further investigate chromatin dynamics during differentiation, we constructed Cicero maps on the two "phases" of the pseudotime trajectory (before versus after the F₂ branch) and computed CCANs for each map (Figure 3E). The general structure of Cicero connections was often maintained around genes of interest. For example, a similar set of distal elements are linked to the promoter of MYOG in both the early and late phases (Figure 3F). To identify CCANs that were maintained, gained, or lost during differentiation, we applied our matching algorithm to compare CCANs between the first and second phases. For experiment 1, this algorithm matched 1,945

CCANs, accounting for 88% and 91% of the sites in CCANs in the first and second phases, respectively. However, although the general structure of CCANs was stable (few sites switched CCANs), many sites joined or left CCANs during differentiation (Figures S4I and S4J). Intriguingly, we identified 60 sequence motifs that were predictive of whether a site would join, leave, or remain within a CCAN, including CTCF, which strongly predicted that an accessible site would remain within a CCAN (Figure S4K).

We hypothesized that the CCANs identified by Cicero constitute “chromatin hubs.” Chromatin hubs, which are thought to involve looping interactions between distal regulatory elements and the genes they target, may act to coordinate the assembly of transcription complexes (de Laat and Grosveld, 2003; Tolhuis et al., 2002). To satisfy the definition of a chromatin hub, we expect CCANs should meet four criteria. First, they should exhibit greater physical proximity than expected based on their distance in the linear genome. Second, they should interact with a common set of protein complexes. Third, they should be epigenetically modified in concordant ways and at similar times. Finally, they should substantially contribute to regulating genes with promoters within the hub.

Co-accessible DNA Elements Exhibit Physical Proximity

To test whether co-accessible sites are closer together in the nucleus than unlinked sites at similar distances in the linear genome, we generated and applied Cicero to sci-ATAC-seq chromatin profiles from 889 human lymphoblastoid cells (GM12878), for which ChIA-PET and promoter-capture Hi-C data are available.

We observed strong concordance between Cicero-based linkages and DNA elements in RNA pol II-mediated contacts captured via ChIA-PET (Tang et al., 2015) as well as contacts found by promoter-capture Hi-C (Cairns et al., 2016; Mifsud et al., 2015), e.g., at the *CD79A* locus (Figure 4A). Approximately half of DNA elements ligated via ChIA-PET (“anchors”) overlapped with accessible sites in our data, with greater overlap between anchors that were supported by multiple ChIA-PET reads and sites that were accessible in many cells (Figures S5A and S5B). Pairs of sites reported by Cicero to be co-accessible were up to 2- to 3-fold more likely to be found in ChIA-PET and promoter-capture Hi-C than unlinked sites separated by similar distances (Figures 4B and 4C). Reciprocally, pairs of sites linked by many independent ChIA-PET or Hi-C ligation fragments were more likely to also be reported as co-accessible by Cicero (Figures 4D and 4E), e.g., ~75% of high-confidence ChIA-PET connections were found in Cicero’s map. Although proximity ligation frequencies should not be taken as a direct measure of physical distance, these analyses show that Cicero-linked sites exhibit greater than expected physical proximity, even when very distant in the linear genome. We also found that Cicero connected sites were more likely to occupy the same topologically associated domain (TAD) than unlinked sites at the same distance (Fisher’s exact test, p value $< 2e-5$ for all distance bins, TADs derived from 1 kb-resolution Hi-C analysis of GM12878; Rao et al., 2014). Similarly, Cicero-linked sites were 1.5-fold more likely than unconnected pairs at the

same distance to be found in the same A/B compartment (Figures S5C and S5D).

Co-accessible DNA Elements Carry Pairs of Motifs for Interacting TFs

We next investigated whether Cicero links might be mediated by interacting TFs. We searched for known sequence motifs within each peak in the HSMM data that could accurately predict whether Cicero would link other sites to it. Promoters with DNA binding motifs for one or more core myogenic TFs were significantly more likely to be connected (co-accessibility score >0.25) to an opening distal site than promoters without them. For example, promoters containing at least one MYOD1, MYOG, or MYF6 motif were 3.6-fold more likely to be connected to an opening distal site than promoters with none of these motifs ($p = 8.7 \times 10^{-270}$; likelihood ratio test for logistic regression model), and similarly, promoters with at least one MEF2 family motif were 2.8-fold more likely to be connected to an opening distal site ($p = 7.9 \times 10^{-119}$).

We hypothesized that these correlations resulted from direct, TF-mediated interactions. To explore this further, we focused on promoters linked to exactly one dynamically accessible distal site (co-accessibility score >0.05) and used Graphical LASSO to identify pairs of motifs where the presence of a motif in the promoter predicted the presence of the paired motif in the dynamically accessible distal site (STAR Methods). We identified a number of motif pairs corresponding to TFs known to physically interact. For example, opening distal elements were significantly more likely to have a MEF2 or RUNX1 motif if they were linked to a promoter with a MYOD1 motif (Figure S6A). Myogenic regulatory factors (MRFs) are known to interact physically with MEF2 and RUNX1 (Knoepfler et al., 1999; Molkentin et al., 1995; Philipot et al., 2010).

MYOD1 Coordinates Histone Modifications in Cohorts of Co-accessible Sites

The physical proximity of co-accessible sites suggested that recruitment of histone-modifying enzymes to one site might induce changes in physically proximate sites. Indeed, pairs of sites were more likely to be undergoing significant, concordant gains in H3K27ac if they were linked by Cicero (Figure 5A). Sites that themselves exhibited static accessibility, but were linked to a dynamic, opening site, showed strong gains in H3K27ac, while static sites that were linked to dynamic, closing sites showed strong losses (Figure 5B). The gains in acetylation might be driven by *de novo* binding of MYOD1 at the opening site followed by recruitment of a histone acetyltransferase (e.g., p300). Supporting this, of the 2,050 sites with significant gains in H3K27ac but static accessibility, only 46% were bound by MYOD1 in myotubes. However, 97% were linked by Cicero to a MYOD1-bound site (Figure 5C). Moreover, equipping a regression model with information about linked sites improved its accuracy in predicting changes in a site’s histone marks (Figure S6B).

We next considered whether gains in MYOD1 binding were concentrated in a few CCANs or widely distributed. Of the 2,323 hubs containing promoters, 74% contained at least one

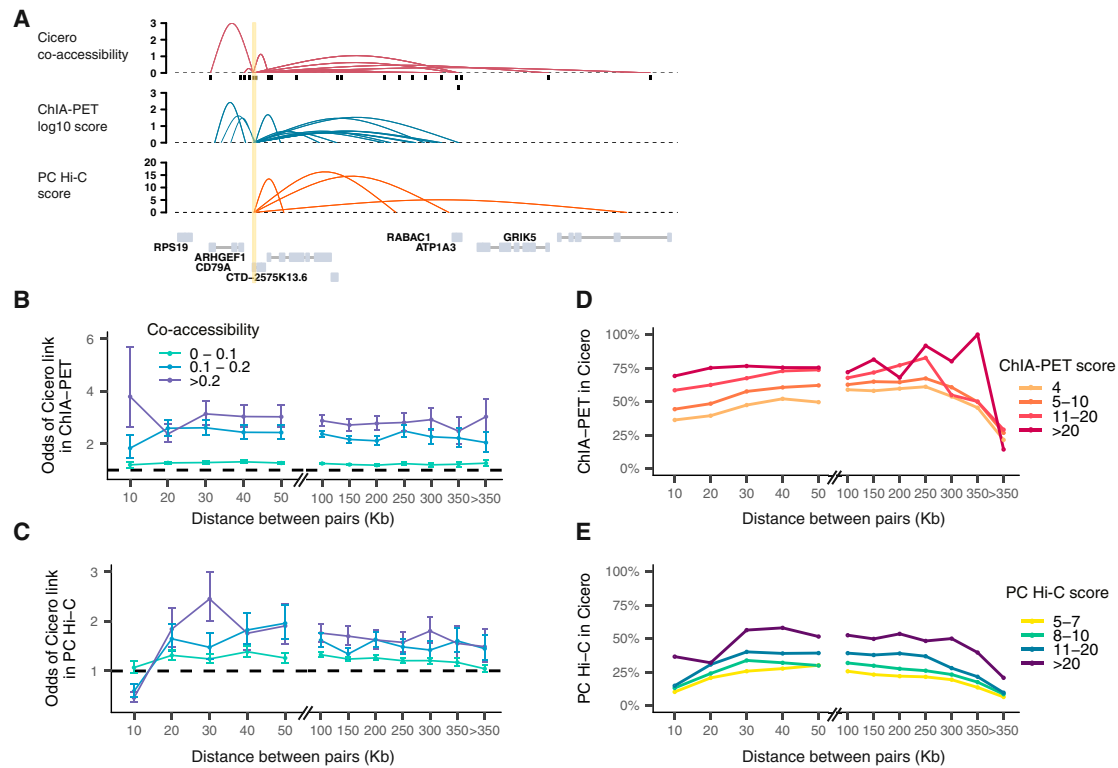


Figure 4. Co-accessible DNA Elements Linked by Cicero Are Physically Proximal in the Nucleus

(A) Cicero connections for the *CD79A* locus compared to RNA pol-II ChIA-PET (Tang et al., 2015) and promoter capture Hi-C (Cairns et al., 2016). Link heights for ChIA-PET are log-transformed frequencies of each interaction PET cluster and for promoter capture Hi-C are soft-thresholded log-weighted p values from the CHICAGO software.

(B) Odds ratio of pairs of sites within a given co-accessibility and distance bin found in RNA pol-II ChIA-PET compared to pairs of sites with co-accessibility ≤ 0 . Color represents the co-accessibility bin. Error bars indicate 95% confidence intervals calculated using Fisher's exact test. All points shown were significantly different than 1 (p values < 0.05 by Fisher's exact test).

(C) Similar to (B), but comparing Cicero links to sites ligated in promoter-capture Hi-C. All points shown were significantly different than 1 (p values < 0.05 by Fisher's exact test) except for at the 10 kb bin that may be impacted by the resolution of Hi-C consequent to the use of a 6-cutter restriction enzyme. For (B) and (C), we fit a linear model that included co-accessibility score and overall accessibility and found in both cases that co-accessibility had a significant effect on presence in comparison datasets even after correcting for this potential confounder (see STAR Methods for details).

(D) Fraction of ChIA-PET contacts found in Cicero connections as a function of distance, stratified by multiplicity of ligation product detections.

(E) Promoter-capture contacts detected in Cicero CCAN connections as a function of distance, stratified by CHICAGO score.

See also Figure S5.

site undergoing a change in MYOD1 binding. For the subset of 431 hubs with a differentially expressed gene, 92% contained at least one site changing in MYOD1 binding. For example, within the single hub that includes myosin heavy chain isoforms 1, 2, 3, 4, 8, and 13 and numerous other genes, 15 sites underwent significant increases in accessibility. Of these, all were bound by MYOD1 in myotubes (Figure 5E). Interestingly, however, two sites very near *MYH3* (marked with asterisks) opened substantially earlier in pseudotime than others and were bound by MYOD1 in myoblasts as well.

