Selectable markers are widely used in transgenesis and genome editing for selecting engineered cells with a desired genotype but the variety of markers is limited. Here we present split selectable markers that each allow for selection of multiple "unlinked" transgenes in the context of lentivirus-mediated transgenesis as well as CRISPR-Cas-mediated knock-ins. Split marker gene segments fused to protein splicing elements called "inteins" can be separately co-segregated with different transgenic vectors, and rejoin via protein trans-splicing to reconstitute a full-length marker protein in host cells receiving all intended vectors. Using a lentiviral system, we create and validate 2-split Hygromycin, Puromycin, Neomycin and Blasticidin resistance genes as well as mScarlet fluorescent proteins. By combining split points, we create 3- and 6-split Hygromycin resistance genes, demonstrating that higher-degree split markers can be generated by a "chaining" design. We adapt the split marker system for selecting biallelically engineered cells after CRISPR gene editing. Future engineering of split markers may allow selection of a higher number of genetic modifications in target cells.
Selecteable markers, such as antibiotic resistance or fluorescent protein genes, are often used in genetic engineering to isolate cells with desired genotypes. However, there are a limited number of well-characterized antibiotic resistance genes for use in eukaryotic cells and fluorescent proteins whose spectra can be unambiguously distinguished by commonly used equipment is similarly limited. Researchers often run into the problem of not having enough choices of selectable markers if they wish to incorporate multiple transgenes into a cell. On the other hand, selection with multiple antibiotics at the same time is often harsh to cells. "Selectable marker recycling" can provide a work-around but is unwieldy, requiring multiple rounds of transgenesis, selection and removal of markers.

To allow multiple transgene selection with a single scheme, we create here split antibiotics resistance and fluorescent protein genes. In this system, a gene encoding an antibiotic resistance or fluorescent protein is split into two or more segments and fused to inteins ("markertrons") that can be rejoined by protein trans-splicing (Fig. 1). Each markertron is inserted onto a transgenic vector carrying a specific transgene. Delivery of transgenic vectors containing a set of markertrons yields cells that harbor either a subset or a complete set of the markertrons. Only cells with a complete set of markertrons produce a fully reconstituted marker protein via protein splicing and thus passes through selection while cells with partial sets of markertrons are eliminated, achieving co-selection of cells containing all intended transgenes.

**Results**

**Intein-split antibiotic resistance (Intres) genes.** We began by engineering 2-markertron intein-split resistance (Intres) genes for double transgenesis. Since flanking residues and local protein folding can affect efficiency of intein-mediated trans-splicing, we set out to identify split points in each of the four commonly used antibiotic resistance genes compatible with two well-characterized split inteins derived from NpuDnaE and SpdDnaB. To facilitate assessment of the effectiveness of double transgenic selection, we cloned markertrons onto lentiviral vectors expressing TagBFP or mCherry fluorescent proteins as test transgenes (Fig. 2a). Viral preparations were transduced into U2OS cells, which were then split into replicate plates with non-selective or selective media. Following appropriate passages for antibiotics selection, the two cell cultures were analyzed by flow cytometry. For Hygromycin resistance (Hygro) gene, one "native" SpdDnaB split point (SpdDnaB-200 = G200S201; Plasmid pair 5,6) with flanking residues "GS" and one "native" NpuDnaE split point (NpuDnaE-89 = Y89C90; Plasmid pair 3,4) with "YC" residues were tested (Supplementary Fig. 1a). Both enabled successful selection when both N- and C-markertrons were transduced yielding >95% BFP + mCherry + double transgenic cells in selected cultures compared to <40% double-positive cells in non-selected culture (Fig. 2b; Plasmid pairs 3, 4 and 5, 6). Cells transduced with either of the single markertrons did not survive Hygromycin selection. In contrast, double transgenesis with conventional full-length non-split Hygro vectors only allowed for ~20% enrichment of BFP + mCherry + cells (Plasmid pairs 97,98) at lower titers and for up to ~50% at higher titers. We screened three additional potential split points (NpuDnaE-52 = 52S53 C; Plasmid pair 7,8), (NpuDnaE-240 = 240A241 C; Plasmid pair 9,10), and (NpuDnaE-292 = 292R293 C; Plasmid pair 11,12) for NpuDnaE with the obligatory cysteine residue on the C-extein junction and a residue on the N-extein junction reported to support substantial trans-splicing activities. We also tested six additional NpuDnaE split points (NpuDnaE-69, 131, 171, 218, 259, and 277) by inserting an "artificial" cysteine on the C-extein junction to support splicing at ectopic sites yielding additional split points. In total, eight out of eleven split points tested supported Hygromycin selection (Fig. 2b). Two of the Hygro Intres designs (NpuDnaE-131 and 292) failed to provide resistance in two of the four replicate experiments at lower titers, while three designs (NpuDnaE-218, 259, and 277) failed to provide resistance in any experiments. These positions may reside within less efficient splicing sequence and structural contexts or may disrupt folding of the Hygro protein upon reconstitution. Indeed, western blot analysis using terminally tagged markertron fragments revealed that among split points 52, 68, 89, 131, and 171, trans-splicing is least active at split point 131 (Supplementary Fig. 1b, lane 5). This is consistent with its failure to consistently provide resistance at a lower titer (Fig. 2b). In addition, the insertion of the artificial cysteine at the NpuDnaE-69, 131, and 171 C-markertrons is required for protein splicing mediated by NpuDnaE intein at these positions (Compare lanes 2/3, 5/6, and 7/8), consistent with a well-established requirement.

