Identifying Personal Genomes by Surname Inference
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as neither C25 nor A26 is recognized specifically. Although 3’hExo can remove the last three nucleotides of the SL (9), further degradation is not possible because the 3’-end of the shortened SL can no longer reach the active site of 3’hExo in the ternary complex (Fig. 3B), thereby explaining how SLBP protects histone mRNAs from excessive trimming by 3’hExo.

Besides recognizing the SL RNA, another function of SLBP is the recruitment of U7 snRNP and stabilization of its interaction with the histone pre-mRNA for 3’-end processing (fig. S1) (23, 29). The 20 residues immediately C-terminal to the RBD of SLBP are required for this processing (29). These residues are present in the recombinant SLBP used in the current structural studies, but they are disordered. A second region required for processing is located in helix aB of the RBD, especially the Tyr-Asp-Arg-Tyr motif (Fig. 1B and fig. S6), where mutation of the Asp and Arg residues to Gin and Cys, respectively, did not affect binding but abolished processing (23). Our structure shows that these two regions are likely located close to each other (fig. S6) and therefore also identifies a surface feature of SLBP that is involved in histone pre-mRNA 3’-end processing (fig. S14).

References and Notes
22. See supplementary materials on Science Online.

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Supplementary Materials
www.sciencemag.org/cgi/content/full/339/6117/318/DC1
Materials and Methods
Figs. S1 to S4
Tables S1 to S4
References (30–40)

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Identifying Personal Genomes by Surname Inference
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Sharing sequencing data sets without identifiers has become a common practice in genomics. Here, we report that surnames can be recovered from personal genomes by profiling short tandem repeats on the Y chromosome (Y-STRs) and querying recreational genetic genealogy databases.

Surnames are paternally inherited in most human societies, resulting in their cosegregation with Y-chromosome haplotypes (1–5). Based on this observation, multiple genetic genealogy companies offer services to reunite distant patrilineal relatives by genotyping a few dozen highly polymorphic short tandem repeats across the Y chromosome (Y-STRs). The association between surnames and haplotypes can be confirmed by nonpaternity events, mutations, and adoption of the same surname by multiple founders (5). The genetic genealogy community addresses these barriers with massive databases that list the test results of Y-STR haplotypes along with their corresponding surnames. Currently, there are at least eight databases and numerous surname project Web sites that collectively contain hundreds of thousands of surname-haplotype records (table S1).

The ability of genetic genealogy databases to breach anonymity has been demonstrated in the past. In a number of public cases, male adoptees and descendants of anonymous sperm donors used recreational genetic genealogy services to genotype their Y-chromosome haplotypes and to search the companies’ databases (6–9). The genetic matches identified distant patrilineal relatives and pointed to the potential surnames of their biological fathers. By combining other pieces of demographic information, such as date and place of birth, they fully exposed the identity of their biological fathers. Lunshof et al. (10) were the first to speculate that this technique could expose the full identity of participants in sequencing projects. Gitschier (11) empirically approached this hypothesis by testing 30 Y-STR haplotypes of CEU participants in these databases and reported that potential surnames can be detected. [CEU participants are multigenerational families of northern and western European ancestry in Utah who had originally had their samples collected by CEPH (Centre d’Etude du Polymorphisme Humain) and were later reconsented to participate in the HapMap project.] However, these surnames could match thousands of individuals, and the study did not pursue full re-identification at a single-person resolution.

Our goal was to quantitatively approach the question of how readily surname inference might be possible in a more general population, apply this approach to personal genome data sets, and demonstrate end-to-end identification of individuals with only public information. We show that full identities of personal genomes can be exposed via surname inference from recreational genetic genealogy databases followed by Internet searches. In all cases in which individuals were studied who had donated DNA samples, the informed consent statements they had signed stated that participation in the HapMap project] was voluntary and that the data would never be used for research. We believe this approach could be extended to large numbers of individuals in the future.

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SMGF (www.smgf.org), the two largest public genetic genealogy databases with free-of-charge, built-in search engines. The interfaces of these engines are quite similar and allow users to insert a combination of Y-STR alleles and search for matching records on the basis of genetic similarity. The retrieved records contain surnames typically with information about the patrilineal line, such as geographical locations, potential spelling variants, and pedigrees. In total, these databases contain ~39,000 unique surname entries from ~135,000 records. The distribution of records per surname is significantly correlated ($R^2 = 0.78$, $P < 1.20 \times 10^{-6}$) with surname frequencies in the United States, suggesting an overall good representation of this population (Fig. 1A).