We wondered, more generally, whether sites bound by MYOD1 in myoblasts and throughout differentiation opened earlier than sites that gained MYOD1 binding during differentiation. A change-point analysis using PELT (Killick et al., 2012) revealed that sites bound by MYOD1 throughout differentiation opened significantly earlier in pseudotime than those that gained MYOD1 (Mann-Whitney test p value $1.2e-122$) or were never bound by

it (Mann-Whitney test p value $8.0e-223$) (Figure 5F). Moreover, rather than being enriched in whole hubs that open early as a group, constitutively MYOD1-bound sites opened significantly earlier than sites linked to them that either gained MYOD1 (two-sided paired Student's t test p value = $1.0e-182$) or were never bound by it (two-sided paired Student's t test p value = $4.5e-318$) (Figure 5G). Constitutively MYOD1-bound sites were enriched for the MEIS1 and AP-1 motifs (Figure 5H) compared with sites that gain MYOD1 later in differentiation. Altogether, sites with MEIS1 motifs were linked to 69% of dynamically opening sites compared with only 16% of sites genome-wide (co-accessibility score >0.25). Murine Meis1, in conjunction with Pbx1, has been reported to act as a complex required for the MYOD1-mediated activation of the myogenin promoter, and mutations in MYOD1 that prevent interaction with PBX1 resulted in loss of many binding sites and regulatory targets (Berkes et al., 2004; Fong et al., 2015). Our results suggest MEIS1 recruitment

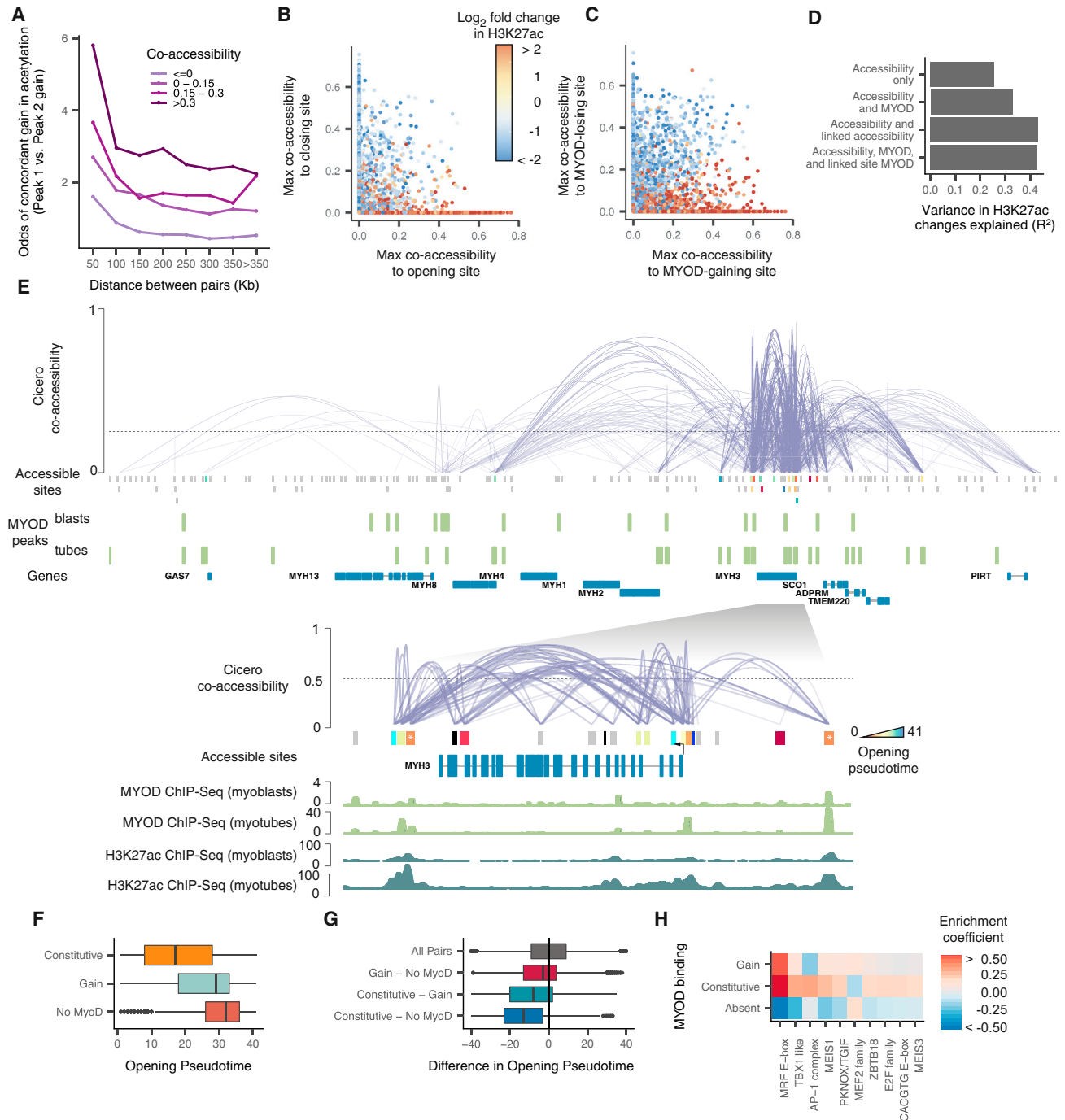


Figure 5. Co-accessible DNA Elements Linked by Cicero Are Epigenetically Co-modified

(A) Odds ratio of a site gaining H3K27ac during myoblast differentiation, given that it is linked to a site that is doing so. Color indicates the strength of the Cicero co-accessibility links. The lightest color indicates pairs of sites that are unlinked by Cicero.

(B) Correspondence between a statically accessible site's gain or loss of H3K27ac and its maximum co-accessibility score to a site that is opening (x axis) or closing (y axis). Sites that are not linked to an opening or closing site are drawn at $x = 0$ or $y = 0$, respectively.

(C) Similar to (B), but describing the correspondence between a site's gain or loss of H3K27ac and its maximum co-accessibility score to a site that is gaining or losing MYOD1 binding.

(D) The variance explained in a series of linear regression models in which the response is the \log_2 fold change in H3K27ac level of each DNA element and the predictors are whether that site is opening, closing, or static, whether it gains or loses MYOD1 binding, and whether it is linked to neighbors that are doing so. See STAR Methods for details on model specifications.

(legend continued on next page)

of MYOD1 may be pervasive throughout the genome and could nucleate activation of other sites within a chromatin hub.

Sequence Features of Active Chromatin Hubs Predict Gene Regulation

We wondered whether Cicero's putative maps could be used to predict changes in gene expression. As a first test, we asked whether two genes with co-accessible promoters exhibited greater correlation in expression across individual cells than genes that were nearby but whose promoters were not linked by Cicero. Indeed, differentially expressed genes showed greater correlation in expression as a function of their co-accessibility score (Figure S7F).

We next sought to develop a linear regression model to predict changes in either gene expression or changes in "barrier region" histone marks associated with promoter activation (Figure 6A). Our first model takes as input a binary map of the TF binding motifs present at the promoter upstream of each TSS. We then train it to predict how much of a gene's observed expression change is attributable to each TF motif using elastic net regression and 50-fold cross-validation (STAR Methods). The promoter-based model explained only 17% of the variance in expression and performed similarly in predicting a panel of histone marks (Figures 6B and 6C). Augmenting this model with TF motifs at linked distal sites improved its ability to explain changes in expression by 2.27-fold (Figure 6C). The TF motifs identified by the model included the MRF E-box, the MADS box bound by MEF2 family proteins, and the MEIS1 binding site, which were associated with upregulation, along with motifs for factors that drive cell proliferation such as AP-1, which were associated with downregulation (Figure 6D). Thus, when tasked with predicting which factors are important for gene regulation, our regression identified the major myogenic TFs using only the sequences in sites linked together by Cicero.

MEIS1 and PBX1 Are Required for Coordinated Myoblast Chromatin Hub Activation

We hypothesized that MYOD1, which recruits p300/PCAF and the BAF complex upon myoblast differentiation, might act to nucleate histone modification and nucleosome remodeling throughout a chromatin hub. To test this hypothesis, we genetically ablated MEIS1 or PBX1 (that forms a heterodimer with MEIS1) with CRISPR/Cas9 in 54-1 cells and then performed bulk ATAC-seq as they differentiated. Both Δ MEIS1 and Δ PBX1 myoblasts differentiated markedly less efficiently, with fewer and smaller myotubes than cells transduced with non-targeting control (NTC) single guide RNAs (sgRNAs) (Figure 7A). Of 14,321 sites that underwent significant changes in accessibility in the 54-1 NTC, 7,868 (55%) and 12,520 (87%) failed to do so

in Δ MEIS1 or Δ PBX1 cells respectively, and nearly 25% of sites that failed to open overlapped sites bound by MYOD1 in both normal myoblasts and myotubes (Figure 7B).

Having observed that pairs of sites Cicero identified as highly co-accessible in HSMMs were more likely to open or close concordantly in the 54-1 cells upon differentiation (Figure 3D), we asked whether co-accessible pairs would be concordantly perturbed in the mutants. Indeed, pairs of sites that opened in the 54-1 NTC and were linked by Cicero tended to both fail to open in the mutants. For example, pairs of sites that Cicero linked with a co-accessibility score >0.3 were 2.3-fold more likely to both fail to open in Δ PBX1 and 1.6-fold more likely in Δ MEIS1 than pairs of sites Cicero deemed not co-accessible, suggesting that co-accessibility is often maintained even when cells fail to differentiate (Figure 7C).

We next assessed whether constitutively MYOD1-bound sites might nucleate changes throughout hubs by first dividing normally opening sites into those that were constitutively MYOD1-bound and those that were not. We then tested whether other sites linked to these groups at varying levels were more or less likely to coordinately fail to open in Δ MEIS1 (Figure 7D). Consistent with our hypothesis, highly co-accessible sites were 1.5-fold more likely to both fail to open in Δ MEIS1 myoblasts when one of the sites was constitutively bound by MYOD1 than when neither was constitutively bound by MYOD1 (p value 0.0011, Fisher's exact test). These findings suggest that MEIS1 may be important for proper MYOD1-mediated recruitment of chromatin remodeling complexes to specific sites that subsequently act on others in 3D proximity.

DISCUSSION

Despite their paramount importance, maps that comprehensively link distal regulatory sequences to their target genes are still lacking. Toward addressing this, we developed Cicero, which constructs putative *cis*-regulatory maps from single-cell chromatin accessibility data. We anticipate these maps will guide downstream validation by other scalable methods such as massively parallel reporter assays and CRISPR-mediated (epi) genome editing. In contrast with other approaches like ChIA-PET and promoter-capture Hi-C, Cicero operates on single-cell data and therefore avoids averaging effects that can confound bulk assays. As described here for a model of skeletal muscle differentiation, downstream analyses of Cicero-based links can advance our quantitative understanding of the eukaryotic gene regulation and may also facilitate the identification of the target genes of noncoding variants underlying GWAS signals.

Pseudotemporal ordering of chromatin accessibility profiles from differentiating myoblasts revealed dynamic changes in thousands of DNA elements. Although changes in promoter

(E) The Cicero map for the 755 kb region surrounding *MYH3* along with called MYOD1 ChIP-seq peaks from (Cao et al., 2010). Sites opening in accessibility are colored by their opening pseudotime (see STAR Methods), sites not opening in accessibility are shown in gray. Inset: 60 kb region surrounding *MYH3* along with MYOD1 ChIP-seq and H3K27ac ChIP-seq signal tracks from Cao et al. (2010) and the ENCODE Project Consortium (2012). Only protein-coding genes are shown.
(F) Opening pseudotimes for all opening sites, subdivided by whether MYOD1 is bound in myoblasts and myotubes, myotubes alone, or neither.
(G) The difference in opening pseudotimes between pairs of linked DNA elements. The pairs are grouped based on whether one or both sites is constitutively bound by MYOD1.
(H) TF binding motifs selected by an elastic net regression ($\alpha = 0.5$), with a response encoding the MYOD1 binding status of each site.
See also Figure S6.

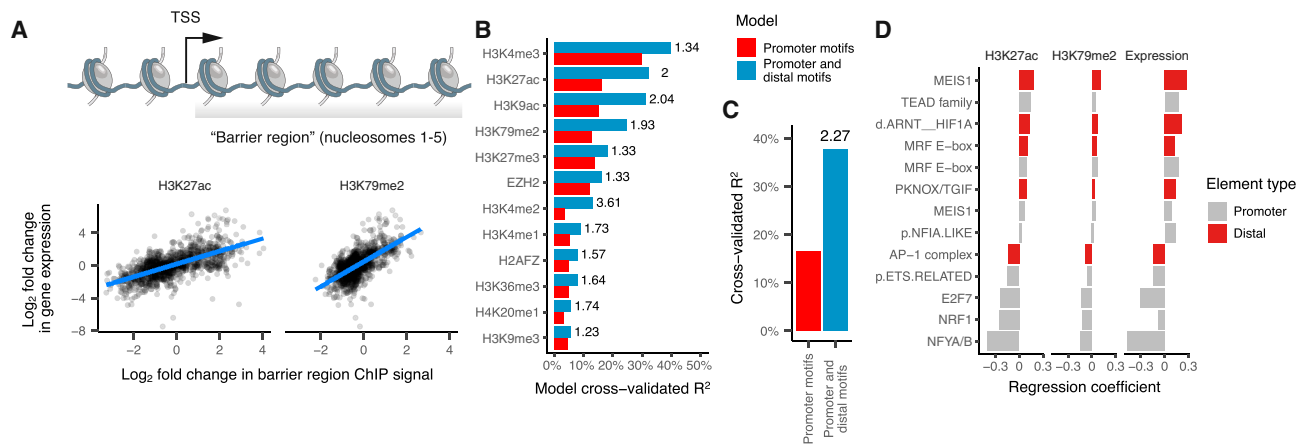


Figure 6. Chromatin Dynamics at Distal DNA Elements Predicts Gene Regulation

(A) Changes in histone acetylation in the first 1 kb downstream of each gene's TSS, corresponding to the "barrier" to RNA pol II elongation posed by nucleosomes, are correlated with changes in the gene's expression.
 (B) Two regression models predict changes in the histone marks deposited throughout each gene's barrier region. The first model predicts changes on the basis of TF binding motifs in gene promoters. The second model adds variables encoding the strength of co-accessibility with linked sites containing the motif. See STAR Methods for details on the various models. Adjusted R^2 is computed as the fraction of null deviance explained. The number to the right of each bar indicates the ratio of variance explained between the first and second model.
 (C) Similar to (B), with changes in expression as the response.
 (D) Coefficients from the model incorporating sequence at distal sites for each motif surviving model selection via elastic net. Note that the model considers each motif twice: once at promoters and again at distal sites, and both can be selected by elastic net.
 See also Figure S7.

accessibility were a poor predictor of gene expression dynamics, distal sites linked to genes by Cicero improved these models, particularly when sequence motifs were incorporated.

