



HAL
open science

Efficient hybrid de novo assembly of human genomes with WENGAN

Alex Di Genova, Elena Buena-Atienza, Stephan Ossowski, Marie-France Sagot

► **To cite this version:**

Alex Di Genova, Elena Buena-Atienza, Stephan Ossowski, Marie-France Sagot. Efficient hybrid de novo assembly of human genomes with WENGAN. *Nature Biotechnology*, 2020, 39, pp.422-430. 10.1038/s41587-020-00747-w . hal-03065904

HAL Id: hal-03065904

<https://inria.hal.science/hal-03065904v1>

Submitted on 15 Dec 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

- 1 Editorial Summary: The genome assembler WENGAN produces high-quality human genome sequences at low
- 2 computational cost.

Efficient hybrid *de novo* assembly of human genomes with WENGAN

Alex Di Genova^{1,2,*}, Elena Buena-Atienza^{3,4}, Stephan Ossowski^{3,4} and Marie-France Sagot^{1,2,*}

¹Inria Grenoble Rhône-Alpes, 655, Avenue de l'Europe, 38334 Montbonnot, France. □

²Université de Lyon, Université Lyon 1, CNRS, Laboratoire de Biométrie et Biologie Evolutive UMR 5558, F-69622 Villeurbanne, France.

³Institute of Medical Genetics and Applied Genomics, University of Tübingen, Tübingen, Germany.

⁴NGS Competence Center Tübingen (NCCT), University of Tübingen, Tübingen, Germany.

*Correspondence should be addressed to Alex Di Genova (email: digenova@gmail.com) and Marie-France Sagot (email: marie-france.sagot@inria.fr).

Generating accurate genome assemblies of large, repeat-rich human genomes has proved difficult using only long, error-prone reads, and most human genomes assembled from long reads add accurate short reads to polish the consensus sequence. Here we report an algorithm for hybrid assembly, WENGAN, that provides highest quality at low computational cost. We demonstrate *de novo* assembly of four human genomes using a combination of sequencing data generated on ONT PromethION, PacBio Sequel, Illumina and MGI technology. WENGAN implements efficient algorithms to improve assembly contiguity as well as consensus quality. The resulting genome assemblies have high contiguity (contig NG50:17.24-80.64 Mb), few assembly errors (contig NGA50:11.8-59.59 Mb), good consensus quality (QV:27.84-42.88), and high gene completeness (BUSCO complete: 94.6-95.2%), while consuming low computational resources (CPU hours:187-1,200). In particular, the WENGAN assembly of the haploid CHM13 sample achieved a contig NG50 of 80.64 Mb (NGA50:59.59 Mb), which surpasses the contiguity of the current human reference genome (*GRCh38* contig NG50:57.88 Mb).

3 **Introduction**

4 Genome assembly is the process by which an unknown genome sequence is constructed by detecting
5 overlaps between a set of redundant genomic reads. Most genome assemblers represent the overlap information
6 using different kinds of assembly graphs [1, 2]. The main idea behind these algorithms is to reduce the genome
7 assembly problem to a path problem where the genome is reconstructed by finding "the" true genome path in a
8 tangled assembly graph [1, 2]. The entanglement comes from the complexity that repetitive genomic regions
9 induce in the assembly graphs [1, 2]. The first graph-based genome assemblers used overlaps of variable length
10 to construct an overlap-graph [2]. The main goal of the overlap graph approach and of its subsequent evolution,
11 namely the string graph [3], is to preserve as much as possible the reads information [2, 3]. However, the read-
12 level graph construction requires an expensive all-vs-all read comparison [3]. The read-level nature implies that
13 a path in such a graph represents a read layout, and a subsequent consensus step must be performed in order to
14 improve the quality of bases called along the path [3]. These graph properties are the foundation of the overlap-
15 layout-consensus (OLC) paradigm [3-5].

16
17 A seemingly counterintuitive idea is to fix the overlap length to a given size (k) to build a *de Bruijn*
18 graph [1]. However, *de Bruijn* graphs have several favorable properties making them the method of choice in
19 many modern short-read assemblers [6-8]. In this approach, the fixed-length exact overlaps are detected by
20 breaking the reads into consecutive k -mers [1]. The k -mers are usually stored in hash tables (constant query
21 time), thus avoiding entirely the costly all-vs-all read comparison [6-8]. Unlike a string graph, the *de Bruijn*
22 graph is a base-level graph [1, 6-8], thus a path (contig) represents a consensus sequence derived from a pileup
23 of the reads generating the k -mers (k -mer frequency). Moreover, the *de Bruijn* graph is useful for characterizing
24 repeated as well as unique sequences of a genome (repeat graph [9]). However, by splitting the reads into k -
25 mers, valuable information from the reads may be lost, especially when these are much longer than the selected
26 k -mer size [3].

27
28 The type of overlap detected, and therefore the type of assembly graph constructed, is related to the
29 sequencing technology used to generate the reads. One class of modern high-throughput sequencing machines
30 produces short (100-300 bp) and accurate (base-error < 0.1%) reads [10, 11], and a second class produces long
31 (>10kb) but error-prone (base-error < 15%) reads [12, 13]. Despite the high per base error rate of long-reads,
32 the latter are the better choice for genome reconstruction [14], as longer overlaps reduce the complexity of the
33 assembly graph [15], and therefore more contiguous genome reconstructions are achievable [14].

34
35 Independent of the sequencing technology, the goals of a genome assembler are to reconstruct the
36 complete genome in (1) the fewest possible consecutive pieces (ideally chromosomes) with (2) the highest base
37 accuracy while (3) minimizing the computational resources (the 1-2-3 Goals). Short-read *de Bruijn* graph
38 assemblers are good for accomplishing goals 2 and 3 [6-8], while long-read assemblers excel at achieving goal
39 1 [4, 5].

