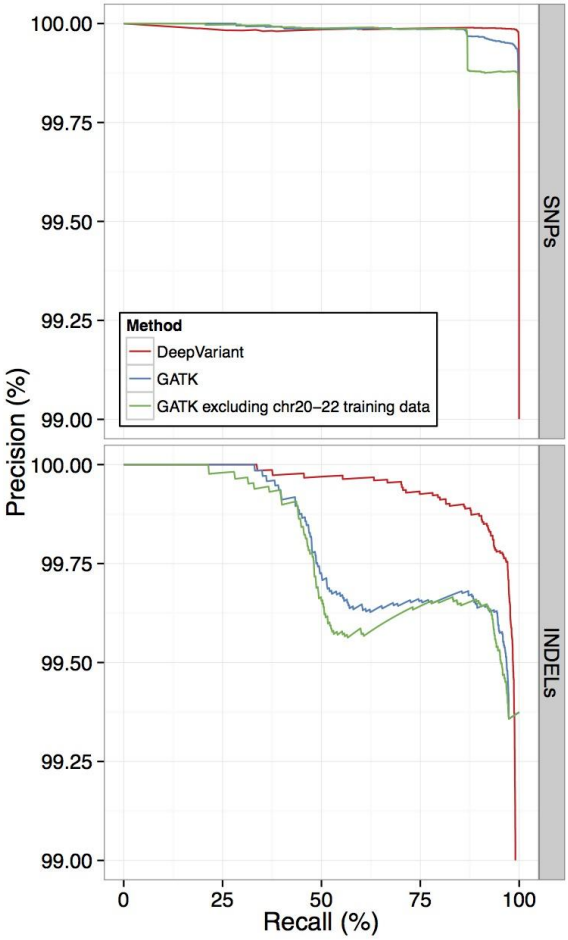
Supplementary Information

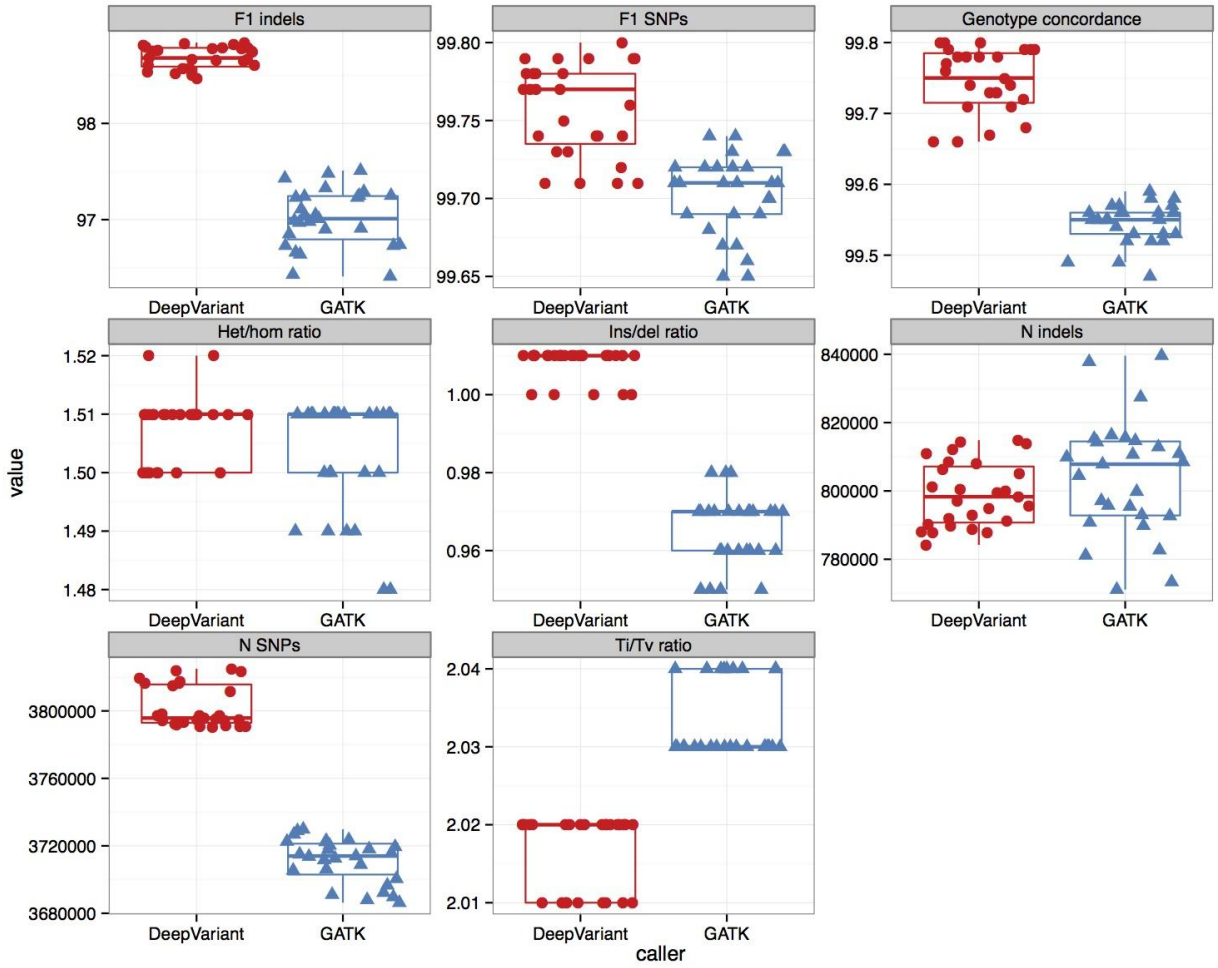
Supplementary Figures

Supplementary Figure 1: DeepVariant accuracy, consistency, and calibration relative to the GATK.