Nonetheless, the six successful designs validate our screening strategy and demonstrate that Hygro is amenable to splitting at different positions spanning a large portion of the protein. Similarly, for Puromycin resistance (Puro) (Fig. 3a), Neomycin/G418 resistance (Neo) (Fig. 3b) or Blasticidin resistance (Blast) (Fig. 3c) genes, we identified four, two, and one functional 2-split Intres pair(s), respectively. In all of these cases, cells transduced with single markertrons did not survive selection, while cells transduced with both yielded 88–100% double transgenic cells in selective cultures compared to <50% in non-selective cultures. Details of the split points of Intres genes and plasmids are presented in Supplementary Figs. 1–4 and Supplementary Table 1. To facilitate adoption of Intres markers, we created Gateway-compatible lentiviral vectors for convenient restriction-ligation-independent LR clonase recombination of transgenes (Supplementary Fig. 5). We tested the functionality of these vectors by recombining TagBFP and mCherry, respectively, to the N- and C-Intres vectors and found robust selection of double transgenic cells (Supplementary Fig. 5b). One potential utility of Intres vectors is presented in Supplementary Fig. 4 and Supplementary Table 1.
of double transgenic cells in an mScarlet-gated population, compared to <20% double transgenic cells in non-gated population (Supplementary Fig. 7b, c).

Three-split Hygromycin Intres for triple transgenesis. With the split points identified for 2-marktron Intres genes, we set out to engineer higher degree split markers. We tested combinations of splits points to partition a marker gene into three or more markertrons to allow for co-selection of more than two “unlinked” transgenes with one antibiotic (Fig. 4a, b). To identify pairs of split points that would allow such an “Intres chain”, we cloned 3-split markertrons into three lentiviral vectors each carrying one of three fluorescent transgenes TagBFP, EGFP, or mCherry, that will allow us to assess effectiveness of selection by flow cytometry (Fig. 4c). Since the Hygromycin resistance gene is the longest and provides the most split points for testing, we focused on engineering 3-split Hygromycin Intres. We tested two 3-split Hygromycin Intres using two intervening NpuDnaE vectors is to install different fluorescent markers in cells to label different cellular compartments. To explore this application, we cloned in NLS-GFP and LifeAct-mScarlet, which label nucleus and F-actin, respectively, by Gateway recombination to conventional full-length (FL) non-split Hygromycin selectable vectors or 2-split Hygromycin Intres vectors. We transduced cells with either sets of plasmids and subjected them to antibiotic selection (Supplementary Fig. 5c). The sample transduced with non-split selectable plasmids contained both singly and doubly labeled cells, while cell transduced with Intres plasmids were all doubly labeled.

Split mScarlet fluorescent genes for double transgenesis. To test whether split fluorescent markers can be used for transgene selection, we screened for NpuDnaE split points in the mScarlet fluorescent protein (Supplementary Figs. 6 and 7a) and identified four split points allowing for >96% enrichment of double transgenic cells and three other split points enabling >60% enrichment
Application of Intres in CRISPR-Cas-mediated knock-in.