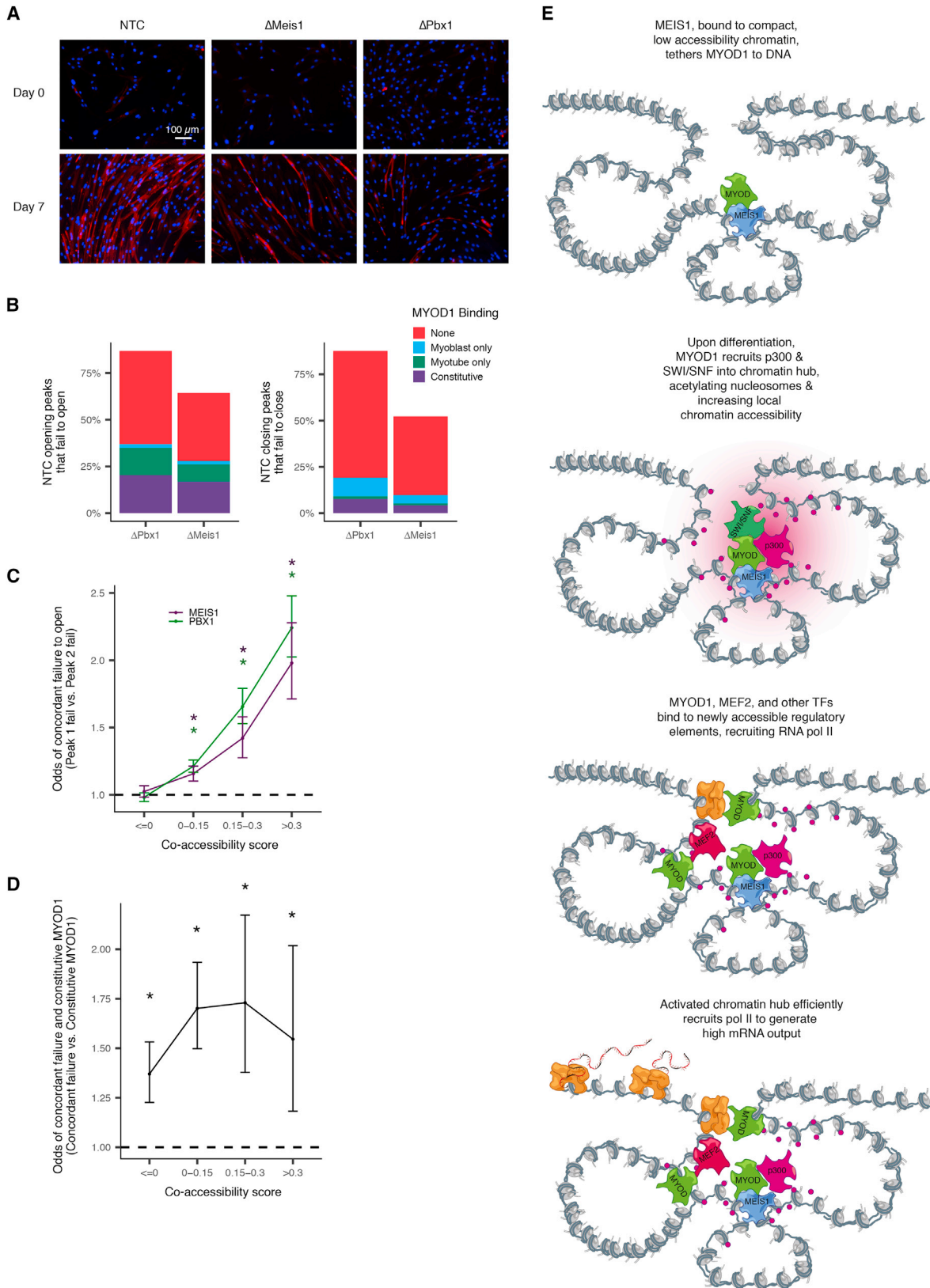
Our analyses show that the CCANs defined by Cicero meet the definition of chromatin hubs: they are physically close in the nucleus, their histone marks change in a coordinated fashion, and their interactions are likely mediated by a common set of TFs, some lineage-specific. For myogenesis, our results support a model of gene activation in which a subset of "precocious" enhancers recruit chromatin remodeling enzymes and other epigenetic modifiers to the hub, which mediates increases in accessibility of other binding sites (Figure 7E). For such a mechanism to work, chromatin hubs enclosing genes silent in myoblasts and activated during differentiation would need to be largely established prior to its onset. Indeed, Cicero linked more than half of activated or upregulated genes into such "pre-established" chromatin hubs. Sites that join or leave a hub are distinguished from those that remain part of it by specific TF motifs.

In differentiating myoblasts, MYOD1 is widely understood to recruit the BAF complex and p300/PCAF to activate enhancers of muscle genes (Serra et al., 2007; Simone et al., 2004). Although the role of MYOD1 in recruitment is well appreciated, how MYOD1 is itself recruited is less clear. We find that early opening sites are enriched for MEIS1 motifs and constitutive MYOD1 binding. Meis1 has previously been reported to tether Myod1 to the inactive myogenin promoter prior to the onset of differentiation and is required for myogenin activation and chromatin remodeling that permits the binding of MYOD1 to nearby MRF E-boxes that were previously inaccessible (Berkes et al., 2004; Maves et al.,

2007; de la Serna et al., 2005). Whether MEIS1/PBX1 acts to tether MYOD1 to inactive chromatin more generally throughout the genome has remained an open question.

Our analyses suggest that MEIS1 and its cofactor PBX1 are required for chromatin remodeling at a large fraction of sites that normally open during myoblast differentiation by serving as initial recruitment sites for epigenetic remodeling enzymes. Binding of p300 to MEIS1/PBX1-tethered MYOD1 could then acetylate histones at all DNA elements physically nearby in the chromatin hub. This model may help explain the pervasive gains and losses of histone acetylation throughout the accessible genome, despite the smaller number of differentially accessible or MYOD1-bound elements. Although we cannot exclude the possibility that some of the defects in chromatin remodeling are due to secondary effects downstream of MEIS1/PBX1, our genome-wide analysis taken together with biochemical and genomic data from previous studies support a direct role for MEIS1/PBX1 in recruiting factors that activate chromatin hubs.

Cicero provides an effective, genome-wide means of generating candidate links between regulatory elements and target genes in a tissue or cell type of interest using data from a single experiment. The chromatin hubs that it defines will facilitate the construction of quantitative models of epigenetic and gene expression dynamics, as well as the identification of genes whose dysregulation underlies GWAS associations. As the field pursues organism-scale cell atlases that comprehensively define each cell type and its molecular profile, such regulatory maps will be essential for understanding the epigenetic basis of each cell type's gene expression program, in both health and disease.



(legend on next page)

Limitations

The primary limitation of Cicero is the putative nature of the regulatory connections it identifies. Determining whether a distal DNA element is necessary or sufficient to exert regulatory influence on the genes Cicero links to it requires downstream experimentation. We note that proximity ligation-based methods for linking DNA elements to genes such as ChIA-PET or promoter capture Hi-C also have this limitation; proximity does not definitively mean regulatory interaction. Moreover, although we have found that our overall comparisons with available proximity ligation-based data are concordant, some individual connections are missing from one or both sets of putative interactions, and it is not clear which should be considered more reliable. On the one hand, ligation is a molecular measurement (albeit an indirect one) of physical proximity, while Cicero's links are based on computational inference. On the other, the ligation assays discussed here operate on bulk cell populations and are therefore subject to the artifacts introduced by averaging cells of different types or states, while Cicero operates at single-cell resolution.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- **KEY RESOURCES TABLE**
- **CONTACT FOR REAGENT AND RESOURCE SHARING**
- **EXPERIMENTAL MODEL AND SUBJECT DETAILS**
 - Human Skeletal Muscle Myoblasts (HSMM)
 - GM12878
 - 54-1 Immortalized Human Myoblasts
- **METHOD DETAILS**
 - Sci-ATAC-Seq Library Construction
 - Bulk ATAC-Seq Library Construction
 - 54-1 Knockout Construction
 - 54-1 Staining
- **QUANTIFICATION AND STATISTICAL ANALYSIS**
 - Processing of Raw Data
 - Defining Accessible Sites
 - Pseudotemporal Ordering
 - Differential Accessibility Analysis

- Gene Set Enrichment Analysis
- Cicero
- Analysis of 54-1 Immortalized Myoblasts
- Motif Enrichment Analysis
- Analysis of ChIA-PET and Hi-C Data
- Analysis of ChIP-Seq Data (MYOD1 and Histone)
- Modeling H3K27 Acetylation Changes
- Regression Models for Barrier Region Histone Marks and Gene Expression
- **DATA AND SOFTWARE AVAILABILITY**
 - Data Availability
 - Code Availability

SUPPLEMENTAL INFORMATION

Supplemental Information includes seven figures and one table and can be found with this article online at <https://doi.org/10.1016/j.molcel.2018.06.044>.

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AUTHOR CONTRIBUTIONS

C.T. and J.S. conceived the project. H.A.P. wrote Cicero. J.L.M.-F., D.A.C., R.M.D., S.S., and D.J. performed the experiments. H.A.P. led data analysis, with specific analyses performed by J.S.P. and D.A. and with assistance from S.S., X.Q., A.M., A.C.A., and F.J.S. C.T., J.S., and H.A.P. wrote the manuscript with assistance from J.S.P. and J.L.M.-F.

DECLARATION OF INTERESTS

F.J.S. has declared competing financial interests in the form of stock ownership and paid employment by Illumina, Inc. One or more embodiments of one or more patents and patent applications filed by Illumina may encompass the methods, reagents, and the data disclosed in this manuscript.

Figure 7. *MEIS1* and *PBX1* Knockout Myoblasts Fail to Differentiate and Show Coordinated Accessibility Defects

(A) Immunofluorescence microscopy images of non-template control, *MEIS1* knockout and *PBX1* knockout 54-1 cells at day 0 and day 7 post induction of differentiation. Nuclei are stained using DAPI, MYH3 is stained using anti-myosin MF20 and Alexa Fluor 594.

(B) Percent of peaks that open during differentiation in the NTC that fail to open in *PBX1* and *MEIS1* knockouts. Colors indicate the presence of MYOD1 binding in myoblasts and myotubes by ChIP-seq in HSMM.

(C) Odds ratios of concordant failure in accessibility gain across differentiation in 54-1 knockout myoblasts between pairs of sites that are co-accessible in HSMM. For each bin of co-accessibility in HSMM, pairs of peaks that overlapped peaks in 54-1 non-template controls were assessed for concordant failure to open (peaks that open in NTC but do not do so in knockouts). Color indicates knockout. Error bars indicate 95% confidence intervals calculated using Fisher's exact test. Stars represent estimates significantly different than 1 (p values < 0.05 by Fisher's exact test).

(D) Similar to (C). Odds ratios of concordant failure in accessibility gain given constitutive MYOD1 binding in one of the peaks. For each bin of co-accessibility in HSMM, pairs of peaks that overlapped peaks in 54-1 were assessed for presence of constitutive binding of MYOD1 in one or both sites as well as coordinated failure to open. Only pairs of sites where both open in NTCs were included. Data are for *MEIS1* knockout only due to a lack of sufficient power in *PBX1*.