41 Modern long-read assemblers widely adopted the OLC-paradigm [4, 5, 16-19] and new algorithms
42 have substantially accelerated the all-vs-all read comparison [16-19]. Such progress has been possible by
43 avoiding entirely the long-reads error-correction step [16-19], and by representing the long-reads as fingerprints
44 derived from a subset of special k -mers (*i.e.* minimizers [20], minhash [19] etc.). The reduced long-read
45 representation is appropriate for detecting overlaps $>2\text{kb}$ in a fast way [16, 18, 19]. The newest long-read
46 assemblers are therefore starting to be good also at goal 3 [16, 18, 19]. However, assembling uncorrected long-
47 reads has the undesirable effect of giving more work to the consensus polisher [17, 19, 21-23]. Genome
48 assembly polishing is the process of improving the base accuracy of the assembled contig sequences [17, 19,
49 21-24]. Usually, long-read assemblers perform a single round of long-read polishing [16, 18, 19], that is
50 followed by several rounds of polishing with long [17, 19, 21, 23] and short [17, 22, 24] reads using third-party
51 tools [17, 19, 21-24].

52

53 Currently, polishing large genomes, such as the human genome, can take much more computational
54 time than the long-read assembly itself [16, 18, 19]. Even after several rounds of polishing, a substantial fraction
55 of consensus errors remains, hampering the subsequent genome analyses such as gene and protein prediction
56 [25]. Lastly, PacBio recently introduced High-Fidelity reads (HiFi reads), increasing significantly the base
57 accuracy of long reads [26]. This technology moves the polishing bottleneck to the upfront by generating
58 multiple error-prone reads (10 passes) of circularized fragments (10-20kb size) [26]. Each fragment is then
59 computationally corrected to generate a single consensus long read ($>10\text{kb}$) with high base accuracy (base-error
60 $< 1\%$). To fully exploit HiFi reads, new assemblers have been developed [27, 28] that do not require a final
61 polishing phase [28].

62

63 When this assembly approach employs short-read polishing [17, 22, 24], then it corresponds to a long-
64 read-first hybrid assembly strategy [29, 30]. Another hybrid assembly strategy consists in starting the assembly
65 process with short reads [31]. However, none of the described hybrid strategies employs the short-reads to
66 tackle the problem of assembly contiguity, *i.e.* they do not aim at joining two long reads by a short-read contig,
67 and therefore exploit only partially the short-read sequence information.

68

69 Here we introduce WENGAN, a hybrid genome assembler that, unlike most long-read assemblers,
70 entirely avoids the all-vs-all read comparison, does not follow the OLC paradigm, and integrates short-reads in
71 the early phases of the assembly process (short-read-first). We validated WENGAN with standard assembly
72 benchmarks. Our results demonstrate that WENGAN optimizes the 1-2-3 Goals and is particularly effective at
73 low long-read coverage (15X). Furthermore, we show that the WENGAN assemblies performed by combining
74 ultra-long Nanopore reads with short or HiFi reads surpass the contiguity of the current human reference
75 genome.

76

77 **Results**

78 **The WENGAN algorithm**

79 WENGAN starts by building short-read contigs using a *de Bruijn* graph assembler [6-8] (Figure 1.1).
80 Then, the pair-end reads are pseudo-aligned [32] back to detect and error-correct chimeric contigs as well as to
81 classify them as repeats or unique sequences (Figure 1.2). Repeated sequences induce complex *de Bruijn* graph
82 topologies in their neighborhood, and short-read assemblers can choose wrong paths while traversing such
83 complex regions, thus leading to chimeric contigs (Supplementary Fig. 1). Chimeric short-read contigs limit the
84 accuracy and contiguity of the assembly when left uncorrected (Supplementary Fig. 2). Each short-read contig
85 is therefore scanned base-by-base and split at sub-regions lacking pair-end read support (Supplementary Fig. 1).
86

87 Following short-read contigs correction, we generate synthetic paired-reads of different insert sizes
88 from long-read sequences, which are mapped to the corrected short-read contigs (Figure 1.3). The spectrum of
89 synthetic libraries is used to span the genomic repeats. For instance with ultra-long nanopore reads, we can
90 create a spectrum composed of 24 synthetic libraries with insert sizes ranging from 0.5kb to
91 200kb (Supplementary Fig. 3). Matched pairs are stored with a reference to the long-read from which they were
92 extracted (colors appearing in pairs, Figure 1.3). Using the mapped pairs and the corrected short-read contigs,
93 we then build the Synthetic Scaffolding Graph (SSG). The SSG is an extension of the scaffolding graph [33],
94 where there is an additional edge-labeling function that labels (colors) the SSG edges with the long-reads
95 (Figure 1.3-4). After the SSG construction (Figure 1.4) and subsequent repeat masking (Figure 1.5), we employ
96 the SSG to compute implicit approximate long-read multiple alignments by searching for transitive long-read-
97 coherent paths (Figure 1.6). The aim of this graph operation (called *transitive reduction*) is to restore the full
98 long-read information in the SSG. Each successful reduction modifies the weight as well as the shape of the
99 SSG (Figure 1.6). After restoring the long-read information, we order and orient the short-read contigs by
100 applying an approximation algorithm [34] that uses all the connectivity information at once to produce an
101 optimal assembly backbone (Figure 1.7). The solution is validated by checking the distance constraints that the
102 reduced long-read-coherent paths impose on the assembly backbone (Figure 1.8).
103

104 A property of the SSG is that all edges connecting two short-read contigs (called *mate-edges*) are
105 spanned by at least one long-read. We therefore use the inner long-read sequence of the synthetic mate-pairs
106 that span the mate-edge to build a long-read consensus sequence using a partial order alignment graph [17,35]
107 (Figure 1.9). The corresponding short-read contig-ends are then aligned [36] to the mate-edge consensus
108 sequence to determine the correct boundaries, thus filling the gap between the two short-read contigs. We
109 computed the Pearson correlation of the mate-edge length before and after filling the gap for a total of 283,727
110 mate-edges. The correlation is very high ($R^2 > 0.99$) even for large gaps (>100 kb, Supplementary Fig. 4).
111

112 The final steps use the SSG to polish the mate-edge consensus sequences by finding long-read-
113 coherent paths that traverse the repeated regions (*i.e.* P4 and P6 for R1, Figure 1.10) or pairwise alignments [36]

114 between the repetitive short-read contigs and the mate-edge consensus sequences (Figure 1.10). Finally, the
115 hybrid contigs are reported in FASTA format (Figure 1).