Another potential application of split selectable markers is to facilitate genome engineering and editing via the CRISPR-Cas system. Although gene knockout based on NHEJ-mediated insertions/deletions (indels) occurs at high frequency, precise editing and knock-in based on homology directed repair (HDR) using exogenous repair templates are inefficient. We tested whether split selectable markers can be used to select for cells with CRISPR-mediated biallelic knock-in at the AAVS1 locus. We constructed targeting constructs with homology arms flanking the target site, and splice acceptor-2A peptide to trap the markertrons within intron one of the host gene. However, we did not obtain any live cells after CRISPR-Cas knock-in experiments in HEK293T cells using these targeting constructs and two weeks of antibiotic selection. We suspected that the endogenous promoter of the host gene might not drive sufficient expression of markertrons to reconstitute enough antibiotic resistance protein to counter the antibiotic. We thus tested an alternative strategy to express Intres markertrons using the TetO promoter which allows activity to be tuned by doxycycline (dox). To allow comparison of Intres-mediated biallelic selection versus full-length (FL) non-split selectable markers, we implemented several different targeting construct designs. First, we drove expression of a full-length (FL) resistance gene (e.g., Hygro) together with rtTA under a constitutive EF1a promoter and to demonstrate the feasibility of incorporating two transgenes into two AAVS1 alleles, we appended EGFP and mScarlet fluorescent genes downstream of the test split or non-split markers via CRISPR-mediated biallelic knock-in at the AAVS1 locus. However, we did not obtain any live cells after CRISPR-Cas knock-in experiments in HEK293T cells using these targeting constructs and two weeks of antibiotic selection. We suspected that the endogenous promoter of the host gene might not drive sufficient expression of markertrons to reconstitute enough antibiotic resistance protein to counter the antibiotic. We thus tested an alternative strategy to express Intres markertrons using the TetO promoter which allows activity to be tuned by doxycycline (dox). To allow comparison of Intres-mediated biallelic selection versus full-length (FL) non-split selectable markers, we implemented several different targeting construct designs. First, we drove expression of a full-length (FL) resistance gene (e.g., Hygro) together with rtTA under a constitutive EF1a promoter and to demonstrate the feasibility of incorporating two transgenes into two AAVS1 alleles, we appended EGFP and mScarlet fluorescent genes downstream of the test split or non-split markers via the self-cleaving 2A peptide. Similarly, to test Hygro Intres, we swapped the EF1a and TetO-driven markers so that FL Hygro or Hygro Intres were placed downstream of TetO and FL Blast downstream of EF1a. We co-transfected pX330-AAVS1 (Plasmid 106)
containing Cas9 and sgRNA targeting AAVSI, and the different pairs of targeting constructs (TC) into HEK293T cells, split into triplicate doxycycline-containing media without antibiotics, with Blasticidin, or with Hygromycin at the subsequent passages. Two weeks after selection, we analyzed the cultures for biallelic targeting by flow cytometric measurement of GFP and RFP fluorescence (Supplementary Fig. 9e). As expected, non-selected cultures harbored a small fraction (<1%) of biallelic knock-in GFP+/RFP+ cells (Supplementary Fig. 9e; Selection = None). Selection of antibiotics where corresponding Flu antibiotic resistance genes were present on targeting constructs yielded <30% biallelic knock-in cells (Supplementary Fig. 9e; Blast: TC a, c, d; Hygro: TC a, b, c). In contrast, selection by antibiotics where corresponding Intres are present on the targeting constructs yielded 75% (Supplementary Fig. 9e; Blast Intres: TC b) and 88% (Supplementary Fig. 9e; Hygro Intres: TC d) biallelic knock-in cells. Selection for an additional two weeks allowed split Blast and Hygro TCs to achieve 96.5% and 97.0% biallelic knock-in cells. Selection for an additional two weeks allowed split Blast and Hygro TCs to achieve 96.5% and 97.0% biallelic knock-in cells.
Puriﬁed Cas9 proteins were complexed with synthetic sgRNA to form Cas9 ribonucleoprotein (RNP) and co-nucleofected with the targeting constructs into KOLF2-C1, followed by dox-induction and antibiotic selection. Surviving colonies were picked into separate wells for establishing single-cell clones. Genotyping PCR revealed that targeting using non-split Blast resistance gene generated only 8% biallelic clones, while targeting using Blasticidin Intres yielded exclusively (100%) biallelically modiﬁed clones (Fig. 5c, d), showing both ﬂuorescent signals (Fig. 5e) indicative of the targeting by each targeting construct at the two alleles of AAVS in these hiPSCs.