(E) A model of how chromatin hub activation could be nucleated by a subset of "precociously" opening DNA elements. Such sites are occupied by TFs competent to bind relatively closed, inactive DNA elements, such as *MEIS1*, which may tether less competent factors such as MYOD1 to the hub. Subsequent recruitment of p300 and the BAF complex, possibly through intermediary factors (e.g., MYOD1), leads to remodeling and acetylation of histones throughout the hub. These newly available sites are then bound by other transcriptional activators (e.g., MEF2), leading to the recruitment of Pol II. Moreover, acetylation of the histones downstream of assembled pre-initiation complexes reduces the barrier they pose to elongation, enhancing efficient transcription of genes within the hub.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Antibodies		
anti-myosin MF20 antibody	eBioscience	Cat#14-6503-80; RRID: AB_2572893
Deposited Data		
Raw and analyzed data	This paper	GEO: GSE109828
MyoD ChIP-seq in human myoblast and human myotube	MacQuarrie et al., 2013	GEO: GSE50413
Histone modification ChIP-seq datasets in HSMM and HSMMtube	ENCODE Project	ENCFF000BKV, ENCFF000BKW, ENCFF000BMB, ENCFF000BMD, ENCFF000BOI, ENCFF000BOJ, ENCFF000BPL, ENCFF000BPM
GENCODE gene definitions	Harrow et al., 2012	https://www.genecodegenes.org/
Experimental Models: Cell Lines		
Human skeletal muscle myoblasts	Lonza	Cat#CC-2580
GM12878	Coriell cell repository	Cat#GM12878
54-1 Immortalized Human Myoblasts	Dr. Robert Bradley and Dr. Silvere van der Maarel	Krom et al., 2012 ; Snider et al., 2010
Oligonucleotides		
sgRNA sequence	This paper	See Table S1
Software and Algorithms		
Cicero	This paper	http://cole-trapnell-lab.github.io/cicero-release
Bowtie2	Langmead and Salzberg, 2012	http://bowtie-bio.sourceforge.net/bowtie2/index.shtml
Samtools	Li et al., 2009	http://www.htslib.org/
Trimmomatic	Bolger et al., 2014	http://www.usadellab.org/cms/?page=trimmomatic
Monocle 2	Qiu et al., 2017a	http://cole-trapnell-lab.github.io/monocle-release/
MACS2	Zhang et al., 2008	https://github.com/taoliu/MACS
BEDTools	Quinlan and Hall, 2010	http://bedtools.readthedocs.io/en/latest/
piano	Våremo et al., 2013	https://bioconductor.org/packages/release/bioc/html/piano.html
FNN	Beygelzimer et al., 2013	https://cran.r-project.org/web/packages/FNN/index.html
Other		
Custom indexed Tn5 transposomes	Amini et al., 2014	N/A

CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Cole Trapnell (coletrap@uw.edu).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Human Skeletal Muscle Myoblasts (HSMM)

HSMM derived from quadriceps biopsy (Lonza, catalog #CC-2580, lot #257130: healthy, age 17, female, of European ancestry, body mass index 19; cells were used within 5 passages of purchase) were cultured in skeletal muscle growth media (GM) using the SKGM-2 BulletKit (Lonza). The cells and differentiation protocol are those from [Trapnell et al. \(2014\)](#). Cells were seeded in 15 cm dishes, media was replenished every 48 hr and cells were allowed to reach 80%–90% confluence. Differentiation was induced at time 0 via a switch to differentiation medium (DM) composed of alpha-mem (Thermo Fisher Scientific) and 2% horse serum. Cells

in GM (time 0) or DM were then harvested at the specified times and processed as described below. HSMM tested negative for mycoplasma contamination within 3 weeks of the experiment.

GM12878

GM12878 (purchased from Coriell Cell Repository) was cultured in RPMI 1640 medium (GIBCO 11875) supplemented with 15% FBS, 100U/ml penicillin and 100 µg/ml streptomycin. Cells were cultured in an incubator at 37°C with 5% CO₂ and were split to a density of 300,000 cells/ml three times a week.

54-1 Immortalized Human Myoblasts

54-1 human myoblasts (Krom et al., 2012; Snider et al., 2010) were a kind gift from Dr. Robert Bradley and Dr. Silvere van der Maarel. For expansion, 54-1 cells were cultured in high serum media containing 20% FBS, 1% penn-strep, 10 ng/mL recombinant human FGF and 1 µM dexamethasone in F-10 media. For myoblast differentiation, media was replaced with low serum media containing 1% horse serum, 1% penn-strep, 10 µg/mL insulin and 10 µg/mL transferrin in F-10 media.

METHOD DETAILS

Sci-ATAC-Seq Library Construction

We prepared sci-ATAC-seq libraries using an improved version of the original protocol (Cusanovich et al., 2015), with improvements reported in the related paper (Cusanovich et al., 2018). Briefly, HSMM cells were harvested at defined times post switch to DM, washed and cells were lysed to obtain nuclei by resuspending cells in cold lysis buffer (CLB, 10 mM Tris HCL pH7.4, 10 mM NaCl, 3 mM MgCl₂ and 0.1% IGEPAL CA-130) supplemented with protease inhibitors (Sigma). For each time point, 2.75×10^5 nuclei were resuspended in a mix of 990 µL of CLB supplemented with protease inhibitors and 1.1 mL of Tagment DNA buffer (Illumina), and divided evenly among the wells of a 96 well LoBind plate (Eppendorf). 1 µL of uniquely barcoded Tn5 (Illumina) was added to each well followed by incubation at 55°C for 30 min. Following Tn5 incubation, 20 µL of a solution containing 40 mM EDTA and 1 mM spermidine were added to each well and incubated at 37°C for 15 min. Tagmented nuclei were pooled, stained by addition of DAPI to a final concentration of 3 µM and 25 DAPI positive nuclei were sorted into the wells of 96 well LoBind plates containing 12.5 µL of 0.8 mg/mL BSA and 0.04% SDS in EB buffer (QIAGEN). Nuclei were lysed by incubation at 55°C for 15 min. ATAC libraries were PCR amplified by addition of unique combinations of P5 and P7 primers for each well of sorted nuclei and PCR conditions were such that amplification did not reach saturation. For each sorted 96 well plate ATAC libraries were pooled and products cleaned using the Zymo Clean & Concentrator kit (Zymo). Libraries were quality controlled by analyzing on PAGE gels and quantified using the Qubit broad range DNA quantitation kit (Thermo Fisher Scientific).

Bulk ATAC-Seq Library Construction

Bulk ATAC-seq experiments were performed as previously described (Buenrostro et al., 2013). Briefly, cells were trypsinized, washed with PBS and resuspended in cold-lysis buffer (CLB: 10 mM Tris-HCl pH 7.4, 10 mM NaCl, 3 mM MgCl₂ and 0.1% IGEPAL CA-630) supplemented with protease inhibitors (Sigma) to obtain nuclei. 100,000 nuclei were pelleted, resuspended in CLB and the equivalent of 20,000 nuclei were transferred, mixed with Tagment DNA buffer and Tn5 enzyme (Illumina). Reactions were incubated at 37°C for 30 min and purified using the MinElute kit (Zymo). Sequencing adapters and indices were added via PCR using standard Nextera P5 and P7 primers with excess primers removed using a 1X Ampure cleanup (Agencourt). Libraries were quality controlled by examining on a PAGE gel and quantified using the Qubit broad range DNA assay (ThermoFisher Scientific).

54-1 Knockout Construction

Oligos containing sequences for single guide RNAs (sgRNAs) targeting *PBX1*, *MEIS1* and non-targeting controls were designed as follows:

5'-tatcttGTGGAAAGGACGAAACACC[G]-[20bp sgRNA]-gttttagagctaGAAAtagcaagttaaataagg-3
corresponding to the following form:

[U6 homology]-[sgRNA]-[sgRNA backbone homology]

The sgRNA sequences targeting *MEIS1*, *PBX1* and non-targeting controls are shown in [Table S1](#).

Oligos were ordered from IDT and made double stranded by PCR using primers that bind the U6 and sgRNA backbone homology sequences. Oligos corresponding to each sgRNA were then ligated using the In-Fusion HD kit (Clontech) into BsmBI and alkaline phosphatase digested lentiCRISPRv2-Blast (Addgene, #83480). Ligations were then transformed into Stellar Competent cells (Clontech), bacteria grown overnight in LB containing ampicillin and plasmids recovered using the QIAGEN MiniPrep kit. Lentivirus was generated by transfection into HEK293T using the ViraPower packaging mix and viral containing supernatant was filtered using a 45 µm steriflip vacuum filter (Fisher Scientific). 54-1 cells were transduced with filtered virus, cultured for 48 hr and sgRNA containing cells selected by incubation with 5 µg/mL blasticidin. Cells were expanded for 21 days post-selection to allow for genome editing prior to myoblast differentiation experiments and bulk ATAC-seq.

Differentiation was induced in 54-1 lines as described for HSMM. Bulk ATAC-seq was conducted on day 0 and day 7 after induction.

54-1 Staining

At various times along the differentiation protocol, 54-1 cells were washed with PBS, fixed by incubating for 20 min in 4% PFA (Electron Microscopy Sciences) in PBS and an additional 10 min in 100% methanol (Sigma). Samples were washed twice with IF buffer (0.2% Triton X-100 and 5% w/v bovine serum albumin in PBS) and incubated with anti-myosin MF20 antibody (eBioscience) overnight at 4°C with rotation. After primary antibody incubation, samples were washed twice with IF buffer and incubated with donkey anti-mouse Alexa Fluor-594 secondary antibody (Molecular Probes) and 5 μM DAPI. Finally, samples were washed twice with IF buffer, PBS added and myosin staining assessed by imaging on a Zeiss Axio Observer (Carl Zeiss Microimaging).

QUANTIFICATION AND STATISTICAL ANALYSIS

Processing of Raw Data

For sci-ATAC-seq, raw reads were processed identically to those in Cusanovich et al. (2018) enclosed. Details are reproduced here for clarity. Briefly, BCL files were converted to fastq using bcl2fastq v2.16 (Illumina). Barcodes were corrected using a custom python script such that if a barcode component (tagmentation or PCR barcode separately) was within 3 edits from an expected barcode component, and the next best matching barcode component was at least 2 further edits away, the barcode component was corrected to the best match. Reads of barcode components that were not unambiguously assignable to an expected barcode were discarded.

Reads were mapped to the hg19 reference genome using bowtie2 with non-default options '-X 2000 -3 1' (Langmead and Salzberg, 2012). Reads with mapping quality less than 10 were filtered. PCR duplicates were removed using a custom python script. Cells with low read counts were removed. The read count cutoff was determined by identifying the trough between the peaks of the bimodal distribution of read counts using the mclust package in R (Scrucca et al., 2016).

For the bulk ATAC-seq datasets, processing was done as above, but without barcode correction.

Defining Accessible Sites

To define peaks of accessibility across all sites, we used the MACS (version 2.1.1) (Zhang et al., 2008) peak caller. Specifically, we used macs2 callpeak, with the following non-default options:--nomodel--extsize 200--shift -100--keep-dup all. Reads from the ENCODE blacklist (ENCFF001TDO) were excluded from peak-calling. Promoter peaks were further defined as the union of the annotated transcription start site (TSS) (Gencode V17) minus 500 base pairs, and MACS defined peaks upstream of the TSS. Cells were determined to be accessible at a given peak if a read from that cell overlapped the peak. Peaks were called as above for both of the HSMM experiments separately, and then the union of the two peak sets was used.

For the GM12878 and HL60 mixed dataset, preliminary peaks were called by MACS and used to separate the cell types using multi-dimensional scaling by Jaccard distance. The subset of reads from GM12878 cells was then used to recall peaks for GM12878 as above.

After accessible peaks were defined, a matrix was generated for each dataset with the count of reads from each cell or time point (in bulk) that overlapped each accessible peak.

Pseudotemporal Ordering

For the HSMM dataset, contaminating interstitial fibroblasts were removed *in silico* based on the absence of promoter accessibility in any of several known muscle markers (MYOG, MYOD1, DMD, TNNT1, MYH1, MYH3, TPM2). In addition, cells with fewer than 1,000 accessible sites were excluded due to low assay efficiency. Finally, peaks present in less than 1% of cells were excluded during pseudotemporal ordering steps.

Despite improvements to the sci-ATAC-seq protocol that delivered a substantial increase in the number of sites detected per cell, sci-ATAC-seq data remain zero-inflated. The quality and efficiency of transposition, which varies between cells and across batches, is likely to be a major technical source of variation in the data. Simple dimensionality reduction techniques such as MDS show that a poorly assayed cell is often more similar to other poorly assayed cells of a different type than to well-assayed cells of the same type. In order to accurately group cells with similar chromatin accessibility profiles, we first clustered peaks that were within 1 kb and summed the reads overlapping them to create an integer-valued count matrix M .

To order the cells by progress through differentiation, we determined which aggregated peaks were relevant to the HSMM time course by fitting the following model:

$$\ln(M_i) = \beta_0 + \beta_T + \beta_S S$$

Where M_i is the mean of a negative binomially distributed random variable for the number of reads overlapping the aggregate region i , T encodes the times at which each cell was harvested and S is the total number of accessible sites in each cell. We compared this full model to the reduced model:

$$\ln(M_i) = \beta_0 + \beta_S S$$

by likelihood ratio test. This approach has been shown to improve power for single-cell RNA-seq transcript counts compared to simple two-group tests comparing cells at the beginning and the end of a trajectory (Qiu et al., 2017a, 2017b). Sites determined by this

method to be time dependent and which were accessible in less than 10% of cells were then used to reconstruct the pseudotime trajectory using Monocle 2 (parameters `ncenter` and `param.gamma` set to 100, see Qiu et al., 2017a). To remove any bias created by different assay efficiency in different cells, total sites accessible was included as a covariate in the tree reconstruction. Each cell was assigned a pseudotime value based on its position along the trajectory tree. Cells that mapped to the F_2 branch were excluded from downstream analysis.

Differential Accessibility Analysis

When testing for differential accessibility across cells at a particular site, it is important to exclude technical variation due to differences in assay efficiency as discussed above. We first grouped cells at similar positions in pseudotime. We did this by k-means clustering along the pseudotime axis ($k = 10$). These clusters were further subdivided such into groups containing at least 50 and no more than 100 cells. Next, we aggregated the binary accessibility profiles of the cells in each group into a matrix A , so that A_{ij} contains the number of cells in group j for which DNA element i is accessible. The average pseudotime ψ_j and average overall cell-wise accessibility S_j for cells in each group j were preserved for use during differential analysis.