116

117 **WENGAN surpasses the contiguity of GRCh38**

118 To explore the contiguity limit of WENGAN, we assembled the human haploid cell line CHM13, which
119 has been sequenced with a plethora of technologies including accurate short Illumina reads, long and accurate
120 PacBio/HiFi reads [28], and ultra-long Nanopore reads [30]. In particular, the HiFi reads were generated using a
121 large insert-size library (20 kb) at 30X of genome coverage, with half of the HiFi data (N50) contained in
122 accurate reads larger than 17 kb (Supplementary Table 1). Similarly, the Nanopore reads were generated using
123 an ultra-long read protocol optimized for MinION [29] resulting in 30X genome coverage by reads of at least
124 100 kb (Supplementary Table 1).

125 We generated two WENGAN assemblies, one that combines 60X of Illumina
126 reads (2x250bp, Supplementary Table 2) with ultra-long Nanopore reads, termed WENGAN (ILL+UL), and a
127 second one that combines both long-read technologies, termed WENGAN (HiFi+UL). The WENGAN (ILL+UL)
128 assembly has a total length of 2.84Gb with half of the genome contained in contig sequences larger than 71.25
129 Mb (NG50, Figure 2A). Similarly, The WENGAN (HiFi+UL) assembly has a total length of 2.84Gb with a contig
130 NG50 of 80.64 Mb (Figure 2A). The contig NG50 of both WENGAN assemblies exceed the contiguity of the
131 human reference genomes GRCh37 and GRCh38 (Figure 2A and Supplementary Fig. 5).

132

133 We compared WENGAN to state-of-the-art non-hybrid long-read assemblers (Figure 2) using public
134 assemblies generated from ultra-long Nanopore [5, 18, 19, 30] or PacBio/HiFi reads [5, 27, 28] (Supplementary
135 Table 3, Methods: Assembly validation). These genome assemblies of CHM13 represent the quality that can be
136 achieved using the two long-read technologies independently. In terms of assembly contiguity, the NG50 of
137 WENGAN (ILL+UL) is almost twice as long compared to PEREGRINE (HiFi) [27] (NG50: 38.11Mb) and
138 CANU (HiFi) [5] (NG50: 46.82Mb), is substantially longer than the assembly generated by SHASTA (UL)
139 [19] (NG50: 58.09Mb), and has similar NG50 as the assemblies generated by FLYE (UL) [18] (NG50: 70.32Mb)
140 and CANU (UL) [5] (NG50: 77.96Mb). The WENGAN (HiFi+UL) assembly reaches an NG50 of 80.64Mb, which
141 outperforms all aforementioned assemblers, except for the recently developed HiCANU (HiFi) assembler [28]
142 (NG50: 82.40Mb, Figure 2A). [An assessment of the assembly quality with QUASt \[37\] based on a whole
143 genome alignment to the GRCh38 reference and subsequent masking of complex genomic regions \(see
144 Methods\), reveals that both WENGAN assemblies have a low rate of assembly errors \(avg: 107.5, Figure 2B\),
145 which is comparable or lower than its peers, except for SHASTA \(78 errors\). Replacing the GRCh38 reference by
146 the curated CHM13 assembly generated by the T2T consortium \(v0.7\) \[30\] confirms the low error rate achieved
147 by WENGAN \(Supplementary Table 4\).](#)

148

149 We evaluated the consensus quality of the assemblies using an independent set of BAC sequences of
150 CHM13 located in unique genomic regions [30] (Supplementary Table 5). Our analysis shows that WENGAN
151 (ILL+UL) and WENGAN (HiFi+UL) assemblies achieved median consensus qualities (median QV \geq 36.06 and
152 QV \geq 42.88) that exceed the base quality of Nanopore assemblers, and are comparable to the base qualities of
153 HiFi assemblers (Figure 2C). Moreover, the WENGAN and HiFi assemblies excel at BUSCO completeness with a

154 recovery of at least 94.5% of the BUSCO genes (Figure 2D). In terms of computational resources, WENGAN
155 (ILL+UL) took 1,198 CPU hours (max. RAM 646Gb, 38 hours real-time). WENGAN's runtime was at least 183
156 times faster than CANU's (UL) (~219,000 CPU hours) [19], while at the same time using less memory than
157 other assemblers such as FLYE and SHASTA. Interestingly, generating HiFi consensus reads for 30X human
158 genome coverage requires ~40,000 CPU hours [28], which is ~40 times more computationally intensive than
159 the WENGAN (ILL+UL) *de novo* assembly. Disregarding the excessive generation time for HiFi reads, WENGAN
160 (HiFi+UL) took 981 CPU hours (max. RAM 125Gb, 85 hours real-time), which is more efficient than
161 HiCANU (5,000 CPU hours) [28], but less efficient than PEREGRINE (58 CPU hours) [28].