Selection of four or more transgenes with Intres. The utility of Intres may become more apparent in cases where more than three transgenes are to be selected. As we have observed in our 3-split Hygromycin Intres engineering exercise that the use of a set of orthogonal inteins represent a better design for a more robust split marker, we tested four other inteins (gp411, gp418, NrdJ1, IMPDH1)14 in splitting HygroR or PuroR. We identiﬁed additional functional splits of HygroR and PuroR at different positions (Supplementary Figs. 10 and 11). Some of these additional Intres were further adapted to the Gateway cloning system (Supplementary Figs. 12 and 13). To directly observe protein splicing as

![Plasmid Diagrams](image1.png)

Fig. 5 Intres for selection of biallelic CRISPR knock-in in human induced pluripotent stem cells. a Plasmids 107 and 108 contain AAVS homology arms, and Dox-inducible full-length (FL) Blasticidin (Blast) and EGFP (plasmid 107) or mScarlet (plasmid 108) separated by a self-cleaving 2A peptide sequence. b Plasmids 109 and 110 contain AAVS homology arms, and Dox-inducible N-split Blast markertron and EGFP (plasmid 109) or C-split Blast markertron and mScarlet (plasmid 110) separated by a self-cleaving 2A peptide sequence. Cas9 ribonucleoprotein was formed in vitro by complexing puriﬁed Cas9 proteins with synthetic sgRNA targeting AAVS locus, introduced to hiPSCs together with targeting constructs by nucleofection, subsequently subjected to dox-induction and antibiotic selection, and ﬁnally cloned by colony picking and analyzed for allelic modiﬁcation. c Genotyping PCR for EGFP- and mScarlet-inserted AAVS alleles of single iPSC clones generated by CRISPR editing using non-split targeting constructs (TCs) 107 and 108. NT: Non-targeted; M: Marker = GeneRuler 1 kb + ladder. d Genotyping PCR for EGFP- and mScarlet-inserted AAVS alleles of single iPSC clones generated by CRISPR editing using Intres TCs 109 and 110. NT: Non-targeted; T: Targeted pool; M: Marker = GeneRuler 1 kb + ladder. e Representative ﬂuorescent microscopic images of hiPSC colonies from the indicated clones derived from the Intres CRISPR experiments using TCs 109 and 110. Scale bar: 200 μm
well as to confirm these inteins are indeed orthogonal, we conducted western blot analysis of protein trans-splicing between N-terminal tagged with 3xFLAG-epitope and C-terminal tagged with HA-epitope (Supplementary Fig. 14). As expected, while cognate markertrons with matching N- and C-inteins supported reconstitution of the full-length Hygro R (lanes 3, 5, 6), markertrons with unmatched N- and C-inteins did not yield full-length Hygro R (lanes 7, 8). To introduce and select cells with four or more transgenes, one approach is through sequential transduction/selection of two or more sets of 2-split Intres vectors. By subjecting cells to two rounds of 2-split Intres transduction/selection (Hygro → Puro or Puro → Hygro) with each round carrying two transgenes, we obtained quadruple transgenic cells (Supplementary Fig. 15). These results demonstrated that four transgenes can be sequentially introduced, and that the Intres system is compatible with sequential cell engineering. Another way to introduce four or more transgenes is with higher-degree split Intres markers. By combining the multiple inteins and positions tested for Hygro R, we designed and tested a 3-split Hygro Intres marker (Supplementary Fig. 16). While cultures transduced with all markertrons yielded viable cells, leave-one-out cultures missing any one of the markertrons did not produce any viable cells after selection. This result demonstrates that up to at least 6 transgenic vectors can be selected simultaneously by one selection scheme using a split selectable marker.

Proviral copy number analysis. We validated Intres lentiviral vectors in additional cell lines (HEK293T and HeLa) (Supplementary Fig. 17). To ask whether split markers require a substantially higher copy number than non-split markers to support selection, we conducted proviral copy number analysis in non-selective and selective cultures of cells transduced with non-split Hygro R or split Hygro Intres markers (Supplementary Fig. 18) in U2OS, HEK293T and HeLa cells. In general, we observed 1.3–3.1-fold proviral copy numbers in the split marker cultures compared to the non-split cultures. Since the two-split markers require the presence of the two different viral genomes hosting the two markertrons to reconstitute a full resistance protein, it is expected to have ~2-fold equivalence of viral integration to support selection.