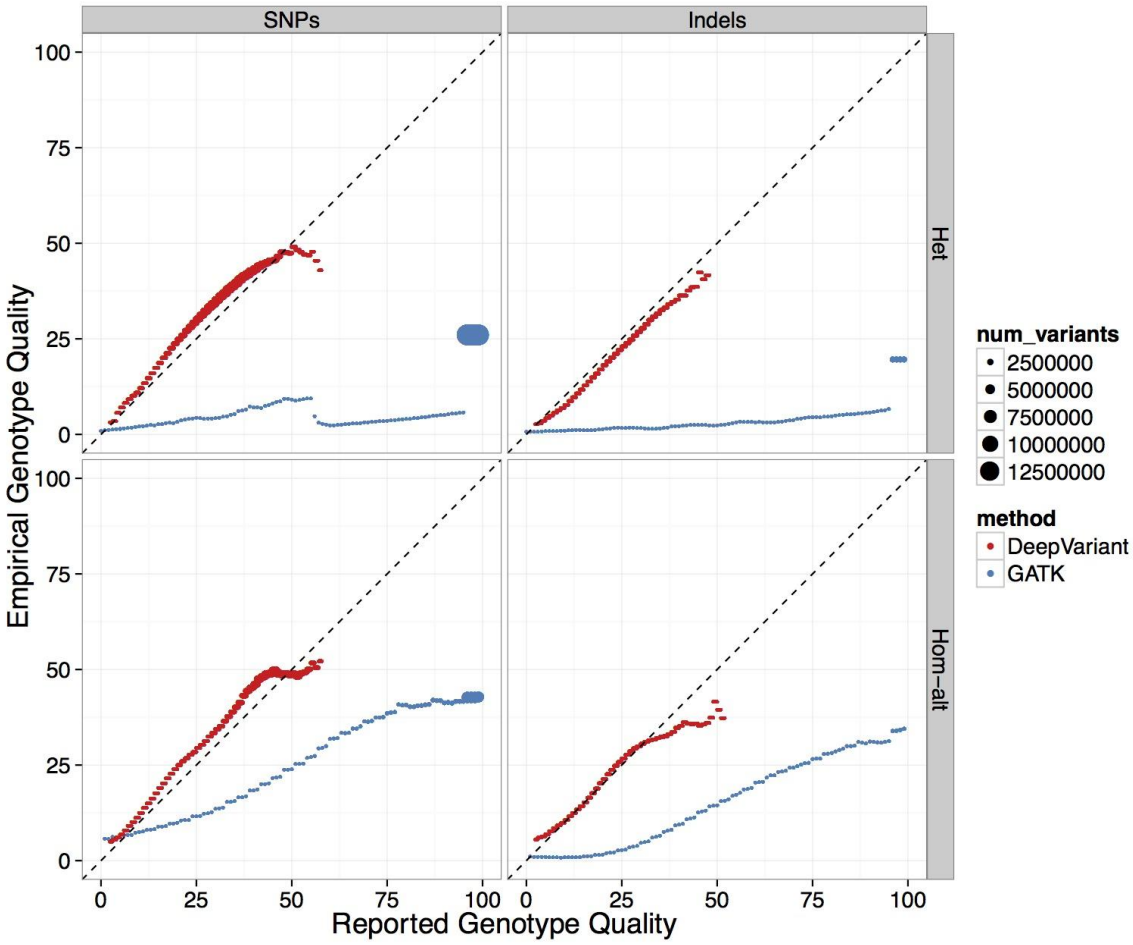
Panel A



Panel B


F1 indels
F1 SNPs
Genotype concordance
Het/hom ratio
Ins/del ratio
N indels
N SNPs
Ti/Tv ratio
value
caller
DeepVariant
GATK

Panel C

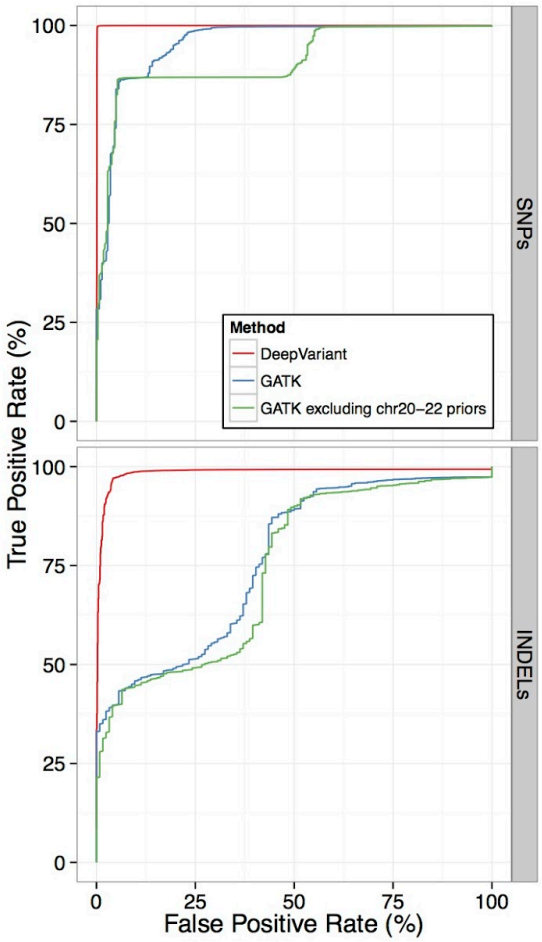


(A) Precision-recall plot for DeepVariant (red) and GATK (green, blue) calls for the Genome in the Bottle benchmark sample NA12878 using 2x101 Illumina HiSeq data from the Platinum Genomes project. The GATK was run in two ways. In the first, GATK best-practices were followed and the variant filtering step (VQSR) was provided data for known variants on both the training and test chromosomes, allowing VQSR to use population variation information to better call variants on the test chromosomes. In the second, we removed all population variation information for the test chromosomes chr20-22, relying on the VQSR model learned only on the training chromosomes, which is more representative of the GATK's calling performance on novel variation. (B) DeepVariant (red circles) and the GATK (blue triangles) were run on 27 independently sequenced replicates of NA12878 (PCR-free WGS 2x151 on an Illumina X10 with coverage from 24x-35x). Each panel shows the distribution of values for the given metric (panel label) for DeepVariant and the GATK. DeepVariant produces more accurate SNP and indel calls (F1) when compared to the Genome in a Bottle standard for NA12878 with a higher fraction of sites having the correct genotype assigned (Genotype concordance). DeepVariant finds a similar numbers of indels to the GATK, but has a more consistent ratio of insertions to deletions. DeepVariant finds more SNPs than GATK with a similar ratio of heterozygous variants to homozygous alternative variants (Het/hom ratio). (C) Comparison of likelihoods assigned to heterozygous and homozygous alternate genotypes emitted by DeepVariant and