162
163 We assessed the performance of the assemblers in hard-to-assemble regions such as the repeat
164 sequences annotated in the curated CHM13 T2T-X chromosome [30], the Major Histocompatibility Complex
165 (MHC), and Segmental Duplications (SDs). The T2T-X chromosome (154Mb, v0.7) is the first human
166 chromosome completely assembled [30], thus useful to assess the performance of assemblers across all the
167 repeat families. The MHC region is repetitive and highly polymorphic [29], while SDs are the most complex
168 repeats annotated in the human genome [38] with more than 100Mb of the SD sequence composed of repeats
169 larger than 100kb (Supplementary Fig. 6A). The T2T-X chromosome is covered by 2 and 4 contigs with a total
170 size of 150.9 Mb and 150.56 Mb in WENGAN (HiFi+UL) and WENGAN (ILL+UL), respectively (Supplementary
171 Fig. 7). Both WENGAN assemblies solve more than 99.6% of the total interspersed repeats annotated in the
172 curated T2T-X chromosome, which is better or comparable to its peers (Supplementary Table 6). All evaluated
173 CHM13 assemblies span the 4.97Mb MHC region in a single contig (Supplementary Fig. 8), with the WENGAN
174 assemblies reaching an NGA50 of 2.8Mb (Supplementary Fig. 8). The WENGAN assemblies resolve between
175 168-176 BAC sequences (Supplementary Table 5), which is better than PEREGRINE (136), comparable to
176 SHASTA (176) and lower than FLYE (253), CANU (314) and HiCANU (326). While the BACs library is enriched
177 in SDs [30], it does not represent the full range of SDs annotated in GRCh38 (175Mb). The WENGAN
178 assemblies resolve between 60.9-65.9Mb (Figure 2E) of the SDs annotated in GRCh38 [38], which is better
179 than PEREGRINE, comparable to HiCANU and lower than FLYE, SHASTA and CANU (Supplementary Fig. 6).
180 However, none of the assemblers resolved more than 42% of such hard-to-assemble regions, with the best
181 performer just assembling 22% (CANU (UL): 23.4Mb) of the SDs \geq 100kb (104.7Mb, Supplementary Fig. 6).
182 Even with ultra-long-reads or accurate HiFi reads, a further improvement of the algorithmic approaches will be
183 necessary to complete the assembly of SDs [38].

184
185 Overall, we demonstrated that WENGAN achieved a genome assembly quality that rivals the curated
186 CHM13 assembly (v0.7) generated by the T2T consortium [30]. Furthermore, replacing the PacBio/HiFi reads
187 for short reads produced a highly competitive assembly contiguity and quality.

189 **Evaluation of assembly accuracy and contiguity using BIONANO**
190 **optical mapping**

191 We observed that the distance between the NG50 and NGA50 values increases at greater assembly
192 contiguity ($\bar{x} = 39.6\text{Mb}$, Figure 2A), which is likely caused by real sequence variation between the sequenced
193 CHM13 sample and the GRCh38 reference genome. Given this limitation of the reference-based validation, we
194 additionally used an independent *de novo* BIONANO genome map of CHM13 [30] to assess the correctness of
195 the WENGAN assemblies. The BIONANO map is 2.97 Gb in size with 255 contigs and an N50 of 59.6 Mbp. The
196 BIONANO map is integrated with the sequence assembly by identifying *in silico* the nicking endonuclease-
197 specific sites on the contig sequences (*in silico* map) followed by alignment of both maps (Figure 3). Conflicts
198 between the two maps are identified and resolved, and hybrid scaffolds are generated by using the Bionano
199 maps to join the contig sequences and vice versa (Figure 3). A total of 72 cuts at conflicting sites were made in
200 32 contig sequences of the WENGAN (ILL+UL) assembly, leading to a corrected contig NGA50 of 50.73 Mb.
201 The WENGAN (HIFI+UL) assembly after BIONANO conflicts correction has an NGA50 of 59.59Mb (52 cuts in
202 24 contigs). Both corrected WENGAN assemblies are more contiguous than the GRCh37 reference
203 genome (Figure 2A). Notably, the contiguity of the corrected WENGAN (HIFI+UL) assembly surpasses the one
204 of the GRCh38 reference genome (59.59 vs 57.88 Mb, Figure 2A). The hybrid scaffolding produced a
205 maximum of 102 super-scaffold sequences with a total size of 2.83Gb and an N50 of at least 80Mb (Figure 3)
206 for both WENGAN assemblies. Only 0.8% (max: 22.42 Mb) of the WENGAN sequence was not integrated into the
207 hybrid scaffolds (short contigs). The BIONANO scaffolding of CHM13 demonstrates that both unpolished
208 WENGAN assemblies are functional and appropriate for subsequent genome analyses.

209

210 **WENGAN optimizes the 1-2-3 *de novo* assembly goals**

211 To validate WENGAN on diploid human genomes, we assembled three human samples, HG00733,
212 NA24385, and NA12878, which were sequenced with very long reads (Supplementary Table 1). All sequencing
213 data were obtained from public repositories (Supplementary Tables 1 and 2). HG00733 was sequenced using
214 the PacBio Sequel I to 90X genome coverage with $N50 \geq 33.2\text{kb}$. NA24385 and NA12878 were sequenced
215 using the Oxford Nanopore technology at 60X and 35X genome coverage and N50s of 54kb and 72kb,
216 respectively. The sequence data of NA24385 and NA12878 were generated using an ultra-long-read protocol
217 [29] for ONT MinION and contain at least 3.3X genome coverage in reads larger than 100 kb (Supplementary
218 Table 1). The long-read data were combined with at least 50X of short-read coverage (pair-ends: 2x150bp or
219 2x250bp, Supplementary Table 2).