To determine which peaks of accessibility were changing across pseudotime, we fit the following model to the binned data:

$$\ln(A_i) = \beta_0 + \beta_\psi \tilde{\psi} + \beta_S \tilde{S}$$

Where A_i is the mean of a negative-binomial valued random variable of cells in which site i is accessible, and the tilde above ψ and S indicates that these predictors are smoothed with natural splines during fitting. This model was compared to the reduced model:

$$\ln(A_i) = \beta_0 + \beta_S \tilde{S}$$

by the likelihood ratio test. Peaks with an adjusted p value of less than 0.05 were determined to be dynamic across pseudotime.

Gene Set Enrichment Analysis

Gene set enrichment analyses was conducted using the R package `piano` (Väremo et al., 2013) using a hypergeometric test. We tested against the Human GO Biological Processes gene set from Merico et al. (2010).

Cicero

Cicero aims to identify all pairs of co-accessible sites. The algorithm takes as input a matrix of m by n binary accessibility values A , where A_{mn} is zero if no read was observed to overlap peak m in cell n and one otherwise. The algorithm also requires either a pseudotemporal ordering of the cells along a developmental trajectory (e.g., with Monocle 2) or the coordinates of the cells in some sufficiently low dimensional space (e.g., a t-SNE map) that the cells can be readily clustered. The algorithm then executes the following steps, which are detailed in the sections below: first, groups of highly similar cells are sampled using the clustering or pseudotemporal ordering, and their binary profiles are aggregated into integer counts. Second, these counts are optionally adjusted for user-defined technical factors, such as experimental batch. Third, Cicero computes the raw covariances between each pair of sites within overlapping windows of the genome. Within each window, Cicero estimates a regularized correlation matrix using the graphical LASSO, penalizing pairs of distant sites more than proximal sites. Fourth, these overlapping covariance matrices are “reconciled” to produce a single estimate of the co-accessibility across groups of cells. These co-accessibility scores are reported to the user, who can extract modules of sites that are connected in co-accessibility networks by first specifying a minimum co-accessibility score and then using the Louvain community detection algorithm on the subgraph induced by excluding edges below this score.

Grouping Cells

In principle, Cicero could analyze the sample covariance computed between the vectors x_i and x_j of binary values encoding accessibility across cells for a pair of sites i and j . However, rather than working with the binary data directly, Cicero groups similar cells and aggregates their binary accessibility profiles into integer count vectors that are easier to work with in downstream steps. Under the grouping discussed below, the number of cells in which a particular site is accessible can be modeled with a binomial distribution or, for sufficiently large groups, the corresponding Gaussian approximation. Modeling grouped accessibility counts as normally distributed allows Cicero to easily adjust them for arbitrary technical covariates by simply fitting a linear model and taking the residuals with respect to it as the adjusted accessibility score for each group of cells.

In order to control for technical variation as discussed above, Cicero operates on a grouped cell count matrix, C . C is constructed by first mapping cells into low dimensions by either Monocle 2 or tSNE. Within this space, Cicero constructs a k -nearest neighbor graph, via the `FNN` package (Beygelzimer et al., 2013), which is based on KD-trees and is highly efficient, scaling to large numbers of cells. Cicero then samples random cells and their k nearest neighbors (default $k = 50$) are grouped. Random cells continue to be chosen and grouped until no new group may be created that does not overlap an existing group by less than 90% of members. Accessibility counts are then summed across all cells in a group to create count matrix C . Cicero’s grouping procedure can be viewed as a type of bootstrap aggregation, or “bagging” (Breiman, 1996), which has been shown to substantially improve the stability of a variety of algorithms in machine learning. Note that with these parameter settings in a typical experiment, a cell will be part of more

than one group and therefore the groups will sometimes contain some of the same cells, which could in principle inflate co-accessibility scores across cells. However, in practice in our analyses of both GM12878 and HSMM, the median number of cells shared between pairs of groups is zero.

Adjusting Accessibility Counts for Technical Factors

To normalize for variations in assay efficiency across groups, matrix C is divided by a group-wise scaling factor (computed using the standard Monocle 2 method for library size calculations (`estimateSizeFactors()`) to create an adjusted accessibility matrix R . Because the entries of C are integer counts that can reasonably be approximated by Gaussian distributions, this matrix can be readily adjusted for arbitrary technical covariates (e.g., using the Limma package's `removeBatchEffect()` function). In this study we did not adjust for factors beyond library size.

Computing Co-accessibility Scores between Sites

Cicero next analyzes the covariance structure of the adjusted accessibilities in R . Given enough data, Cicero could in principle simply compute the raw covariance matrix U . However, because the number of possible pairs of sites is far larger than the number of groups of cells, Cicero uses the Graphical Lasso to compute a regularized covariance matrix to capture the co-accessibility structure of the sites. The Graphical LASSO computes the inverse of the sample covariance matrix, which encodes the partial correlations between those variables as well as the regularized covariance matrix (Friedman et al., 2008). These constitute a statistically parsimonious description of the correlation structure in the data: informally, two variables are partially correlated when they remain correlated even after the effects of all other variables in the matrix are excluded. The Graphical LASSO expects a small fraction of the possible pairs of variables to be partially correlated, preferring to select a sparse inverse covariance matrix over a dense one that fits the data equally well. Those pairs of sites that lack sufficient partial correlation to be worth the penalty term are assigned zero partial correlation in the inverse covariance matrix reported by Graphical LASSO. Formally, Cicero uses Graphical LASSO to maximize:

$$\log \det \Theta - \text{tr}(U\Theta) - \|\Theta * \rho\|_1$$

Where Θ is the inverse covariance matrix capturing the conditional dependence structure of p accessible sites, and U is the sample covariance matrix computed from their values in R . In order to ensure stability of GLASSO, which can hang on poorly conditioned input, we add a small conditioning constant of $1e-4$ to the diagonal of U prior to running it. The matrix ρ contains penalties that are used to independently penalize the covariances between pairs of sites, and $*$ denotes component-wise multiplication.

In Cicero, we aim to find local *cis*-regulatory interactions, rather than global covariance structure that might be expected due to overall cell state. To achieve this, we set each penalty term in ρ such that peaks closer in genomic distance had a lower penalty term. Specifically, we used the following equation to determine ρ :

$$\rho_{ij} = \left(1 - d_{ij}^{-s}\right) \alpha$$

Where d_{ij} is the distance in the genome (in kilobases) between sites i and j and s is a constant that captures the power-law distribution of contact frequencies between different locations in the genome as a function of their linear distance. A complete discussion of the various polymer models of DNA packed into the nucleus is beyond the scope of this paper, but we refer readers to Dekker et al. (2013) for a discussion of justifiable values for s . We use a value of 0.75 by default in Cicero, which corresponds to the “tension globule” polymer model of DNA (Sanborn et al., 2015). The scaling parameter α controls the distance at which Cicero expects no meaningful *cis*-regulatory contacts, and its value is calculated automatically from the data. To calculate α , Cicero selects 100 random 500 kb genomic windows, and determines the minimum α value such that no more than 5% of pairs of sites at a distance greater than 250 kb (a user-adjustable value) had non-zero entries in Θ and less than 80% of all entries in Θ were nonzero. The mean of these values of α is then used to set the penalties for the whole genome. Cicero then applies Graphical LASSO to overlapping 500 kb windows of the genome (windows are spaced by 250 kb such that each region is covered by two windows).

Reconciling Overlapping Local Co-accessibility Maps

Cicero calculates correlation values (co-accessibility scores) from the resulting estimated sparse covariance matrix for each pair of peaks within 500 kb of each other. Because the genomic windows are overlapping, the majority of pairs of peaks have two calculations of co-accessibility. To consolidate these sites and create a genome-wide map of the accessible regulome, Cicero considers the co-accessibility scores for each pair of peaks to determine if they are in qualitative agreement (both calculated scores in the same direction). The qualitative agreement in our two test datasets were both >95%. Pairs of peaks not in qualitative agreement are considered undetermined. For peaks in qualitative agreement, the mean score of the two values is assigned.

Extracting *cis*-Co-accessibility Networks (CCANs)

Positive Cicero co-accessibility scores indicate that a pair of peaks is connected, with the magnitude of the co-accessibility corresponding to Cicero's confidence in the link. To identify hubs of co-accessibility, Cicero can create a graph where each node is a peak of accessibility, and edges are the co-accessibility scores above a user-defined threshold. Communities within this genome-wide graph can be found using the Louvain community finding algorithm. Cicero can then assign peaks to *cis*-co-accessibility networks (CCANs) based on these communities.

Calculating Gene Activity Scores

Cicero calculates an overall measure of the accessibility of sites linked to each gene k by first selecting rows of the binary accessibility matrix A that correspond to sites proximal to the gene's transcription start sites or to distal sites linked to them. These rows, are

weighted by their co-accessibility and then summed to produce a vector of accessibility scores R_k , where the overall accessibility of gene k in cell i is:

$$R_{ki} = \sum_{p \in P} \sum_{j \in D_p} A_{ij} \frac{u_{pj}}{\sum_{k \in D_p} u_{pk}} + A_{pi}$$

Where P indexes the promoter proximal sites of k , D_p indexes distal sites linked to proximal site p , and u is the Cicero co-accessibility score linking distal site j to proximal site p , and A is the binary score for accessibility at site j or p in cell i . In principle, D_p could include all distal sites linked to p , but here we restrict the set to distal sites that are differentially accessible (FDR < 1%) across pseudotime.

Because the magnitude of these aggregate accessibility values will depend on overall sci-ATAC-seq library depth in each cell, we capture this relationship via a linear regression:

$$\log\left(\sum_k R_k\right) = \beta_0 + \beta_A \log\left(\sum_j A_{ji}\right)$$

The aggregate accessibility for each gene k in cell i is then scaled using the output of this model r_i for cell i :

$$\tilde{R}_{ki} = R_{ki} \cdot \frac{\sum_j r_j}{r_i}$$

Gene expression values measured by RNA-seq are typically approximately log-normally distributed. We therefore transform aggregate accessibility values to gene “activity” scores G_{ki} for each gene k in each cell i by simply exponentiating them. We also scale them by the total (exponentiated) gene accessibility values to produce “relative” activities:

$$C_{ki} = \frac{e^{\tilde{R}_{ki}}}{\sum_k e^{\tilde{R}_{ki}}}$$

Comparing Two Cicero Maps

Different Cicero CCAN maps were matched using the push-relabel algorithm for maximum matching in a weighted bipartite graph (Goldberg and Tarjan, 1986). Specifically, we used the maxmatching package in R to calculate the matching. Maximum matching in weighted bipartite graphs is a one-to-one matching such that the edge weights are maximized. In the case of comparing Cicero CCAN maps, the maximum matching is the one-to-one match of CCANs from map 1 to CCANs from map 2 such that the largest number of peaks is shared across the maps overall.

Analysis of 54-1 Immortalized Myoblasts

Bulk ATAC-seq libraries from 54-1 cells were processed as above. Data from the multiple guides at each time point and targeting each gene were merged for peak calling as described above. The resulting peaks were merged to create a master peak list. Reads per peak were then counted for each guide and time point separately. DESeq2 (Love et al., 2014) was used to test for differential accessibility between day 0 and day 7 across each of the three conditions (non-template control, *MEIS1* targeted and *PBX1* targeted). Two libraries (NTC guide 5 day 0 and *PBX1* guide 4 day 7) were removed as major outliers by PCA. Peaks with a greater than 2-fold moderated fold change were considered to be dynamic. When comparing 54-1 peaks to HSMM peaks, overlap was determined by overlapping coordinates with a maximum gap of zero.

Motif Enrichment Analysis

Transcription factor motifs from the JASPAR 2016 database (Mathelier et al., 2016) were located in the sci-ATAC-seq peaks using FIMO (Grant et al., 2011). Motifs for TFs not expressed at ≥ 2 transcripts per million in bulk RNA-seq (HSMM myoblasts or myotubes) were excluded from downstream analysis. Many TF motifs are similar or identical to each other. To prevent this correlation from confounding regression analyses, we clustered motifs into motif families. For each pair of motifs A and B, we computed the conditional probability that given motif A is called at a genomic location with a FIMO p value < 2e-5 (a stringent threshold), an overlapping instance of motif B will be called at $p < 1e-4$ (a permissive threshold). We constructed an undirected graph of motifs where there is an edge between motifs A and B if $P(B \text{ at } p < 1e-4 \mid A \text{ at } p < 2e-5) \geq 0.5$ or $P(A \text{ at } p < 1e-4 \mid B \text{ at } p < 2e-5) \geq 0.5$. Edges in this graph are assigned weights equal to the greater of these two conditional probabilities minus 0.5. We clustered the motifs on this graph using Louvain clustering (Blondel et al., 2008) and manually assigned names to each cluster. For downstream regression analyses, a genomic location is considered to have an instance of a motif family if any motif in the family is called at that location at $p < 5e-5$ (an intermediate threshold).