the GATK shows the likelihood model learned by DeepVariant is substantially better calibrated than that employed by the GATK. On the x-axis is the reported genotype quality (GQ) for calls for DeepVariant (red) and GATK (blue) compared to the observed error rate in each of these GQ bands (y-axis), for true heterozygous and homozygous variants (vertical facet) and SNPs and indels (horizontal facet) separately. The size of each calibration point reflects the number of variant calls used to estimate the empirical accuracy. The calibration curves were calculated using genotype likelihoods from the held-out evaluation data in eight sequenced replicates of NA12878. For example, the set of all Q30 heterozygous calls should be in aggregate accurate at a rate of 999 in 1000. Genotypes should be correct at a rate declared by their confidence; perfect calibration would follow the marked x=y line.

In Supplementary Figures 1A and 2, DeepVariant and GATK calling performance is shown for the Genome in the Bottle benchmark sample NA12878 using 2x101 Illumina HiSeq data from the Platinum Genomes project. The GATK was run in two ways. In the first, GATK best-practices were followed and the variant filtering step (VQSR) was provided data for known variants on both the training and test chromosomes, allowing VQSR to use population variation information to better call variants on the test chromosomes. In the second, we removed all population variation information for the test chromosomes chr20-22, relying on the VQSR model learned only on the training chromosomes, which is more representative of the GATK's calling performance on novel variation. Variants were sorted by QUAL score for DeepVariant and VQSLOD for GATK. Variants that are filtered out in the VCF files are included in the ranking to give a more complete picture of the effectiveness of these ranking methods. This means that the curve includes all candidate variants seen by DeepVariant except those with a homozygous-reference genotype according to the CNN and everything emitted by GATK, including those filtered with LOW_VQSLOD (which, by definition, have a low VQSLOD score).

Supplementary Figure 2: Receiver operating characteristic (ROC) curve for DeepVariant (red) and GATK (green, blue) calls for the Genome in the Bottle benchmark sample NA12878.



Supplementary Figures 1A and 2 are similar but emphasize different things. The precision-recall plot in Supplementary Figure 1A gives a better sense of how the end-to-end assay (variant calling) is performing, while the ROC curve in Supplementary Figure 2 emphasizes the effectiveness of the ranking of true positives relative to false positives, independent of the number of true and false positive variants in each SNP and indel class. In NGS variant calling, a traditional ROC curve can be misleading and is shown here only for completeness. The first of two issues is that the set of false positives is defined as variant calls made into confidently homozygous reference regions by a specific calling method, and so usually differs between calling methods. The second issue is that there is no clear definition of specificity since every allele at every position is a potential true negative. As a consequence, ROC curves across methods are not directly comparable, and so cannot be used to assess the quality of a callset produced by one method relative to another. Precision-recall plot, on the other hand, can be safely compared across methods despite differences in their total number of false positives.

Supplementary Tables

Supplementary Table 1: DeepVariant calling across genome builds

Variants	Training data	Evaluation data	PPV	Sensitivity	F1
SNPs + indels	b37 chr1-19	b38 chr20-22	99.93%	98.98%	99.45%
	b38 chr1-19	b38 chr20-22	99.87%	99.21%	99.53%
SNPs	b37 chr1-19	b38 chr20-22	99.98%	99.23%	99.60%
	b38 chr1-19	b38 chr20-22	99.93%	99.35%	99.64%
Indels	b37 chr1-19	b38 chr20-22	99.60%	97.35%	98.46%
	b38 chr1-19	b38 chr20-22	99.42%	98.22%	98.81%

Supplementary Table 2: Calling performance of DeepVariant on human and mouse datasets

Variants	Training data	Evaluation data	PPV	Sensitivity	F1
SNPs + indels	Human chr1-19	Mouse chr18-19	99.53%	97.07%	98.29%
	Mouse chr1-17	Mouse chr18-19	99.90%	95.85%	97.84%
SNPs	Human chr1-19	Mouse chr18-19	99.98%	97.86%	98.91%
	Mouse chr1-17	Mouse chr18-19	99.99%	99.10%	99.54%
Indels	Human chr1-19	Mouse chr18-19	96.41%	91.75%	94.02%
	Mouse chr1-17	Mouse chr18-19	99.15%	73.80%	84.62%

Supplementary Table 3: Training DeepVariant to call variants on a variety of sequencing technologies and experimental protocols.