220

221 WENGAN was benchmarked in its three assembly modes, namely WENGANM (MINIA3 [6]),
222 WENGANA (ABYSS2 [7]) and WENGAND (DISCOVARDENOVO [8]). We compared WENGAN to six state-of-the-
223 art assemblers (Table 1). The list is composed of 5 long-read-only assemblers [4, 5, 16, 18, 19] and a hybrid
224 assembler [31] (MASURCA, Table 1). All benchmarked genome assemblies were generated by the developer of
225 the respective assembler (Supplementary Table 3). In particular, the SHASTA assemblies were generated using
226 an independent Nanopore dataset [19], with a genome coverage of $\sim 60\text{X}$, and including at least 6X coverage of
227 ultra-long-reads ($>100\text{kb}$).

228

229 For NA12878 (Table 1), WENGAN produced the most contiguous assemblies, with contig NG50s of
230 17.24, 25.99, and 35.31 Mb for WENGANM, WENGANA and WENGAND, respectively. The best long-read
231 assembler among the four evaluated, namely FLYE (NG50 22.91Mb), is comparable to WENGANA (NG50
232 25.9Mb), but is surpassed by WENGAND (NG50 35.3Mb). All the other evaluated assemblers are outperformed
233 by any WENGAN mode (NG50 $\geq 17.24\text{Mb}$, Table 1, Supplementary Fig. 9). Moreover, WENGAN increased the
234 contiguity of the short-read-only assemblies by a factor of 1,833X, 2,014X and 388X, for MINIA3 (NG50
235 9.6kb), ABYSS2 (NG50 12.9kb) and DISCOVARDENOVO (NG50 91kb), respectively (Supplementary Table 7).
236 The WENGAND assembly of HG00733 has the fewest gaps of any PacBio CLR assembly of a human genome,
237 with more than half of the genome contained in contig sequences at least 32.3 Mb long (Table 1, Supplementary
238 Fig. 9), a substantial improvement in contiguity over the FALCON (NG50 22,3Mb) and SHASTA (NG50 21.7Mb)
239 assemblies (Table 1). The WENGAND assembly of NA24385 (NG50 50.59Mb) more than doubles the contiguity
240 of SHASTA (NG50 20.35Mb, Table 1), surpasses the contiguity of the GRCh37 reference (NG50 38.5Mb), and
241 matches the contiguity of the GRCh38 reference (Supplementary Fig. 9).

242

243 The structural quality was determined using QUASt [37]. The WENGAN assemblies cover up to 96.3%
244 of the reference genome with few assembled sequences ($< 0.4\%$) unmapped to GRCh38 (Table 1, Ref.
245 Covered% and U. length), and the contigs have fewer duplicates than the contigs of its peers (except SHASTA,
246 Table 1, Duplication ratio). The NGA50 (which corresponds to the NG50 corrected of assembly errors) of

247 WENGAND (16.41-24.52 Mb) is the highest across the three assembled genomes (Table 1, Supplementary Fig.
248 9). For NA12878, the NGA50 of WENGAN (11.8Mb-16.41Mb) almost doubles the ones of
249 MASURCA (5.69Mb), WTDBG2 (7.38Mb) and CANU (7.12Mb) (Table 1). Moreover, WENGAN consistently
250 showed a lower number of assembly errors than its peers (Table 1, Supplementary Table 8). **The only exception**
251 **is SHASTA, a conservative assembler [19], that has a lower number of assembly errors than WENGAND on the**
252 **HG00733 (107 vs. 119) and NA24385 (126 vs. 156) genomes. However, WENGAND reaches higher NGA50s**
253 **than SHASTA and almost doubles the NGA50 achieved by SHASTA on the NA24385 genome (24.5 vs. 14.3 Mb,**
254 **Table 1, Supplementary Fig. 9).**

255

256 The consensus accuracy of genome assemblies was determined using different sequence analyses
257 (Table 1, Supplementary Table 9). The level of polishing of the assemblies goes from none to
258 complete (Table 1), including examples of long-read-only (SHASTA and FALCON) and hybrid (short+long reads,
259 CANU and FLYE) polishing (Table 1). For all three genomes, WENGAN reaches a higher consensus accuracy than
260 unpolished or long-read-only polished assemblies (Table 1). In the NA12878 genome, the hybrid polished
261 assemblies of CANU and MASURCA have better short indel rates than the WENGAN assemblies, but WENGAN
262 has better than or comparable medium and long indel rates (Table 1). Moreover, unlike long-read assemblers,
263 the majority ($\geq 73\%$) of the WENGAN consensus errors are located in the mate-edge consensus
264 sequences (Supplementary Fig. 10), representing at most 10% of the WENGAN assembled sequence. The 100-
265 mer analysis reveals that the WENGAN assemblies contain at least 84.5% of the 100-mers of the
266 reference (Table 1). The BUSCO gene completeness of the WENGAN assemblies ranges from 94.62% to 95.20%,
267 which is higher than the result of any other evaluated assembler and reflects the high consensus quality and
268 contiguity of the WENGAN assemblies (Table 1). Hybrid polishing of the FLYE assembly consumed 755 CPUs
269 hours (Supplementary Table 10). While the hybrid polishing removed millions of consensus errors
270 (Table 1, Supplementary Table 10), and increased the median quality value and the BUSCO gene completeness
271 (to 23.39 and 89.7%), the hybrid polished FLYE assembly still has a lower quality than any of the unpolished
272 WENGAN assemblies (Table 1).