To test the probability of surname inference, we challenged the two databases with an orthogonal cohort of Y-STR haplotypes consisting of 34 markers (table S2) from 911 individuals, primarily with Caucasian ancestry, whose surnames are known (table S3). This cohort was compiled from YBase, a distinct genetic genealogy database, and contains individuals with 521 surnames that segregate in the U.S. population. In each haplotype query, our surname recovery algorithm began by retrieving the database record with the shortest time to most recent common ancestor (TMRCA) with the input haplotype (fig. S1 and table S4). Then, it calculated a confidence score that the surname match of the retrieved record is significantly better than other matches. If the score passed a user-defined threshold, the algorithm assigned the record’s surname to the input haplotype; otherwise, it categorized it as “unknown.” We tested the algorithm with a range of confidence thresholds to explore the trade-off between successful versus wrong recovery of surnames. Finally, we weighted the results using a stratified sampling approach to reflect the frequency of surnames in the U.S. population ($13$).

Our analysis projects a success rate of $\sim12\%$ (SD = 2%) in recovering surnames of U.S. Caucasian males (Fig. 1B and fig. S2). This rate can be accomplished with a conservative threshold that would return a wrong surname in 5% of cases and label 83% of cases as unknown. Higher success rates of up to 18% can be achieved at the price of increased probability to recover an incorrect surname. Because our input cohort is based on individuals who were tested with genetic genealogy services, our results are presumably mostly relevant to socio-economic groups with high participation in these services—namely, upper- and middle-class U.S. Caucasians.

Combining the recovered surname with additional demographic data can narrow down the identity of the sample originator to just a few individuals. The analysis above indicated that most recovered surnames are quite rare, with frequencies of less than 1:4000 in the U.S. population, corresponding to ~40,000 males (Fig. 1C and fig. S3) ($13$). We considered a scenario in which the genomic data are available with the target’s year of birth and state of residency, two identifiers that are not protected by the United States Health Insurance Portability and Accountability Act (HIPAA) ($14$). Searching individuals by year of birth, state, and surname combinations is supported by various online public record search engines, such as PeopleFinders.com or USApeople-search.com. On the basis of extensive simulations with the U.S. Census data, our results predict that year of birth and state alone are weak identifiers and searches based on their combination would match at least 60,000 U.S. males in 50% of cases (Fig. 1D). However, when surname information is added to the search, the median list size shrinks to only 12 males, which are few enough matches to investigate individually.

Next, we established the feasibility of Illumina sequencing to produce accurate Y-STR haplotypes. Using lobSTR, an algorithm for STR
Table 1. Comparison of CEU identification cases.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Pedigree 1</th>
<th>Pedigree 2</th>
<th>Pedigree 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genome for surname recovery</td>
<td>Paternal grandfather</td>
<td>Paternal grandfather</td>
<td>Paternal grandfather</td>
</tr>
<tr>
<td>Surname freq. in U.S.*</td>
<td>Rare</td>
<td>Rare</td>
<td>Common</td>
</tr>
<tr>
<td>Meioses between target and source</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Relationship between target and source</td>
<td>Nephew</td>
<td>First cousin once removed</td>
<td>Second cousin once removed</td>
</tr>
<tr>
<td>Supporting evidence</td>
<td>State of residency, pedigree structure, age, and maiden name are the same</td>
<td>State of residency, pedigree structure, age, and maiden name are the same</td>
<td>State of residency, pedigree structure are the same</td>
</tr>
<tr>
<td>$P$ (random match)$^\dagger$</td>
<td>$&lt;5 \times 10^{-9}$</td>
<td>$&lt;5 \times 10^{-6}$</td>
<td>$&lt;10^{-5}$</td>
</tr>
</tbody>
</table>

$^\dagger$The estimated probability of finding at least one family with the same characteristics after scanning all Utah households.

lobSTR produced Y-STR haplotypes with an average number of 53 out of the possible 79 genealogical markers (table S5). Comparing these haplotypes to capillary electrophoresis results revealed 99% accuracy. We further found that even at lower sequencing coverage of $10^\times$, informative haplotypes can be obtained by lobSTR (fig. S4).

To test the ability to retrieve genetic genealogy records with the Illumina haplotypes, we profiled STRs from the genome of a U.S. Caucasian male from our lab collection that was sequenced with Illumina 100-base pair (bp) reads to a coverage of $13^\times$. In parallel, we submitted this sample to the genealogy service of Sorenson Genomics and created a Ysearch record based on their results. A search with the Illumina haplotype returned his Ysearch entry as a top record (fig. S5).

The National Center for Biotechnology Information archives host a small number of genomes from identified individuals, providing good test cases for identification via surname inference. We used lobSTR to extract Y-STR haplotypes from the genomes of John West (16), Michael Snyder (17), and Craig Venter (18) (table S6). Searching Ysearch and SMGF with the Y-STR haplotypes of West and Snyder did not return their surnames and resulted in low matches to records with relatively ancient MRCAs 23 to 28 generations ago (13). A search with Craig Venter’s haplotype returned a clear match to a “Venter” record that was concordant at all 33 comparable markers and with an estimated TMRCA of less than eight generations ago (Fig. 2 and table S7). We further tested whether it would be feasible to trace back Craig Venter by combining the inferred surname with demographic profiling. A query for “Surname: Venter; Year of Birth: 1946; State: California” in online public record search engines retrieved two matching records of males, one of whom was Craig Venter himself.