	Sensitivity		PPV		F1	
Dataset	Candidate variants	Called variants	Candidate variants	Called variants	Candidate variants	Called variants

10X Chromium 75x WGS	99.66%	98.73%	89.55%	99.91%	94.34%	99.32%
10X GemCode 34x WGS	97.03%	94.34%	75.19%	99.47%	84.73%	96.84%
Illumina HiSeq 31x WGS	99.88%	99.76%	95.14%	99.98%	97.45%	99.87%
Illumina HiSeq 60x WGS	99.95%	99.88%	90.90%	99.98%	95.21%	99.93%
Ion AmpliSeq exome	91.94%	89.28%	8.05%	99.70%	14.81%	94.21%
PacBio 40x WGS	93.36%	88.51%	22.14%	97.25%	35.79%	92.67%
SOLID SE 85x WGS	82.50%	76.62%	14.27%	99.01%	24.33%	86.39%
Illumina TruSeq exome	94.04%	92.58%	65.31%	99.31%	77.08%	95.83%
Mean	94.79%	92.46%	57.57%	99.33%	65.47%	95.63%
Median	94.79%	92.58%	65.31%	99.47%	77.08%	95.83%

Datasets are labeled to indicate instrument, protocol, target area (WGS for whole genome, gene regions as exome), with sequencing depth shown for whole genome targets. For each dataset, a set of candidate variants were identified across the genome in the NGS reads (methods). The baseline Illumina model was retrained using the candidate variants with labeled genotypes on chromosomes 1-19. This retrained model was then used to assign genotype likelihoods to the candidate variants, keeping those confidently non-reference on the held-out chromosomes 20-22. The sensitivity, positive predictive value (PPV), and overall accuracy (F1) are shown for the candidate and called variants on chr20-22 only.

Supplementary Table 4: Comparison datasets for Genome in a Bottle analysis

Dataset	Comparator callset	Comparator notes
TruSeq exome	ftp://ftp-trace.ncbi.nlm.nih.gov/giab/ftp/data/NA12878/Nebraska_NA12878_HG001_TruSeq_Exome/NIST-hg001-7001-ensemble.vcf and GATK	An ensemble callset that includes calls from the GATK HaplotypeCaller, UnifiedGenotyper, and FreeBayes over the TruSeq exome targeted regions (BED).

10X GemCode 34x WGS	None	No callset submitted to Genome in a Bottle. Focusing on Chromium callset from 10x instead.
10X Chromium 75x WGS	ftp://ftp-trace.ncbi.nlm.nih.gov/giab/ftp/data/NA12878/10Xgenomics_ChromiumGenome_LongRanger2.1_09302016/NA12878_hg19/NA12878_hg19_phased_variants.vcf.gz and GATK	
PacBio raw reads 40x WGS	Samtools; we could not get GATK to run on this dataset.	Only structural variant calls were submitted for the Pacific BioSciences WGS data.
Ion AmpliSeq exome	ftp://ftp-trace.ncbi.nlm.nih.gov/giab/ftp/data/AshkenazimTrio/analysis/IonTorrent_TVC_03162015/AmpliseqExome.20141120.NA24385.vcf and GATK	variant calls from the Torrent Variant Caller (VCF) made on the Ion effective intervals (BED). The TVC caller used all four lanes of Ion torrent exome data, but DeepVariant made its call only one a single lane of data.
HiSeq 60x WGS	None	Not analyzed as DeepVariant performance already well-established on Illumina data
HiSeq 31x WGS	None	Not analyzed as DeepVariant performance already well-established on Illumina data
SOLID 85x WGS	GATK	No calls submitted to Genome in a Bottle for NA24385. There appear to be no maintained variant callers for SOLID data.

Supplementary Table 5: Comparison of technology specific callsets and DeepVariant for SNPs + indels combined

Data	Caller	Sensitivity	PPV	F1
Ion AmpliSeq exome	DeepVariant	94.12%	99.79%	96.87%
	TVC	96.47%	98.11%	97.28%
	GATK	93.24%	19.15%	31.78%
Illumina TruSeq exome	DeepVariant	93.01%	99.39%	96.09%
	Ensemble	92.92%	98.08%	95.43%
	GATK	91.02%	99.30%	94.98%
10X Chromium 75x WGS	DeepVariant	98.73%	99.91%	99.32%
	Long-ranger	98.13%	98.26%	98.19%

	GATK	99.08%	94.62%	96.80%
PacBio raw reads 40x WGS	DeepVariant	88.51%	97.25%	92.67%
	samtools	89.34%	40.89%	56.10%
SOLID 85x	DeepVariant	76.62%	99.01%	86.39%
	GATK	73.91%	84.26%	78.75%

Supplementary Table 6: Mouse dataset sources

Sample	Data	Location
129S1_SvImJ	BAM	ftp://ftp-mouse.sanger.ac.uk/REL-1502-BAM/129S1_SvImJ.bam
	VCF	A combed VCF of ftp://ftp-mouse.sanger.ac.uk/REL-1505-SNPs_Indels/mgp.v5.merged.indels.dbSNP142.normed.vcf.gz and ftp://ftp-mouse.sanger.ac.uk/REL-1505-SNPs_Indels/mgp.v5.merged.snps_all.dbSNP142.vcf.gz
	REF	GRCm38 from ftp://ftp-mouse.sanger.ac.uk/ref/GRCm38_68.fa

Supplementary Table 7: Training and evaluation chromosomes

	Training chromosomes	Evaluation chromosomes
Human NA12878	chr1-19	chr20-22
Mouse 129S1_SvImJ	chr1-17	chr18-19

Supplementary Table 8: Multiple sequence technologies datasets

Dataset	Sample	BAM FTP location	Notes
TruSeq exome	NA12878	Nebraska_NA12878_HG001_TruSeq_Exome/NIST-hg001-7001-ready.bam	Exome
10X GemCode 34x WGS	NA12878	10XGenomics/NA12878_phased_possorted_bam.bam	Fixed BAM header
10X Chromium 75x WGS	NA12878	10Xgenomics_ChromiumGenome/NA12878_GRCh37.bam	Fixed BAM header
PacBio raw reads 40x WGS	NA12878	NA12878_PacBio_MtSinai/sorted_final_merged.bam	Fixed BAM header
Ion AmpliSeq exome	NA24385	ion_exome/HG002_NA24385_SRR1767409_IonXpress_020_rawlib_24038.bam	Exome; Fixed BAM header; Trimmed

			unneeded BAM tags
HiSeq 60x WGS	NA24385	NIST_HiSeq_HG002_Homogeneity-10953946/NHGRI_Illumina300X_AJtrio_novoalign_bams/HG002.hs37d5.60x.1.bam	
HiSeq 31x WGS	NA24385	NIST_Illumina_2x250bps/novoalign_bams/HG002.hs37d5.2x250.bam	
SOLID 85x WGS	NA24385	NIST_SOLiD5500W/alignment/5500W_HG002_merged.b37.bam	Trimmed unneeded BAM tags