273

274 We analyzed how hard-to-assemble regions are resolved on these diploid human
275 genomes (Supplementary Figures 11A and 12). WENGAN with ultra-long reads spans the MHC region with less
276 than 4 contigs (Supplementary Fig. 11B). The top performers, namely CANU (NA12878), FALCON (HG00733),
277 and WENGAND (NA243875), solve the MHC region in a single contig achieving NGA50s \geq
278 3.5Mb (Supplementary Fig. 11B). However, all the evaluated assemblers produce a mix of haplotypes, and
279 therefore subsequent phasing must be performed to fully solve the MHC region [29]. Regarding segmental
280 duplications (Supplementary Fig. 12), WENGANM and WENGANA resolve over 41Mb (~6Mb of SDs > 100Kb),
281 which is better than WTDBG2 (17Mb) and comparable to SHASTA (\bar{x} =42Mb, Supplementary Fig. 12).
282 WENGAND resolves more SD sequences with ultra-long nanopore reads (56.09-60.12 Mb) and matches the top
283 performer CANU on NA12878 (56.09 vs 56.98Mb). With PacBio reads, the FALCON assembler resolves 6.4Mb
284 more SD sequences than WENGAND (Supplementary Fig. 12). The SD analysis of these three diploid samples
285 shows that WENGANA and WENGANM are more conservative than WENGAND for SDs assembly, and that

286 WENGAND is comparable to the top performers (FLYE, CANU), while achieving a lower rate of assembly
287 errors (Table 1, Figure 2B, Supplementary Fig. 12).

288

289 In terms of computational resources, the WENGAN assemblies consumed less than 1,000 CPU-
290 hours (Table 1, Supplementary Table 8, max. elapsed time of 45 hours). WENGANM, the fastest WENGAN mode
291 based on MINIA3, consumed ~738 times less CPU-hours than CANU (203 vs.~150,000 hours, Table 1) and only
292 required 53Gb of RAM to complete the assembly (Table 1).

293

294 Collectively, the benchmark results demonstrate that WENGAN is the only genome assembler evaluated
295 that optimizes all of the 1-2-3 *de novo* assembly goals, namely, contiguity, consensus accuracy, and
296 computational resources.

297

298 **WENGAN is effective at low long-read coverage**

299 We investigated the required long-read coverage to produce *de novo* assemblies with NG50 of at least
300 10Mb. Moreover, we assessed the suitability of the BGI sequencing technology [11] (MGISEQ-2000) as an
301 alternative to Illumina SBS [10] for hybrid assembly using matched short-read genomic data. We sequenced the
302 NA12878 human cell line using the short-read sequencers NovaSeq-6000 [10] and MGISEQ-2000 [11] as well as
303 the long-read sequencer ONT PromethION [13] (Methods section). We generated a total of 548.2 million pair-
304 end reads (2x150bp) of sequence (53.06X) from both short-read sequencers (Supplementary Table 2).
305 Furthermore, three flow-cells of PromethION produced a total of 10.4 million reads (40X) with a N50 of 17.18
306 kb (Supplementary Table 1). We randomly subsampled the long-read data from 10X to 30X of genome
307 coverage in increasing batches of 5X. The N50 was nearly identical for all the long-read subsamples (N50 =
308 19.6 kb, Supplementary Table 11). WENGAN and the best long-read assembler among those evaluated, namely
309 FLYE (v2.5), were used to build hybrid and long-read assemblies for each subsample (Figure 4, Supplementary
310 Table 12).

311

312 A major increase in contiguity for WENGAN was observed when going from 10X to 15X of long-read
313 coverage (Figure 4A, Supplementary Table 12). In particular, we observed an NG50 increase from 2.5, 2.9, 6.9
314 Mb to 7.4, 8.2, 15.5 Mb for WENGANM, WENGANA, and WENGAND, respectively. At shallow long-read
315 coverage (10-15X), FLYE is outperformed by all WENGAN modes. Over 20X coverage, FLYE outperforms
316 WENGANM and is comparable in contiguity to WENGANA (Figure 4). Notably, WENGAND using 15X long-read
317 coverage leads to an NG50 of 15Mb, which FLYE can only reach at 30X long-read coverage (Figure 4A).

318

319 All assemblies generated by WENGAN cover more than 93.8% of the reference genome at any long-
320 read coverage (Figure 4B). As expected, FLYE achieves its highest consensus quality at 30X long-read
321 coverage (max QV=21.08, Supplementary Table 13). Polishing FLYE with long and short (NovaSeq) reads
322 increased its median consensus quality to QV=27.21 (Supplementary Table 14). Almost all WENGAN
323 assemblies achieve higher consensus quality than the polished FLYE assembly (min WENGAN QV=27.67
324 excluding WENGANA-BGI-10X, Figure 4B, Supplementary Tables 12 and 13).

325

326 The contiguity and consensus quality of the WENGAN assemblies vary more as a function of
327 WENGAN's mode than with the type of short-read data used (Figure 4A-B). Indeed, under the same WENGAN
328 mode, the largest difference in contiguity between the short-read technologies of Illumina and BGI is
329 NG50=2.8Mb (WENGAND at 30X, Figure 4A) and their consensus quality is almost identical (Figure 4B).
330 WENGANM required a maximum of 187 CPU hours (max elapsed time < 18.1 hours on 20 CPUs) and 44 Gb of
331 RAM to complete the assemblies (Figure 4B, Supplementary Table 12). To our knowledge, this is the first time
332 that a genome assembler reaches a contiguity of 10Mb and consensus quality of QV 29.4 on such minimal and
333 accessible sequencing and computing resources.

334

335 We checked the assemblies of FLYE and WENGAN to see if they solved the 4.97Mb MHC
336 region (Figure 4C). The WENGAN assemblies at low coverage ($\leq 20X$) reach higher NGA50 than the FLYE
337 assemblies (Figure 4C, Supplementary Fig. 13). However, FLYE over 25X coverage assembles the MHC region
338 in less than two contigs with a NGA50 of 4Mb (Figure 4C, Supplementary Fig. 13).

339

340 In summary, we demonstrated that WENGAN reduces the computational resources and the long-read
341 coverage required for assembling a human genome. WENGAN produced a high quality assembly with NG50 >
342 10Mb (QV > 29) by combining 20X long-read coverage with 50X short-read coverage using less than one day
343 of computing time on a low-end server (20 cores, $\leq 50Gb$ RAM).