Surname inference from personal genomes puts the privacy of current de-identified public data sets at risk (19). We focused on the male genomes in the collection of Utah Residents with Northern and Western European Ancestry (CEU). The informed consent of these individuals did not definitively guarantee their privacy and stated that future techniques might be able to identify them (20). To test the ability to trace back the identities of these samples from personal genomes, we processed with lobSTR 32 Illumina genomes of CEU male founders that reside in public repositories of the 1000 Genomes Project (21) and the European Nucleotide Archive that were sequenced with read lengths of at least 76 bp. Most of these genomes were sequenced to a shallow depth of less than $5^\times$ and produced sparse Y-STR haplotypes. We selected the 10 genomes that had the most complete Y-STR haplotypes with a range of 34 to 68 markers to attempt surname recovery. Searching the genetic genealogy databases returned top-matching records with Mormon ancestry in 8 of the 10 individuals for whom the top hit had at least 12 comparable markers. Moreover, for four individuals, the top match consisted of multiple records with the same surname, increasing the confidence that the correct surname was retrieved. This potentially high surname recovery rate stems from a combination of the deep interest in genetic genealogy among this population and the large family sizes, which exponentially increases the number of targeted individuals for every person who is tested.

In five surname recovery cases, we fully identified the CEU individuals and their entire families with very high probabilities (Table 1). These five cases belonged to three pedigrees, in two of which the surnames of both the paternal and maternal grandfathers were recovered. Our strategy for tracing back individual pedigrees relied on the recovered surnames as well as publicly available Internet resources such as record search engines, obituaries, and genealogical Web sites, and demographic metadata available in the Coriell Cell Repository Web site. The year of birth was inferred by subtracting the ages in Coriell from the year of collecting samples. Each complete pedigree re-identification took 3 to 7 hours by a single person. The identified families matched exactly to the corresponding pedigree descriptions in the Coriell database: The number of children, the birth order of daughters and sons, and the state of residence were identical. All grandparents were alive in 1984, the year that the CEU cell line collection was established (22). In the two cases of a dual surname recovery from both grandfathers, the surname of the father

Fig. 3. Illustrations of the three CEU pedigrees (black) showing how genetic information from distant patrilineal relatives (arrow; red, patrilineal lines) can identify individuals. Filled squares represent sequenced individuals. To respect the privacy of these families, only abbreviated versions are presented. The sex of the CEU grandchildren was randomized. The numbers of grandchildren are not given.

 profiling from raw sequencing reads (15), we processed 10 high-coverage male genomes from the Human Genome Diversity Panel (HGDP).
and the maiden name of the mother matched exactly to the grandfathers’ surnames, substantially increasing the confidence of the recovery. Coriell also lists the ages (23) during sample collection for these two pedigrees, which agreed with the age differences of all tested cases with the identified family members. Using genealogical Web sites, we traced the patrilineal lineage that connects each identified genome through the MRCA. These records were linked until we reached the database (Fig. 3). This analysis revealed that two pedigrees, which agreed with the public to stop donating samples or for data sharing to stop. These would be devastating re-actions that could substantially hamper scientific progress. Rather, we believe that establishing clear policies for data sharing, educating participants about the benefits and risks of genetic studies (31), and the proposition of proper usage of genetic information (32) are pivotal ingredients to support the genomic endeavor.

References and Notes
13. See supplementary materials on Science Online.
19. Full details of this analysis were provided to the reviewers. However, they are not presented here to respect the privacy of these families. Further inquiries can be made to the corresponding author.
23. Based on the results of this study, the NIH removed the ages from Coriell to a secure location (12).

Supplementary Materials
www.sciencemag.org/cgi/content/full/339/6117/321/DC1
Supplementary Text
Fig. S1 to S6
Tables S1 to S7
References
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GDE2 Promotes Neurogenesis by Glycosylphosphatidylinositol-Anchor Cleavage of RECK

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The six-transmembrane protein glycoprophodiester phosphodiesterase 2 (GDE2) induces spinal motor neuron differentiation by inhibiting Notch signaling in adjacent motor neuron progenitors. GDE2 function requires activity of its extracellular domain that shares homology with glycoprophodiester phosphodiesterases (GDPDs). GDPDs metabolize glycoprophodiesters into glycerol-3-phosphate and corresponding alcohols, but whether GDE2 inhibits Notch signaling by this mechanism is unclear. Here, we show that GDE2, unlike classical GDPDs,cleaves glycosylphosphatidylinositol (GPI) anchors. GDE2 GDPD activity inactivates the Notch activator RECK (reversion-inducing cysteine-rich protein with Kazal motifs) by releasing it from the membrane through GPI-anchor cleavage. RECK release disinhibits ADAM (a disintegrin and metallopeptinase) protease-dependent shedding of the Notch ligand Delta-like 1 (D11), leading to Notch inactivation. This study identifies a previously unrecognized mechanism to initiate neurogenesis that involves GDE2-mediated surface cleavage of GPI-anchor targets to inhibit D11-Notch signaling.