FTP paths are given relative to:

- For NA12878: ftp://ftp-trace.ncbi.nlm.nih.gov/giab/ftp/data/NA12878/
- For NA24385: ftp://ftp-trace.ncbi.nlm.nih.gov/giab/ftp/data/AshkenazimTrio/HG002_NA24385_son/

Supplementary Notes

Supplementary Note 1: DeepVariant vs. GATK on NA12878 replicates

Libraries were prepared from 35 independent replicates of 1ug aliquots of purified genomic DNA isolated from GM12878. During the library preparation process, samples were acoustically sheared to target fragment lengths of 400bp before proceeding through SPRI-based size selection, end repair, a-tailing, adapter ligation, and a final SPRI-based cleanup. The resultant libraries were quantified by Picogreen, Fragment Analyzer, and qPCR. Sequencing was performed using a 2x150 paired-end runs on Illumina HiSeq X sequencers with a targeted sequencing depth of 30x per sample.

Chromosomes 1-18 of the first eight sequenced replicates were used to train a single DeepVariant model by concatenating the labeled pileup images from each replicate into a single training set for DistBelief as previously described. Due to the timing of this experiment, version 2.19 of the Genome in a Bottle reference intervals and variant calls were used to label the genotypes in the training images and to evaluate the quality of the resulting variant calls on held out chromosomes 20-22. The previously described Verily GATK pipeline was used to process each NA12878 sample independently.

Supplementary Note 2: Training and generalization of DeepVariant models across genome builds

DeepVariant was trained on data from human genome builds b37 and applied to b38. 80 hours of training was performed using data from chromosomes chr1-19 of the human NA12878 sample and evaluated on the held out human chromosomes chr20-22 (Supplementary Table 1). The model trained with read data aligned to b37 of the human reference and applied to b38 data had similar performance (overall F1 = 99.45) to one trained on b38 and then applied to b38 (overall F1 = 99.53) thereby demonstrating the generalizability of the model (Supplementary Table 1).

Supplementary Note 3: Training and generalization of DeepVariant models across species

In order to evaluate the transferability of a DeepVariant model across species we devised the following experiment. We trained a model using the Platinum Genomes NA12878 read set (aligned to b38) and Genome in a Bottle ground truth labels as described previously. We then applied that model to call variants in the synthetic mouse strain 129S1_SvImJ from the Mouse Genome Project (MGP)[1]. For the sake of comparison we also trained models from the mouse read set using as ground truth the genotypes as provided by MGP.

We downloaded the read files (BAM) and variant calls (VCF) for the synthetic mouse strain 129S1_SvImJ from the MGP website (Supplementary Table 6).

The v5 of the mouse callset was created, according to this README, with the following procedure:

> *Reads were aligned to the reference genome (GRCm138) using BWA-MEM v0.7.5-r406 (Li and Durbin, 2009; Li, 2013). Reads were realigned around indels using GATK realignment tool v3.0.0 (McKenna et al., 2010) with default parameters. SNP and indel discovery was performed with the SAMtools v1.1 with parameters:*
>
> *Samtools mpileup -t DP,DV,DP4,SP,DPR,INFO/DPR -E -Q 0 -pm3 -F0.25 –d500*
>
> *and calling was performed with BCFtools call v1.1 with parameters:*
>
> *Bcftools call -mv -f GQ,GP -p 0.99*
>
> *Indels were then left-aligned and normalized using bcftools norm v1.1 with parameters:*
>
> *bcftools norm -D -s -m+indels*
>
> *The vcf-annotate function in the VCFtools package was used to soft-filter the SNP and indel calls. SNP calling was performed for each strain independently. A single list of all polymorphic sites across the genome was then produced from all of the 36 strains' SNP calls. This list was then used to call SNPs again, this time across all 36 strains simultaneously, using the 'samtools mpileup -l' option. The calls from all 36 strains were then merged into a single VCF file. All strain specific information was retained in the sample columns for each strain. For indels, the same approach was taken with the*

addition of the indel normalisation step after the initial variant calling. Information regarding the filtering of SNP and indel calls can be found in the VCF file headers in the '##FILTER' and '##source' lines.

DeepVariant was run using the computational pipeline described above with all default settings. SNP and Indel mutations that were identified in the MGP ground truth set with genotype as 0/0 for this specific mouse were given the hom-ref label and likewise for heterozygous and homozygous variants. No-called sites were ignored during model training.

In order to protect against model overfitting, we divided our human and mouse genomes into a training set of chromosomes and an independent, held-out set of chromosomes (Supplementary Table 7):

80 hours of training was performed using images prepared from the training chromosomes. After training the model was frozen and applied to call the variants from the read set. The resulting callsets were evaluated on variants on the held out chromosomes only (Supplementary Table 2). As the Mouse project did not provide confident regions like the Genome in a Bottle project for NA12878, only non-reference variant calls that occur at a site present in the MGP with a genotype of homozygous reference are counted as false positives.

Supplementary Note 4: DeepVariant training on multiple sequencing technologies

BAM files were downloaded from the Genome in a Bottle project FTP server (Supplementary Table 8). After downloading the BAM files are fixed up as indicated and converted to GA4GH protocol buffer format for processing with DeepVariant. The conversion preserves all of the essential read information in the BAM.

Once converted to GA4GH format, candidate variants are identified using the read bases, qualities, QC flags, and mapping information in the original BAM file. The optional local assembly step was skipped for all datasets, as the assembler is tuned for Illumina data. The two exome datasets were trained and evaluated using confident intervals derived from the intersection of the Genome in a Bottle confident intervals and the RefSeq[2] exon intervals.