To generate the motif co-accessibility networks shown in Figure S6A, we computed two sets of binary variables for each protein coding gene that had at least one sci-ATAC-seq peak in its promoter(s). The first set of variables are indicators of whether or not at least one instance of a motif family is present in any promoter peak for the gene. The second set of variables are indicators of whether or not at least one motif instance is present in any distal peak (excluding promoters of other genes) connected to the gene’s promoter(s) with a co-accessibility score greater than 0. We constructed a matrix where rows are genes and columns are these two sets of motif indicator variables. This matrix was provided as input to the Graphical LASSO subject to the constraint that partial

correlations between two promoter motif variables or two distal motif variables are fixed to zero. The regularization parameter ρ for the Graphical LASSO was set as the smallest value that could achieve an estimated false discovery rate (FDR, the proportion of truly-zero partial correlations that are estimated as non-zero) of less than 5%. The FDR for a given value of ρ was estimated by running the Graphical LASSO with that value of ρ on versions of the motif indicator matrix with the distal variables row-shuffled (essentially assigning each gene to a random other gene's set of distal motifs) and counting the proportion of motif pairs that are assigned a non-zero partial correlation (ideally, all should be zero in a shuffled matrix).

In Figure S6A, an edge is drawn between a pair of motif families A and B if both 1) the co-accessibility of the indicator variable for A being at a distal site to the indicator variable of B being at a linked promoter site is >0.02 , and 2) the same is true if B is in the distal position and A is in the promoter.

Analysis of ChIA-PET and Hi-C Data

To compare our Cicero connections to promoter-capture (PC) Hi-C, we used publicly accessible GM12878 data (Cairns et al., 2016). We used the provided ChICAGO score as our indicator of physical proximity.

To compare our data to PC Hi-C, we first overlapped our peaks with peaks from PC Hi-C. Peaks were considered to overlap if they were within 1 kb of each other. For this analysis, we only considered pairs of sci-ATAC-seq peaks where at least one was a promoter represented in the PC Hi-C data. In addition, we only considered pairs of peaks that were within the same A/B compartment to avoid potential confounding of cross-compartment connections (Fortin and Hansen, 2015). To check that the effect of a pair of peaks' co-accessibility on presence in the dataset in Figure 4C was beyond the effect of the overall accessibility of the peaks, we ran a logistic regression predicting presence of the pair in PC Hi-C using binned co-accessibility and the geometric mean of the accessibility of the two peaks in the pair and found the coefficient for co-accessibility to be significant (p value $< 2e-16$).

As a second comparison dataset, we used publicly accessible GM12878 polII ChIA-PET data (Tang et al., 2015) (GSE72816). To compare these data to Cicero's connections, we first looked for overlap between our peaks, and ChIA-PET anchors. Because ChIA-PET anchors often overlap each other, we first merged overlapping anchors to create comparable ChIA-PET "peaks." We considered accessible peaks within 1 kb of ChIA-PET peaks to be overlapping. To generate Figures 4B and 4D, we considered the subset of ChIA-PET and Cicero connections where the peaks were present in both datasets. Similarly as for PC Hi-C, to check that the effect of a pair of peaks' co-accessibility on presence in the dataset in Figure 4B was beyond the effect of the overall accessibility of the peaks, we ran a logistic regression predicting presence of the pair in ChIA-PET using binned co-accessibility and the geometric mean of the accessibility of the two peaks in the pair and found the coefficient for co-accessibility to be significant (p value $< 2e-16$).

Analysis of ChIP-Seq Data (MYOD1 and Histone)

To compare our accessible peaks to the known myogenesis master regulator MYOD1, we used publicly accessible MYOD1 ChIP-seq in human myoblast and human myotube (MacQuarrie et al., 2013) (GEO: GSE50413). We considered our peaks to be bound by MYOD1 if they overlapped one of the annotated MacQuarrie et al. (2013) ChIP-seq peaks.

To compare our accessible peaks to histone modifications, we used publicly accessible ENCODE datasets in HSMM and HSMMtube (ENCODE Project Consortium, 2012) (ENCFF000BKV, ENCFF000BKW, ENCFF000BMB, ENCFF000BMD, ENCFF000BOI, ENCFF000BOJ, ENCFF000BPL, ENCFF000BPM). We counted both HSMM and HSMMtube histone ChIP-seq reads in each accessible peak. To determine whether sites were changing in accessibility between HSMM and HSMMtube, we used DESeq2 differential analysis (Love et al., 2014) (FDR $< 5\%$). To determine whether the barrier regions of genes were differentially histone modified, we similarly used DESeq2 to compare the read counts in the first 1000 base pairs of each GENCODE v17 transcript in HSMM and HSMMtube datasets.

To compare agreement between H3K27 acetylation marks of peaks connected by Cicero, we divided the odds of a site gaining acetylation if its connected site gained acetylation by the odds of a site gaining acetylation if it is connected to a site that is not gaining acetylation (Figure 5A).

Modeling H3K27 Acetylation Changes

To model changes in acetylation among linked sites (Figure 5D), we compared four linear regression models:

$$\begin{aligned} \ln(a_i) &= \beta_0 + \beta_1 A_{icl} + \beta_2 A_{iop} \\ \ln(a_i) &= \beta_0 + \beta_1 A_{icl} + \beta_2 A_{iop} + \beta_3 m_{ig} + \beta_4 m_{il} + \beta_5 m_{ic} \\ \ln(a_i) &= \beta_0 + \beta_1 A_{icl} + \beta_2 A_{iop} + \beta_3 \theta_{op} + \beta_4 \theta_{cl} \\ \ln(a_i) &= \beta_0 + \beta_1 A_{icl} + \beta_2 A_{iop} + \beta_3 m_{ig} + \beta_4 m_{il} + \beta_5 m_{ic} + \beta_6 \theta_{mg} + \beta_7 \theta_{ml} + \beta_8 \theta_{mc} \end{aligned}$$

where a_i is the log2 fold-change in H3K27 acetylation from myoblast to myotube at site i , A_{icl} and A_{iop} are indicator variables for whether site i is closing or opening across pseudotime, m_{ig} , m_{il} , and m_{ic} are indicator variables for whether site i is gaining, losing, or constitutively bound by MYOD1 from myoblast to myotube according to ChIP-seq, θ_{op} and θ_{cl} are the highest Cicero co-accessibility scores that connect site i to another opening or closing site respectively, and θ_{mg} , θ_{ml} and θ_{mc} are the highest Cicero co-accessibility scores that connect site i to another MYOD1 gaining, MYOD1 losing or MYOD1 constitutive site. For each of the fitted models, we used elastic net regression (Zou and Hastie, 2005) to estimate the effect of each predictor.

Similarly, in [Figure S6B](#), we predict the log₂ fold-change in each of the 12 ENCODE histone mark ChIP-seq datasets described above using only indicator variables for whether a site is gaining losing or constitutively bound by MYOD1, or using these variables and the highest Cicero co-accessibility scores connecting a site to an opening or closing site.

Regression Models for Barrier Region Histone Marks and Gene Expression

For each of the 12 ENCODE histone mark ChIP-seq datasets described previously, we fit two regression models that predict, for each transcription start site, the log fold change in the number of reads from the given ChIP-seq dataset that fall in the barrier region of that TSS (first 1000 bp downstream) for myotubes versus myoblasts. We exclude TSSs that do not have a significantly different number of barrier region reads in myotubes versus myoblasts for any of the 12 datasets ($p > 0.01$), leaving 5,563 TSS included in the model.

In the first set of models (“promoter motifs”), the features are a set of binary indicator variables that have value 1 if any promoter sci-ATAC-seq peak for the TSS has at least one instance of a motif from a given motif family. In the second set of models (“promoter and distal motifs”), the features are the promoter motif indicator variables plus a second set of real-valued variables that encode the presence of distal sequence motifs. For a given motif family and TSS, the corresponding distal motif variable has a value equal to the highest co-accessibility score from any promoter sci-ATAC-seq peak for that TSS to any connected distal peak that has at least one instance of a motif from the motif family. If no such distal peak exists (the motif is absent in all connected distal sites), the distal motif variable is assigned a value of 0. The models were trained using elastic net regression.

We additionally fit models with the same features (“promoter motifs” and “promoter and distal motifs”) to predict the expression of the subset of the above TSSs ($n = 937$), that were additionally expressed in at least 4 cells in sc-RNA-seq and which were predicted by smoothed average across pseudotime to be expressed at above 1 copy per cell at some pseudotime.

DATA AND SOFTWARE AVAILABILITY

Data Availability

The accession number for the sci-ATAC-seq data reported in this paper is GEO: GSE109828.

Code Availability

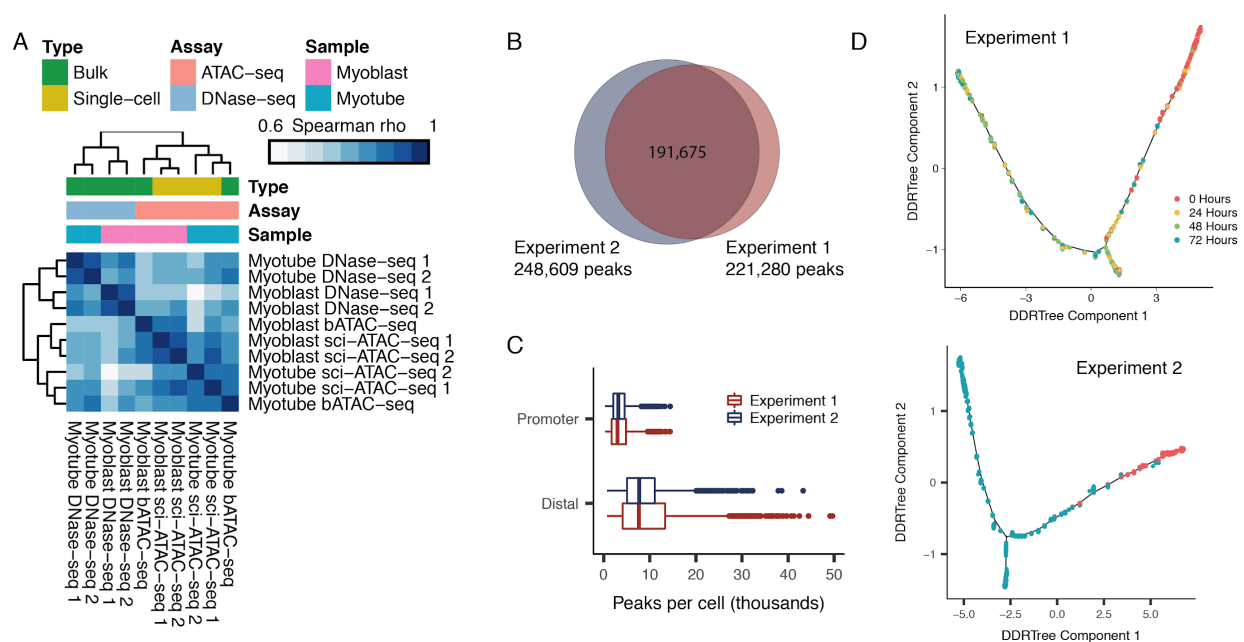
Cicero is available as an R package at <http://cole-trapnell-lab.github.io/cicero-release>.