344

345 Discussion

346 We have demonstrated that WENGAN is the only genome assembler that optimizes the three main goals of *de*
347 *nov*o assembly algorithms, namely, contiguity, consensus accuracy and computational resources. Furthermore,
348 WENGAN is effective at shallow long-read coverage ($\geq 15X$), and in combination with ultra-long-reads generated
349 *de novo* assemblies that surpass the contiguity of the human reference genome GRCh38. We introduced a
350 hybrid assembly combining accurate PacBio/HiFi reads with ultra-long Nanopore reads and achieved an
351 assembly quality that rivals the quality of the assembly generated by the T2T consortium (v0.7) [30].

352 Additionally, we observed no significant difference in assembly quality between using the short-read platforms
353 Illumina NovaSeq-6000 [10] or MGISEQ-2000 [11] for hybrid assembly with WENGAN. Moreover, WENGAN
354 produces high quality assemblies with any combination of short-read (NovaSeq or MGISEQ-2000) and long-read
355 (ONT MinIon/PromethION or PacBio Sequel I) technologies.

356 Unlike current long-read assemblers, WENGAN generates functional and ready to use genome reconstructions.
357 The consensus quality benchmark demonstrated that short-read polishing remains mandatory for assemblies
358 generated from Nanopore and PacBio CLR reads (Table 1, Supplementary Tables 3, 9, and 13). Although
359 PacBio's HiFi-reads represent an option that mitigates the post-assembly polishing, and, in combination with
360 ultra-long Nanopore reads generates assemblies with the highest contiguity, this comes at a reduced throughput
361 (~ 10 CLR reads to generate 1 HiFi read) and a substantially increased computational resources [26, 28]. We
362 found that hybrid WENGAN assemblies provide a computationally efficient solution for human genome
363 assembly to date, producing, at the same time, highly competitive assembly contiguity and quality.

364
365
366 Previous genome assemblers cannot cope with the high-throughput of a long-read and a short-read sequencer.
367 Although other long-read-only assemblers may have a similar real-time execution [19](1 day), they require less
368 accessible computational resources, more long-read coverage, and process half the data compared with
369 WENGAN. Still, our analyses of hard-to-assemble regions demonstrated that further algorithmic improvements
370 are necessary for all examined assemblers. Even though we have centered our analysis on human genomes,
371 WENGAN also achieves high assembly quality of non-human genomes (Complete BUSCO genes $\geq 95\%$,
372 Supplementary Table 15). Moreover, the WENGAN approach also provides a natural framework to combine
373 long-read with linked-read data, and/or Sanger size short-reads [39], and/or optical maps (BIONANO), which
374 may lead to the assembly of 'telomere-2-telomere' scaffolds without the need for extra polishing and finishing
375 methods. Therefore, WENGAN should facilitate the democratization of *de novo* assembly of human genomes,
376 enabling high-quality genome-assembly for many applications. The WENGAN assembler is available at GITHUB
377 (<https://github.com/adigenova/wengan>) and CODE OCEAN
378 (<https://doi.org/10.24433/CO.9469612.v1>).

379 **Acknowledgements.** The authors are grateful to Vincent Lacroix for helpful comments on initial versions of the
380 manuscript. We would like to thank the NCCT members Antje Schulze Selting and Christina Engesser for
381 excellent technical assistance.

382

383 **Funding.** This work was supported by INRIA and by the German Research Foundation (DFG). The genome
384 assemblies were performed on the supercomputing infrastructure of the NLHPC (ECM-02), Chile.

385

386 **Author contributions.** ADG devised the original ideas for WENGAN, developed, implemented and bench-
387 marked WENGAN. MFS guided the development of WENGAN. EBA performed sequencing of NA12878 and
388 primary quality control of sequenced data. ADG wrote the initial version of the manuscript. MFS and SO
389 improved initial versions of the manuscript. All authors were involved in discussions and revisions of the
390 project and manuscript.

391 **Competing Interests.** The authors declare that they have no competing financial interests. **Correspondence.**
392 Correspondence should be addressed to Alex Di Genova (email: digenova@gmail.com) and Marie-France
393 Sagot (email: marie-france.sagot@inria.fr).

References

1. Pevzner, P. A., Tang, H. & Waterman, M. S. An Eulerian path approach to DNA fragment assembly. *Proceedings of the National Academy of Sciences* **98**, 9748–9753 (2001).
2. Myers, E. W. *et al.* A whole-genome assembly of drosophila. *Science* **287**, 2196–2204 (2000).
3. Myers, E. W. The fragment assembly string graph. *Bioinformatics* **21**, ii79–ii85 (2005).
4. Chin, C.-S. *et al.* Phased diploid genome assembly with single-molecule real-time sequencing. *Nature Methods* **13**, 1050–1054 (2016).
5. Koren, S. *et al.* Canu: scalable and accurate long-read assembly via adaptive k-mer weighting and repeat separation. *Genome Research* **27**, 722–736 (2017).
6. Chikhi, R. & Rizk, G. Space-efficient and exact de Bruijn graph representation based on a Bloom filter. *Algorithms for Molecular Biology* **8**, 22 (2013).
7. Jackman, S. D. *et al.* ABySS 2.0: resource-efficient assembly of large genomes using a Bloom filter. *Genome Research* **27**, 768–777 (2017).
8. Weisenfeld, N. I. *et al.* Comprehensive variation discovery in single human genomes. *Nature Genetics* **46**, 1350–1355 (2014).
9. Pevzner, P. A., Tang, H. & Tesler, G. *De novo* repeat classification and fragment assembly. *Genome Research* **14**, 1786–1796 (2004).
10. Bentley, D. R. *et al.* Accurate whole human genome sequencing using reversible terminator chemistry. *Nature* **456**, 53–59 (2008).
11. Huang, J. *et al.* A reference human genome dataset of the BGISEQ-500 sequencer. *GigaScience* **6**, 1–9 (2017).
12. Eid, J. *et al.* Real-time DNA sequencing from single polymerase molecules. *Science (New York, N.Y.)* **323**, 133–138 (2009).
13. Jain, M., Olsen, H. E., Paten, B. & Akeson, M. The Oxford Nanopore MinION: delivery of nanopore sequencing to the genomics community. *Genome Biology* **17**, 239 (2016).
14. Sedlazeck, F. J., Lee, H., Darby, C. A. & Schatz, M. C. Piercing the dark matter: bioinformatics of long-range sequencing and mapping. *Nature Reviews. Genetics* **19**, 329–346 (2018).
15. Koren, S. & Phillippy, A. M. One chromosome, one contig: complete microbial genomes from long-read sequencing and assembly. *Current Opinion in Microbiology* **23**, 110–120 (2015).
16. Ruan, J. & Li, H. Fast and accurate long-read assembly with wtdbg2. *Nature methods* **17**, 155–158 (2020).
17. Vaser, R., Sović, I., Nagarajan, N. & Šikić, M. Fast and accurate de novo genome assembly from long uncorrected reads. *Genome Research* **27**, 737–746 (2017).
18. Kolmogorov, M., Yuan, J., Lin, Y. & Pevzner, P. A. Assembly of long, error-prone reads using repeat graphs. *Nature Biotechnology* **1** (2019).
19. Shafin, K. *et al.* Nanopore sequencing and the shasta toolkit enable efficient de novo assembly of eleven human genomes. *Nature Biotechnology* **1**–10 (2020).
20. Roberts, M., Hayes, W., Hunt, B. R., Mount, S. M. & Yorke, J. A. Reducing storage requirements for biological sequence comparison. *Bioinformatics* **20**, 3363–3369 (2004).