For training of each dataset, candidate variants were identified using default parameters* as well as emitting reference "variants" at ~0.1% of randomly selected reference bases. Pileup images were created for each candidate variant and labels assigned using Genome in a Bottle truth variants and intervals for the dataset's sample (see methods for details). These labeled images were filtered to only variants occurring on chromosomes 1-19, leaving 20-22 as an independent evaluation set. Training of the deep learning model was carried out for 250,000 steps starting from a model trained against chr1-19 variants from eight NA12878 replicates (see section DeepVariant vs. GATK on NA12878 replicates for details). After training completed the model was frozen and used to evaluate genotype likelihoods as the "technology-trained model".

For evaluation, candidate variants were identified using default parameters* and pileup images were created for each candidate variant on chromosomes 20-22 only. The technology-trained

model for the dataset was applied to these images to compute genotype likelihoods and the likelihoods were combined with the candidate variants to create final variant calls (see methods for details). The candidate variants and the final callset were evaluated again using only chr20-22.

*The RAW PacBio read set was called with a slightly different parameter for the minimum fraction required for an alternate indel allele; we require a fraction of 0.18 rather than the default of 0.12 for all other datasets. At 0.12 over ~150M candidates are found, while at 0.18 we only have ~25M variants to consider. Using 0.18 significantly reduces indel sensitivity, from ~60% with 0.12 to around ~40% with 0.18, but is required to make the creation of pileup images tractable in the current implementation. The SNP threshold remains at 0.12 and produces a highly sensitive set at >99%.

Supplementary Note 5: Comparison of DeepVariant exome calls with technology-specific variant calls submitted to Genome in a Bottle

We sought to compare the quality of DeepVariant calls to baseline callsets for each technology. As we already established the relative performance of DeepVariant and GATK on Illumina WGS data, we focused primarily on non-Illumina WGS and exome datasets. The challenge is that each technology uses a different data processing pipeline needing dataset-specific settings that are often not documented to produce optimal results. Therefore, we first sought SNP and indel variant calls submitted to Genome in a Bottle by the read data depositors as these are likely already optimized for calling performance on that technology. If not available, we applied the Verily GATK pipeline or, when that proved impossible, samtools, as an alternative variant calling option. The dataset and comparison callsets are given in Supplementary Table 4.

It's important to recognize that these are apples-to-oranges comparisons. There is no way to ensure information on our evaluation chromosomes were not used to tune the submitters calling pipelines. Given that many tools, like the GATK, make direct use of population variation information to aid in filtering variants, we should expect these callsets to be biased towards higher quality calls. Additionally, in some cases the submitters have used more information than DeepVariant to make calls, such as Ion AmpliSeq exome calls which used four lanes of data rather than our single lane. Finally, the callsets can differ in what regions of the genome were called, an acute issue for the exome datasets. To mitigate differences in exome intervals, we further intersected our RefSeq intervals down to those overlapping the calling intervals provides for the two exome datasets. Nevertheless, we feel that these issues are outweighed by the value of natural comparison points to assess the effectiveness of DeepVariant on these technologies.

Samtools calling on PacBio raw reads 40x WGS

```
#!/bin/bash

# Only calling on chromosomes 20, 21, and 22.
CHROMS=('20:1-20,000,000' '20:20,000,000-40,000,000' '20:40,000,000-63025520'
'21:1-20,000,000' '21:20,000,000-40,000,000' '21:40,000,000-48129895'
'22:1-20,000,000' '22:20,000,000-40,000,000' '22:40,000,000-51304566')

# Run calling on each interval separately.
parallel -j ${#CHROMS[@]} "samtools view -u NA12878_PacBio-RAW.bam {} \
```

```
  | samtools mpileup -ugf GRCh37.genome.fa - \
  | bcftools call -vmO z -o NA12878_PacBio-RAW.samtools.calls.{}.vcf.gz" ::: 
${CHROMS[*]}

# Conconcate parallel calling VCFs.
bcftools concat -a -O z --rm-dups all \
 NA12878_PacBio-RAW.samtools.calls.??\:*.vcf.gz \
 -oNA12878_PacBio-RAW.samtools.calls.vcf.gz
tabix NA12878_PacBio-RAW.samtools.calls.vcf.gz

# Filter recommendations taken from bcftools website with depth of 40x.
bcftools filter -O z -o NA12878_PacBio-RAW.samtools.calls.filtered.vcf.gz \
  -s FAIL -i'DP < 67 && QUAL > 10 & DP >= 3' --SnpGap 3 \
  NA12878_PacBio-RAW.samtools.calls.vcf.gz
tabix NA12878_PacBio-RAW.samtools.calls.filtered.vcf.gz
```

Supplementary Table 5 shows the PPV, sensitivity, and F1 metric of the DeepVariant and comparator callsets on the previously-indicated regions on the held-out chromosomes 20-22. For exomes the evaluation interval is the intersection of the targeted regions with the RefSeq intervals on chromosomes 20-22.

As noted in the "evaluation of variants" section, the difference between evaluation methods may be exaggerated in this multiple sequencing technologies experiment. We intentionally chose to use the already aligned BAM files as provided by Genome in a Bottle in order to highlight the robustness of DeepVariant to variation in input alignments without applying local assembly, which may perform better on Illumina read than other NGS read types. One consequence of this choice, though, is that DeepVariant will only call alleles present in the CIGAR elements of the BAMs, which vary in their accuracy depending on the sophistication of the aligner and post-alignment cleanup steps performed during processing by each technology's data depositor. The DeepVariant CNN is sufficiently robust to train accurate genotyping models even with errorful allele determination, as evident by the high PPV values, but inevitably produces variant calls with incorrect alleles at any site where the reads have been aligned with an incorrect allele in their CIGAR elements. As noted in the main text, better pre-processing via tools like the GATK's IndelRealigner[3] or technology-agnostic local assembly will improve the alleles emitted by DeepVariant. Additionally, it is possible that our comparator callsets may use variant representations that are differentially penalized by our evaluation tool. Because of these concerns, we ran both our internal evaluation tool and vcfeval (version 3.6.2) and note that the results are quite concordant between both methods. The full output is available as a Supplementary Data: Evaluation Metrics.