Molecular Cell, Volume 71

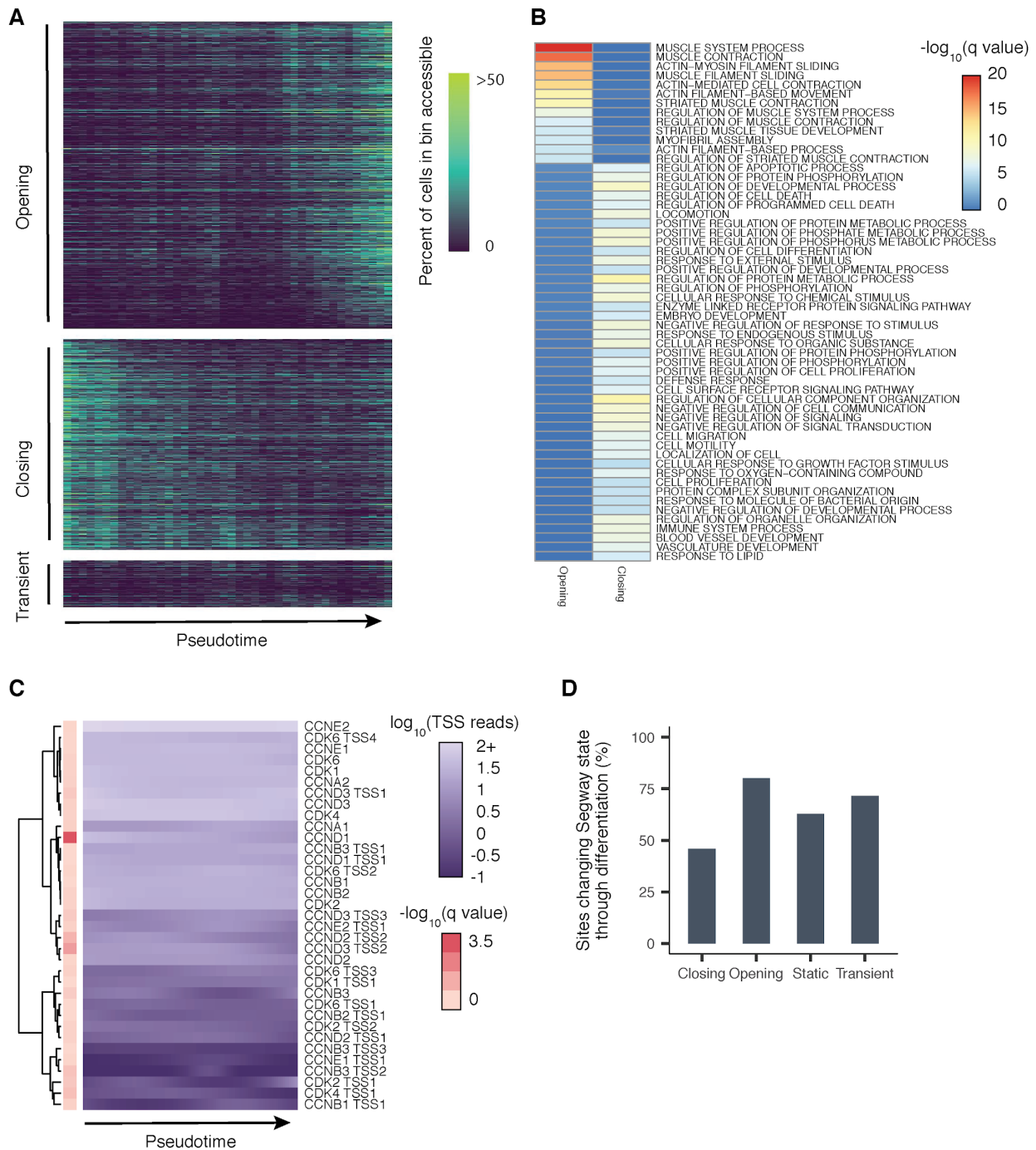
Supplemental Information

**Cicero Predicts *cis*-Regulatory DNA Interactions
from Single-Cell Chromatin Accessibility Data**

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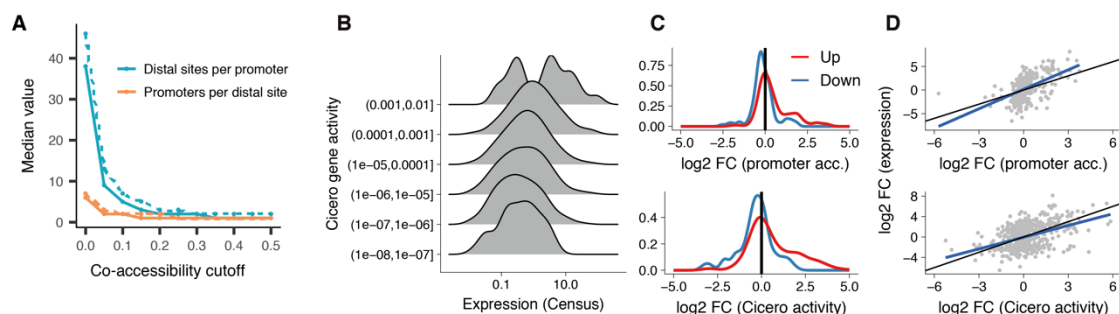


Supplemental Figure 1. Chromatin accessibility profiles of differentiating myoblasts are highly reproducible, related to Figure 1. A) Spearman correlation heatmap between pairs of chromatin accessibility profiles as measured by bulk ATAC-seq, DNase-seq, and aggregated sci-ATAC-seq from 0 and 72 hours. MACS was used to call new peaks on each dataset; these peaks were merged, and reads were counted in each peak from each dataset. These counts were used to calculate Spearman correlations. **B)** Venn diagram illustrating reproducibility in MACS2 peaks calls between independent sci-ATAC-seq experiments. Peaks in the intersection correspond to DNA elements called in both experiments. **C)** Boxplot of the number of MACS-called sci-ATAC-seq peaks per cell. Promoter-proximal peaks are peaks intersecting the first 500 base pairs upstream of a transcription start site (see Methods). Distal peaks are all other peaks. **D)** Monocle trajectories on each of the sci-ATAC-seq experiments. The top panel is identical to Figure 1C and included for comparison purposes.

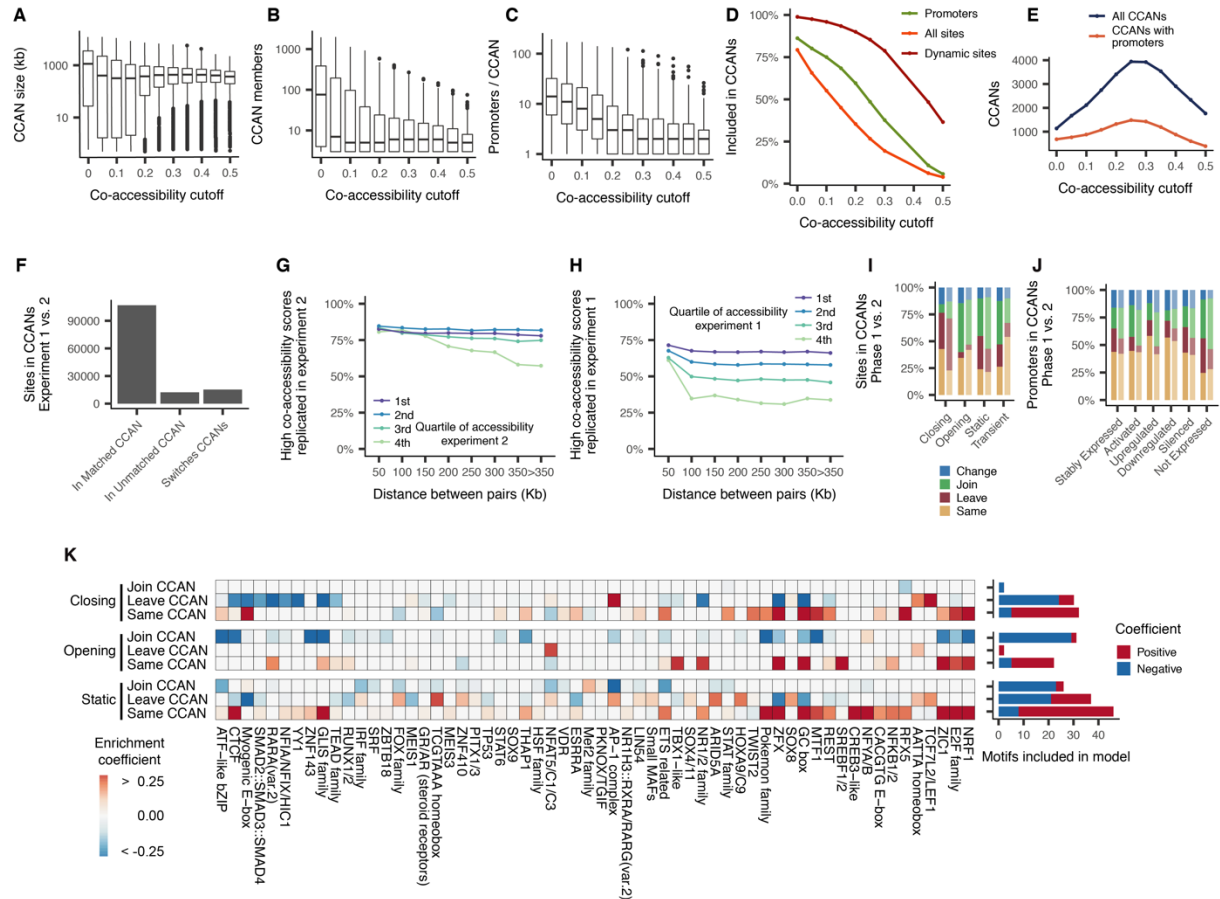


Supplemental Figure 2. DNA elements that open during differentiation are enriched for muscle related promoters, related to Figure 2. A) Heatmap of accessibility across pseudotime. Color represents the percent of cells per bin that are accessible at a given DNA element. Each row indicates a different DNA element, each column represents a bin of approximately even numbers of cells divided by pseudotime. Rows are in the same order as Figure 2A. **B)** Gene set enrichment analysis of significantly opening and closing accessible sites. Adjusted p-values were

computed using a hypergeometric test. Terms shown are all sites with an adjusted p-value $< 1e-6$ in either the opening set or the closing set. Color represent the $-\log_{10}$ adjusted p-value. Sites are ordered by the $-\log_{10}$ adjusted p-value of the opening set. **C)** Smoothed pseudotime-dependent accessibility curves, generated by a negative binomial regression of each for a set of selected cell cycle relevant genes. Each row indicates a different DNA element. Annotation column represents the $-\log_{10}$ adjusted p-value for the test of differential accessibility across pseudotime. For visualization, fitted curve range was capped at 100. **D)** Percent of dynamic and static sites with changing Segway state assignment from myoblast to myotube.

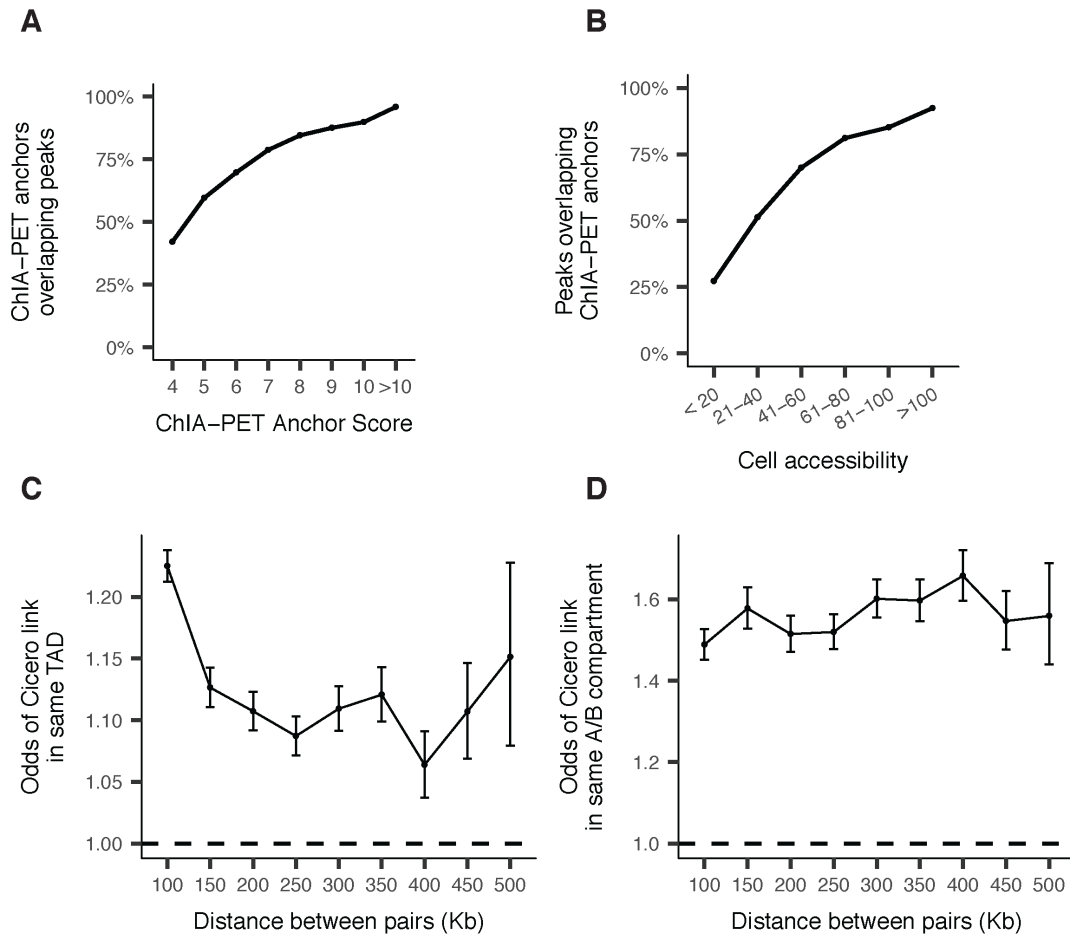


Supplemental Figure 3. Cicero gene activity scores correlate with gene expression, related to Figure 3. **A)** The median number of linked distal sites per promoter and promoters per distal site as a function of the co-accessibility threshold of the links considered. Dashed lines indicate experiment 2. Solid lines indicate experiment 1. **B)** Average Cicero gene activity scores across cells in phase 1 compared to their average expression from sc-RNA-seq libraries from myoblasts. Cicero gene activity scores were computed by summing the reads falling in distal sites linked to a gene's promoter (see Methods for details). **C)** Top panel: Log₂ fold changes in mean accessibility at gene promoters for genes that are significantly up- (red) or down-regulated (blue) between 0 and 72 hours as measured by sc-RNA-seq. Bottom panel: corresponding changes in Cicero gene activity scores. **D)** Top panel: comparison of log₂ fold changes between expression and promoter accessibility. Bottom panel: fold changes in expression versus changes in Cicero gene activity scores. Black lines indicate perfect concordance between log₂ fold changes, while blue lines indicate linear regressions between Cicero activity or promoter accessibility and expression.