Discussion
In this study, we have engineered split antibiotic resistance and fluorescent protein genes that allow selection for two or more “unlinked” transgenes. By inserting unnatural residues at selectable markers, we showed that additional high-efficiency split point pairs could be utilized, expanding the positions available for engineering. We demonstrated that split selectable markers could be incorporated into lentiviral vectors or as targeting constructs in CRISPR-Cas9 genome editing experiments for positive selection of cells with double transgensics or biallelic knock-ins. By combining two splits points, we showed that 3-split markers could be generated to allow higher degree transgenic selection. By conducting sequential transduction/selection with two-split markers, or by combining even more split points we showed the potential to use split selectable markers to select for 4 vectors with two antibiotics or up to 6 vectors with one antibiotic respectively. It is intriguing to anticipate future work to design even higher-degree split selectable markers and to explore the limit of this system for “hyper-engineering” of cells.

Methods
Cloning. To generate a test plasmid for each markertron, we first generated a Gateway donor plasmid containing its ORF and then recombined into lentiviral destination vector with TagBFP2 (Plasmid 94: pLX-DEST-INES-TagBFP2), EGFP (Plasmid 95: pLX-DEST-INES-EGFP), or mCherry (Plasmid 96: pLX-DEST-INES-mCherry) reporters, which were derived from pLX302 (Gift from David Root; Addgene: #25896) by removing YcMinC resistance gene (GenBank accession: NC_000001.10). To produce mCherry-RFP fusion proteins, we subcloned mCherry and RFP-GFP fluorescent genes downstream of the Gateway cassette. The markertron-ORF Gateway donor plasmids were generated either by a nested fusion PCR procedure to combine intein with the coding sequence of fragments of the selectable marker followed by insertion into the pCRII-ORF TOPO plasmid by sequence- and ligation-independent cloning (SLIC), or PCR-amplifying the relevant fragment of the selectable marker followed by insertion into “scaffold” plasmids (Plasmids 27–32) containing the intein sequences by SLIC. DNA sequences encoding inteins were codon optimized for Homo sapiens, and synthesized as GBlocks (IDT). Selection of marker fragments was amplified from plasmid containing these markers. Plasmids created in this study are listed in Supplementary Table 1 with links to webpages for plasmid sharing and GenBank sequence files.

HEK293T, U2OS, and HeLa cell cultures. HEK293T (ATCC® CRL-3121), U2OS (ATCC® HTB-96), HeLa (ATCC® CCL-2.2) cells were cultivated in Dulbecco’s modified Eagle’s medium (DMEM) (Sigma) with 10% fetal bovine serum (FBS) (Lonza), 4% Glutamax ( Gibco), 1% Sodium Pyruvate ( Gibco), and penicillin-streptomycin ( Gibco). Incubator conditions were 37°C and 5% CO2.

Viruses. A viral packaging mix of pLP1, pLP2, and pVSV-G were cotransfected with each lentiviral vector into Lenti-X 293T cells (Clontech/Takara #632180), seeded the day before in 6-well plates at a concentration of 1.2 × 105 cells per well, using Lipofectamine 3000. Media was changed 6 h after transfection then incubated overnight. 24 h post transfection, the media supernatant containing virus was filtered using 45 μm PES filters then stored at ~80°C until use.

Transduction, transfection, flow cytometry, and microscopy. The day prior to transduction, U2OS, HEK293T, or HeLa cells were seeded into 12-well plates at a density of 1.5 × 105 cells per well. Prior to transduction, media was changed to media containing 10 μg/mL polybrene, 1 mL per well. In all, 25 μL (or indicated otherwise) of each respective virus (50 μL total for experimental samples with two viruses; 25 μL total for experimental samples with three viruses) was added to each well and incubated overnight. Media was changed 24 h post-transduction. Four days post-transduction, cells were split into duplicate plates. Five days post-transduction, media with antibiotics (130 μg/mL Hygromycin, 2 μg/mL Puromycin, 700 μg/mL G418, or 6 μg/mL Blasticidin) was added to each respective well of one replicate plate (the other remained under no selection). Antibiotics selection continued for 2 weeks before analysis with flow cytometry. For flow cytometry, cells were trypsinized, suspended in media then analyzed on a LSRFortessa X-20 or FACSymphony flow cytometers (BD Biosciences). Fifty thousand events were collected each run. Exemplary gating strategy is presented in Supplementary Fig. 19. Microscopy images were taken with the iRiS Digital Cell Imaging System (Logos Biosystems). For transfection for the CRISPR experiment in HEK293T, 600 ng of total plasmids, in equal ratios, were mixed with 100 μL of DMEM and 1.5 μg of attractene (QIAGEN), incubated at RT for 10 min then added to each well and incubated overnight. Media was changed 24 h post-transfection. Two days post transfection, cells were split into duplicate plates with media containing doxycycline (2 μg/mL). Three days post transfection, media with doxycycline and anti-biotics was added to each respective well of one replicate plate (the other remained under no selection).