Supplementary Note 6: General guidance on selection of training data for DeepVariant

For most of the experiments presented here DeepVariant was trained on 8 whole genome replicates of NA12878 sequenced under a variety of conditions related to library preparation. These conditions include loading concentration, library size selection, and laboratory technician. We believe this diversity in training data is one reason that DeepVariant is able to generalize to a variety of new datasets. In general in order to be robust to a particular class of errors training data sequenced from that class should be included in the set of training data. We also believe

that by training with even more sequencing data will improve the performance of DeepVariant even further but there is a tradeoff with the number of training iterations required as the number of training examples increases.

Supplementary Note 7: Details on the computation for Table 2 and Supplementary Table 3

The supplementary material contains a shell script with all of the commands used to calculate the results in Table 2. The results in Supplementary Table 3 can be reproduced using a similar approach but using the CHM-Eval evaluation tools instead of hap.py.

Supplementary Note 8: Code Snippet 1

An allele is considered a candidate if it satisfies:

```
def is_candidate(counts, allele):

  allele_count = counts[allele]

  total_counts = sum(counts.values())

  return not is_reference_base(allele)

       and allele_count >= min_count

       and allele_count / total_count >= min_fraction
```

Supplementary Note 9: Code Snippet 2

```
WIDTH = 221

HEIGHT = 100;


def create_pileup_images(candidate_variants):

  for candidate in candidate_variants:

    for biallelic_variant in split_into_biallelics(candidate):

      start = biallelic_variant.start - (WIDTH-1) / 2

      end = WIDTH - span_start

      ref_bases = reference.get_bases(start, end)

      image = Image(WIDTH, HEIGHT)

      row_i = fill_reference_pixels(ref, image)

      for read in reads.get_overlapping(start, end):
```

```
        if row_i < HEIGHT and is_usable_read(read):
          add_read(image, read, row_i)
          row_i += 1
      yield image


def fill_reference_pixels(ref, image):
  for row in range(5):
    for col in range(WIDTH):
      alpha = 0.4
      ref_base = ref[col]
      red = get_base_color(ref_base)
      green = get_quality_color(60)   # The reference is high quality
      blue = get_strand_color(True)   # The reference is on the positive strand
      image[row, col] = make_pixel(red, green, blue, alpha)
  return 5


def add_read(image, read, row_i):
  # Don't incorporate reads with a low quality base at the call position. This
  # function still returns true because the image isn't yet full.
  # base_quality_at_call_position() returns the quality of the base aligned to
  # our call.start, or 255 if no bases are aligned there.
  if base_quality_at_call_position(read) < MINIMUM_BASE_QUALITY:
    return

  for ref_pos, read_pos, cigar_elt in per_base_alignment(ref, read):
    read_base = None
    if cigar_elt in {'D', 'I'}:
      col = ref_pos - 1
      read_base = INDEL_ANCHORING_BASE
    elif cigar_elt == 'M':
      col = ref_pos
```

```
      read_base = read.bases[read_pos]

    if read_base:
      quality = min(read.quals[read_pos], read.mapping_quality)
      alpha = get_base_alpha(read_base, ref[col], read, call)
      red = get_base_color(read_base)
      green = get_quality_color(quality)
      blue = get_strand_color(read.is_on_positive_strand)
      image[row_i, col] = make_pixel(red, green, blue, alpha)

def make_pixel(red, green, blue, alpha):
  return RGB(int(alpha * red), int(alpha * green), int(alpha * blue))

def get_base_alpha(read_base, ref_base, read, call):
  # read_supports_alt_allele() returns True if the read supports the alt_allele.
  # This is implemented by associating each alternative allele in our candidate
  # variants with a list of the names of the reads that contained that allele.
  alpha1 = 1.0 if read_supports_alt_allele(read, call.alt_allele) else 0.6
  alpha2 = 0.2 if read_base == ref_base else 1.0
  return alpha1 * alpha2

def get_base_color(base):
  base_to_color = {'A': 250, 'G': 180, 'T': 100, 'C': 30}
  return base_to_color.get(base, 0)

def get_quality_color(quality):
  return int(254.0 * (min(40, quality) / 40.0))

def get_strand_color(on_positive_strand):
  return 70 if on_positive_strand else 240
```

```
def is_usable_read(read):
  return (read.has_alignment and
          not (read.is_duplicate or read.failed_vendor_quality_checks or
               read.is_secondary or read.is_supplementary) and
          (not read.is_paired or read.is_properly_placed) and
          read.mapping_quality >= 10)
```

Supplementary Note 10: GATK pipeline

For all GATK[6] analyses (except the Platinum Genomes analysis, see below) we used the Verily production GATK pipeline:

Versions

Reference: hg38.genome.fa

dbSNP: v146 on b38 downloaded from NCBI

1000 Genomes Phase 3 callset:

1000G_ALL.wgs.phase3_shapeit2_mvncall_integrated_v5b.20130502.sites.hg38.vcf

downloaded from 1000G FTP

BWA version: 0.7.12

Samtools version: 1.1

Picard version: 2.1.0

GATK version: 3.5

BWA

```
bwa mem -t 32 fastq1.gz fastq2.gz
  | samtools view -u -
  | samtools sort -@ 12 -O bam -T sorted.bam.sort_tmp -o sorted.bam -
```

Mark Duplicates

```
java -Xmx12G -jar picard.jar MarkDuplicates INPUT=sorted.bam
OUTPUT=sorted.deduped.bam ASSUME_SORTED=true CREATE_INDEX=true
MAX_RECORDS_IN_RAM=2000000 METRICS_FILE=MarkDuplicates_metrics.txt
REMOVE_DUPLICATES=false
```

After MarkDuplicates, all lanes for the sample are merged into a single BAM file with MergeSamFiles in picard.