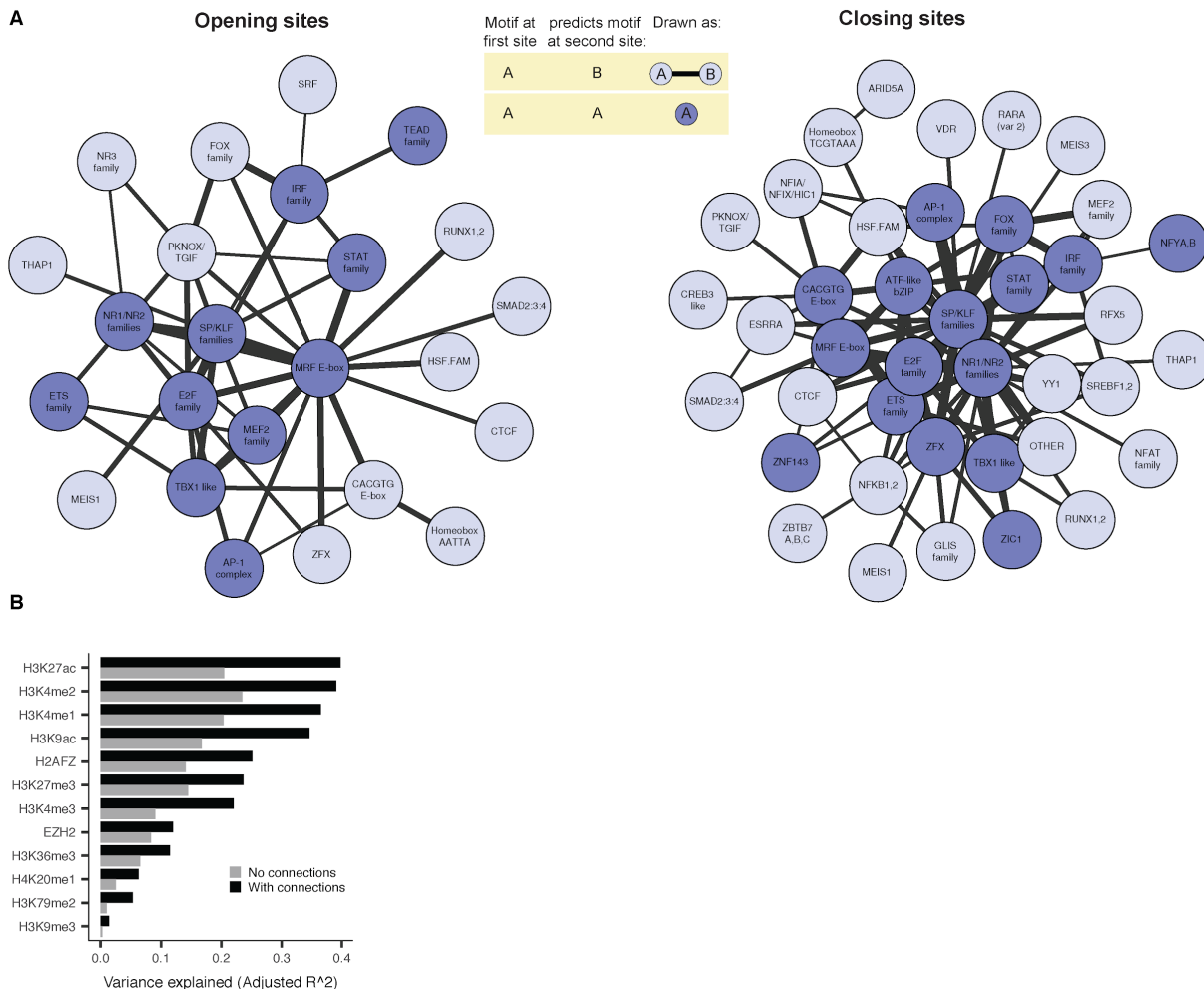


Supplemental Figure 4. Cis-co-accessibility networks (CCANs) maintain properties at varying cutoffs, related to Figure 3. **A)** Boxplots of the length in the linear genome (in kilobases) of CCANs formed at varying thresholds of co-accessibility in experiment 1. CCANs are defined as groups with 3 or more co-accessible DNA elements identified with Louvain community detection. Prior to running Louvain, connections below the indicated Cicero co-accessibility score are excluded (see Methods for details). **B)** Boxplots of the number of sites in CCANs formed at varying thresholds of co-accessibility. **C)** Boxplots of the number of expressed gene (at a level of 10 transcripts per cell on average in sc-RNA-seq) promoters per CCAN at increasing co-accessibility score cutoffs. **D)** Percent of sites recruited into a CCAN at increasing co-accessibility score cutoff. Colors represent subsets of sites: green represents promoters for genes that are expressed; orange and red represent sites that are accessible and differentially accessible across pseudotime, respectively. **E)** Number of CCANs identified with varying co-accessibility cutoffs. Blue series shows the total number of CCANs, orange shows the number of CCANs that include a promoter of at least 1 detectably expressed gene. **F)** Number of sites that linked into CCANs that are matched in experiment 1 and experiment 2 by a maximum weighted bipartite matching method (see Methods). Also shown are sites that are linked into CCANs that are not matched at all and sites that are linked into CCANs that are matched in experiment 1 and experiment 2, but not to one another. **G)** Fraction of pairs of sites linked in experiment 1 at co-accessibility > 0.25 that are also linked in experiment 2 at co-accessibility > 0. Colors indicate the quartile of accessibility in experiment 2. **H)** Reciprocal plot to panel G, examining sites linked at co-accessibility > 0.25 in experiment 2 and > 0 in experiment 1. Colors indicate the quartile of accessibility in experiment 1. **I)** Sites linked into CCANs found in both phase 1 and phase 2 by maximum matching, subdivided by those that were linked into the CCAN in both phases (yellow),

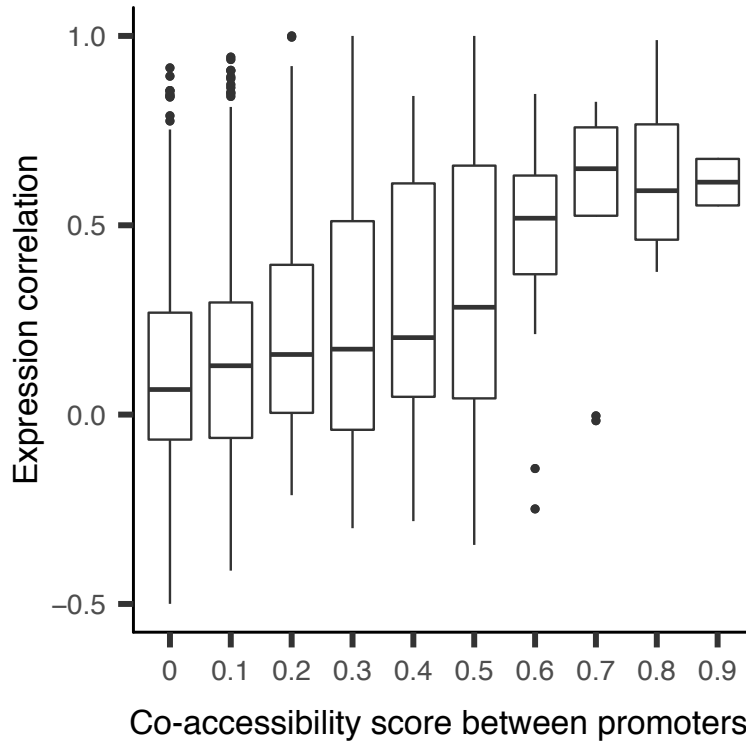
those linked in phase 1 but unlinked in phase 2 (red), those unlinked in phase 1 but linked in phase 2 (green), and those linked into different (i.e. non-matched) CCANs in the two phases. The four groups of sites from Figure 2B,C,E are considered. The left bar in each group corresponds to experiment 1, while the right bar corresponds to experiment 2. **J)** Similar to panel I but considering only promoters: groups are promoters of genes that are “stably” expressed at an unchanged level, those that are silent in myoblasts but expressed in myotubes (“activated”), and those expressed in both myoblasts and myotubes, but higher in myotubes (“upregulated”). Similarly, we show promoters of genes that are downregulated or fully silenced in myotubes, as well as those that are not detectably expressed (at a level of 10 transcripts per cell on average) in either cell type. **K)** A heatmap of regression coefficients from three multinomial elastic net regression analyses that predict whether a site will join, leave, or remain linked into its CCAN during differentiation on the basis of varying sequence motifs. Coefficients were capped at -0.25 and 0.25 for visualization. Only sites with consistent CCAN dynamics across both experiments were included in the models. The number of positive and negative coefficients surviving regularization in each model are shown in the barplot to the right. Regression was performed using the glmnet package in R and the regularization parameter was chosen that produced the minimum mean cross-validated error after 10-fold cross validation.



Supplemental Figure 5. ChIA-PET anchors are concordant with sci-ATAC-seq peaks, related to Figure 4. **A)** Percent of pol II ChIA-PET anchors within 1 kb of a sci-ATAC-seq peak as a function of ChIA-PET anchor score provided by Tang et. al. (2015). **B)** Percent of sci-ATAC-seq peaks within 1 kb of pol II ChIA-PET anchors as a function of overall cell accessibility (number of cells where the peak is accessible). **C)** Odds ratio that both members of Cicero linked pairs (co-accessibility > 0) are in the same TAD, compared with unlinked pairs at the same distance. GM12878 TAD calls are from (Rao et al., 2014). **D)** Odds ratio that both members of Cicero linked pairs (co-accessibility > 0) are in the same A/B compartment, compared with unlinked pairs at the same distance. A/B compartment calls are from (Fortin and Hansen, 2015).



Supplemental Figure 6. DNA motifs predict motifs in Cicero-linked sites, related to Figure 5. A) Motifs in accessible sites predict motif content of Cicero-linked sites. The network summarizes a graphical model that captures how occurrences of motifs in pairs of sites predict whether they are connected. Each motif is connected to the motifs it suggests will exist in one or more connected sites. A motif that predicts itself in a connected site is shown in dark blue. If motif “A” at a distal site predicts that “B” will be found at a promoter, and symmetrically “B” at a distal site suggests “A” will be found at a promoter, they are connected with a black line, with a width proportional to the strength of the co-accessibility. Asymmetric motif relationships are not shown. **B)** Variance explained by a linear model that aims to predict log₂-transformed fold changes in the listed ChIP-seq read counts between myoblasts and myotubes. Two models are considered. The first, with performance indicated as gray bars, uses a site’s accessibility and MYOD1 binding status. The second, indicated as black bars, augments the first with accessibility and MYOD1 at linked sites. The predictor for MYOD1 at linked sites was significant (p -value $< .05$) for all augmented models. See Methods for more details.



Supplemental Figure 7. Expression correlation increases with increasing co-accessibility, related to Figure 6. Correlation in expression among linked differentially expressed genes. Boxplots of the cell-wise correlation between gene expression among pairs of differentially expressed genes whose promoters have different Cicero co-accessibility scores.

Supplemental Table 1. sgRNA sequences targeting *Meis1*, *PBX1* and non-targeting controls, related to STAR Methods

sgRNA	Gene targeted	sgRNA sequence
<i>Meis1_1</i>	<i>Meis1</i>	TACTTGTACCCCCCGCGAGC
<i>Meis1_2</i>	<i>Meis1</i>	CACAGCTCATACCAACGCCA
<i>Meis1_3</i>	<i>Meis1</i>	GGTGGCCACACGTCACACAG
<i>Meis1_4</i>	<i>Meis1</i>	ACTCGTTCAGGAGGAACCCC
<i>PBX1_1</i>	<i>PBX1</i>	GATCCTGCGTTCCCGATTTT
<i>PBX1_2</i>	<i>PBX1</i>	TGGTCCGGCTTTGCTCTCGC
<i>PBX1_3</i>	<i>PBX1</i>	CCTGCGCCTCATCCAAACTC
<i>PBX1_4</i>	<i>PBX1</i>	CGGCCATCCCGACCCCAGCA
<i>PBX1_5</i>	<i>PBX1</i>	TGTGAAATCAAAGAAAAAAC
NTC_1	Non-targeting control	ACGGAGGCTAAGCGTCGCAA
NTC_2	Non-targeting control	CGCTTCCGCGGCCCGTTCAA
NTC_3	Non-targeting control	ATCGTTTCCGCTTAACGGCG
NTC_4	Non-targeting control	GTAGGCGCGCCGCTCTCTAC
NTC_5	Non-targeting control	CCATATCGGGGCGAGACATG