Human iPSC culture and nuclearfection. Feeder-free KOLF2-C1 (gift from Bill Skarnes, subclone of HspHSc HPS0114-kolf_2) were maintained on plate coated with Synthema 11-SC Substrate (Corning) in StemFlex media (Thermo Fisher Scientific). Subculture was carried out every 4–6 days via Accutase (STEMCELL) detachment method. After plating, iX RevitaCell supplement (Gibco Life Technologies) was added for 1 day to increase cell viability. For Cas9/gRNA ribonuclease-protein (Cas9/gRNA RNPs) and donor plasmids nuclearfection, 4D-Nucleofector™ System (Lonza) was used with the P3 Primary Cell 4D-Nucleofector kit (Lonza). Cells were nucelofected at 60–70% confluency (Lonza). For transfection, donor plasmids were co-transfected with Cas9/gRNA RNPs, synthetic single-guide RNA (Synthego) was resuspended in TE buffer (Synthego) at 2 μg/μL, and 8 μL of stock solution was mixed with 20 μg Cas9 protein before nuclearfection. For each reaction, 2 × 105 cells were collected, resuspended in 100 μL complete P3 solution and mixed with pre-assembled Cas9/gRNA RNPs and donor plasmids DNA. Doxycycline (Sigma) was added 6 days after nuclearfection at 5 μg/mL. Two days after doxycycline was added, 4 μg/mL Blasticidin (Sigma) was applied to select cells with resistance. Surviving single colonies were picked and expanded into Matrigel-coated 24-well plates. If surviving colonies were too large to be manually picked as single colony, cells were replated onto new plate at the density of 2500 cells per 1 cm² plate. Blastcidin treatment continued during single colony expansion in 24-well plates. For genotyping, genomic DNA was extracted using DNeasy Blood and Tissue Kit (QIAGEN), and PCR was performed using the following primers to identify correctly targeted VAA1 insertions: (i) EGFP-AAVs (fwd: GCCGGCAACCC ACTACCTGCA, rev: GTGAGTTTGGCAAGACTGCA), (ii) mScarlet-AAVs (fwd: CTGAGTTCAAGCCACCTACAA, rev: GTGAGTTTGGCAAGACTGCA). Uncropped gel photos are available within the Source Data file.
Quantitation of proviral copy number in genomic DNA. Proviral copy number was measured using Lenti-X ProVirus Quantitation Kit (Takara). To perform the analysis, genomic DNA was isolated from transduced cells with NucleoSpin Tissue Genomic DNA Purification (Takara). Serial dilutions of each gDNA sample was subjected to qPCR amplification alongside dilutions of a provirus control template (provided in kit), which was used to generate a standard curve. Since the viral fragments in gDNA and the control template would be amplified with different PCR sensitivities, the provirus copy number was finally calculated based on the standard curve and correlated with a correction factor (provided in manual by Takara).

Western Blot. Proteins were separated by 4–20% precast polyacrylamide gel then transferred onto nitrocellulose membrane. After protein transfer, the membranes were incubated in room temperature 5% non-fat milk for 1 h. Membranes were then probed with antibodies against HA-epitope (#3724, 1:1000, Cell Signaling), FLAG-epitope (#F7425, 1:1000, Millipore Sigma), and Vinculin (EPR8185, 1:2000, Abcam). Proteins of interest were detected with HRP-conjugated anti-mouse (9044, 1:20,000, Sigma) and anti-rabbit (0545, 120,000, Sigma) and visualized with Clarity™ Western ECL Substrate. Uncropped scans of blots are available in the Source Data file.