Indel realignment

```
java -jar CommandLineGATK_deploy.jar -Xmx4G -R hg38.genome.fa -ip 50 -T
RealignerTargetCreator -I sorted.deduped.merged.bam -known
1000G_ALL.wgs.phase3_shapeit2_mvncall_integrated_v5b.20130502.sites.hg38.vcf -o
realignment_targets.interval_list -nt 8 -mismatch 0.0

java -jar CommandLineGATK_deploy.jar -Xmx4G -R hg38.genome.fa -ip 50 -T
IndelRealigner -I sorted.deduped.merged.bam -targetIntervals
realignment_targets.chr1.interval_list -known
1000G_ALL.wgs.phase3_shapeit2_mvncall_integrated_v5b.20130502.sites.hg38.vcf --
consensusDeterminationModel KNOWNS_ONLY -o sorted.deduped.merged.realigned.bam
```

Base recalibration

```
java -jar CommandLineGATK_deploy.jar -Xmx4G -R hg38.genome.fa -T BaseRecalibrator -
```

```
I sorted.deduped.merged.realigned.bam -knownSites dbsnp_146.hg38.vcf -o
base_recalibration.table -nct 32 --useOriginalQualities --disable_indel_quals -cov
ReadGroupCovariate -cov QualityScoreCovariate -cov CycleCovariate -cov
ContextCovariate


java -jar CommandLineGATK_deploy.jar -Xmx4G -R hg38.genome.fa -T PrintReads -nct 8
-I sorted.deduped.merged.realigned.bam -BQSR base_recalibration.table --
disable_indel_quals --emit_original_quals -o
sorted.deduped.merged.realigned.recalibrated.bam
```

HaplotypeCaller

```
java -jar CommandLineGATK_deploy.jar -Xmx4G -R hg38.genome.fa -ip 50 -T
HaplotypeCaller -I sorted.deduped.merged.realigned.recalibrated.bam -ERC GVCF -o
g.vcf --annotation QualByDepth


java -jar CommandLineGATK_deploy.jar -Xmx4G -R hg38.genome.fa -T GenotypeGVCFs -o
raw_calls.vcf -nt 8 -D dbsnp_146.hg38.vcf --variant g.vcf
```

VQSR

```
java -jar CommandLineGATK_deploy.jar -Xmx20G -R hg38.genome.fa -T
VariantRecalibrator --max_attempts 4 -input raw_calls.vcf -
resource:ALL_1000G_phase3,known=false,training=true,truth=true,prior=12.0
1000G_ALL.wgs.phase3_shapeit2_mvncall_integrated_v5b.20130502.sites.hg38.vcf -
```

```
resource:dbsnp,known=true,training=false,truth=false,prior=2.0 dbsnp_146.hg38.vcf -
an DP -an QD -an FS -an SOR -an MQ -an MQRankSum -an ReadPosRankSum -mode SNP -nt 4
-tranche 99.5 -recalFile snps.recal -tranchesFile snps.tranches -allPoly


java -jar CommandLineGATK_deploy.jar -Xmx20G -R hg38.genome.fa -T
ApplyRecalibration -input raw_calls.vcf -mode SNP --ts_filter_level 99.5 -recalFile
snps.recal -tranchesFile snps.tranches -o recal.snps.raw.indels.vcf


java -jar CommandLineGATK_deploy.jar -Xmx20G -R hg38.genome.fa -T
VariantRecalibrator --max_attempts 4 -input recal.snps.raw.indels.vcf -
resource:ALL_1000G_phase3,known=false,training=true,truth=true,prior=12.0
1000G_ALL.wgs.phase3_shapeit2_mvncall_integrated_v5b.20130502.sites.hg38.vcf -
resource:dbsnp,known=true,training=false,truth=false,prior=2.0 dbsnp_146.hg38.vcf -
an QD -an DP -an FS -an SOR -an MQRankSum -an ReadPosRankSum -mode INDEL -nt 4 -
tranche 99.0 -recalFile indels.recal -tranchesFile indels.tranches -allPoly


java -jar CommandLineGATK_deploy.jar -Xmx20G -R hg38.genome.fa -T
ApplyRecalibration -input recal.snps.raw.indels.vcf -mode INDEL -ts_filter_level
99.0 -recalFile indels.recal -tranchesFile indels.tranches -o final.vcf
```

Supplementary Note 11: DeepVariant and GATK on Platinum Genomes NA12878

We trained a deep learning model as described above using only the reads aligned to chromosomes 1 through 18 and evaluated variant calling accuracy on chromosomes 20 to 22 using both our algorithm and the community gold standard GATK best practices pipeline. We reserved chromosome 19 for hyperparameter optimization of the deep learning model. We created a non-overfitted GATK callset in which training does not see the data from chr20-22 by excluding that data during the GATK VQSR step.

For a comparison, we ran GATK v3.3 following Broad best practices as implemented by Google Cloud Genomics + Broad in the alpha version (see https://cloud.google.com/genomics/), run in

January 2016 on the NA12878 Platinum Genomes BAM file from https://cloud.google.com/genomics/data/platinum-genomes.

References

1. Keane, T. M. *et al.* Mouse genomic variation and its effect on phenotypes and gene regulation. *Nature* **477,** 289–294 (2011).

2. O'Leary, N. A. *et al.* Reference sequence (RefSeq) database at NCBI: current status, taxonomic expansion, and functional annotation. *Nucleic Acids Res.* **44,** D733–45 (2016).

3. DePristo, M. A. *et al.* A framework for variation discovery and genotyping using next-generation DNA sequencing data. *Nat. Genet.* **43,** 491–498 (2011).