Crystal violet assay. After virus infection, cells were seeded at 10–15% confluency into 12-well plates in parallel and cultured in hygromycin selection media. Media was changed every 3 days during selection. Crystal violet staining was applied on day0, day3, day5, day7 as well as day14. If cells were greater than 80% (as in the case of sample 1 of Supplementary Fig. 16) confluent on day7, they were split at a 1:20 ratio. For Crystal violet staining, each well was stained with 500 μl 0.1% crystal violet (Sigma) for 10 min at room temperature, then washed gently with 500 μl DPBS for three times before the photographs were taken with an iPhone.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Plasmids created in this study are listed in Supplementary Table 1 with links to webpages for plasmid sharing and GenBank sequence files. The source data underlying Fig. 5 and Supplementary Figs. S1b, S1d as well as raw plot numbers are provided as a Source Data file.

Received: 6 March 2018; Accepted: 7 October 2019; Published online: 31 October 2019

References

1. Shearer, R. F. & Saunders, D. N. Experimental design for stable genetic manipulation in mammalian cell lines: lentivirus and alternatives. Genes Cells 20, 1–10 (2015).
2. Abuin, A. & Bradley, A. Recycling selectable markers in mouse embryonic stem cells. Mol. Cell. Biol. 16, 1851–1856 (1996).
3. Shah, N. H. & Muir, T. W. Intein: nature’s gift to protein chemists. Chem. Sci. 5, 446–461 (2014).
4. Zettler, J., Schütz, V. & Mootz, H. D. The naturally split Npu DnaE intein exhibits an extraordinarily high rate in the protein trans-splicing reaction. FEMS Lett. 583, 909–914 (2009).
5. Iwai, H., Ziegler, S., Jin, J. & Tam, P.-H. Highly efficient protein trans-splicing by a naturally split DnaE intein from Nostoc punctiforme. FEMS Lett. 580, 1853–1858 (2006).
6. Sun, W., Yang, J. & Liu, X. Q. Synthetic two-piece and three-piece split inteins for protein trans-splicing. J. Biol. Chem. 279, 35281–35286 (2004).
7. Cheriyani, M., Pedamallu, C. S., Tori, K. & Perler, F. Faster protein splicing with the Nostoc punctiforme DnaE intein using non-native extein residues. J. Biol. Chem. 288, 6202–6211 (2013).
8. Chee, J. & Chin, C. Gateway cloning technology: advantages and drawbacks. Cloning Transgenes 4, 138 (2015).
9. Bindels, D. S. et al. mScarlet: a bright monomeric red fluorescent protein for cellular imaging. Nat. Methods 14, 53 (2017).
10. Wang, H., La Russa, M. & Qi, L. S. CRISPR/Cas9 in genome editing and beyond. Annu. Rev. Biochem. 85, 227–264 (2016).
11. Peng, R., Lin, G. & Li, J. Potential pitfalls of CRISPR/Cas9-mediated genome editing. FEBS J. 283, 1218–1231 (2016).
12. Oceguera-Yanez, F. et al. Engineering the AAVS1 locus for consistent and scalable transgene expression in human iPSCs and their differentiated derivatives. Methods 101, 43–55 (2016).
13. Streeter, J. J. et al. The human-induced pluripotent stem cell initiative—data resources for cellular genetics. Nucleic Acids Res. 45, D691–D697 (2016).
14. Carvajal-Vallejos, P., Pallissé, R., Mootz, H. D. & Schmidt, S. R. Unprecedented rates and efficiencies revealed for new natural split inteins from metagenomic sources. J. Biol. Chem. 287, 28686–28696 (2012).

Acknowledgements

Research reported in this publication was partially supported by internal funds provided by The Jackson Laboratory as well as grants from the National Human Genome Research Institute (1R01HG009900) and National Cancer Institute (P30CA034196). KOLF2-C1 cells were a gift from Bill Skarnes and were derived from the HipScI consortium. We gratefully acknowledge the contribution of the Flow Cytometry, Cell Engineering Services at The Jackson Laboratory for expert assistance with this publication. Special thanks to our Research Program Development group for assistance with the editing of the manuscript.

Author contributions

N.J., M.D., J.J.Z., and A.W.C. conceived and designed the study. N.J., M.D., J.J.Z., and A.W.C. performed the experiments. N.J., M.D., J.J.Z., and A.W.C. analyzed data and wrote the manuscripts.

Competing interests

A.W.C., N.J., and M.D. filed PCT patent application (WO/2019/075200) for the invention.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41467-019-12891-2.

Correspondence and requests for materials should be addressed to A.W.C.

Peer review information Nature Communications thanks the anonymous reviewers for their contribution to the peer review of this work. Peer reviewer reports are available.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2019