21. Chin, C.-S. *et al.* Nonhybrid, finished microbial genome assemblies from long-read SMRT sequencing data. *Nature Methods* **10**, 563–569 (2013).
22. Walker, B. J. *et al.* Pilon: An Integrated Tool for Comprehensive Microbial Variant Detection and Genome Assembly Improvement. *PLOS ONE* **9**, e112963 (2014).
23. Loman, N. J., Quick, J. & Simpson, J. T. A complete bacterial genome assembled *de novo* using only nanopore sequencing data. *Nature Methods* **12**, 733–735 (2015).
24. Warren, R. L. *et al.* ntEdit: scalable genome sequence polishing. *Bioinformatics* (2019). Btz400.
25. Watson, M. & Warr, A. Errors in long-read assemblies can critically affect protein prediction. *Nature Biotechnology* **37**, 124–126 (2019).
26. Wenger, A. M. *et al.* Accurate circular consensus long-read sequencing improves variant detection and assembly of a human genome. *Nature biotechnology* 1–8 (2019).
27. Chin, C.-S. & Khalak, A. Human genome assembly in 100 minutes. *BioRxiv* 705616 (2019).
28. Nurk, S. *et al.* HiCanu: accurate assembly of segmental duplications, satellites, and allelic variants from high-fidelity long reads. *Genome Research*. **30**, 1291-1205 (2020).
29. Jain, M. *et al.* Nanopore sequencing and assembly of a human genome with ultra-long reads. *Nature Biotechnology* **36**, 338–345 (2018).
30. Miga, K. H. *et al.* Telomere-to-telomere assembly of a complete human X chromosome. *Nature* **585**.79-84 (2020).
31. Zimin, A. V. *et al.* Hybrid assembly of the large and highly repetitive genome of *Aegilops tauschii*, a progenitor of bread wheat, with the MaSuRCA mega-reads algorithm. *Genome Research* **27**, 787–792 (2017).
32. Di Genova, A., Ruz, G. A., Sagot, M.-F. & Maass, A. Fast-sg: an alignment-free algorithm for hybrid assembly. *GigaScience* **7**, giy048 (2018).
33. Huson, D. H., Reinert, K. & Myers, E. W. The Greedy Path-merging Algorithm for Contig Scaffolding. *J. ACM* **49**, 603–615 (2002).
34. Moran, S., Newman, I. & Wolfstahl, Y. Approximation algorithms for covering a graph by vertex-disjoint paths of maximum total weight. *Networks* **20**, 55–64 (1990).
35. Lee, C. Generating consensus sequences from partial order multiple sequence alignment graphs. *Bioinformatics* **19**, 999–1008 (2003).
36. Sobic, M. & Sikic, M. Edlib: a C/C++ library for fast, exact sequence alignment using edit distance. *Bioinformatics (Oxford, England)* **33**, 1394–1395 (2017).
37. Mikheenko, A., Prjibelski, A., Saveliev, V., Antipov, D. & Gurevich, A. Versatile genome assembly evaluation with quast-lg. *Bioinformatics* **34**, i142–i150 (2018).
38. Vollger, M. R. *et al.* Long-read sequence and assembly of segmental duplications. *Nature methods* **16**, 88 (2019).
39. Drmanac, S. *et al.* CoolMPS: Advanced massively parallel sequencing using antibodies specific to each natural nucleobase. *BioRxiv* 2020.02.19.953307 (2020).

394 **Figure legends:**

395 **Figure 1:** The WENGAN algorithm. The WENGAN workflow consists of first assembling and error correcting
396 the short-read contigs (1-2), creating a spectrum of synthetic mate-pair libraries from long-reads (3), and
397 building of the Synthetic Scaffolding Graph (SSG, 4). The SSG is used to compute approximate long-read
398 overlaps by building long-read-coherent paths (5-6). The long-read overlaps restore the long-read information
399 and facilitate the construction and validation of the assembly backbone (7-8). The SSG is used to fill the gaps
400 by building for each mate-edge a consensus sequence using the Partial Order Alignment graph (9). In the final
401 step the SSG is used to polish the consensus sequences (10). The repeat contigs (2-10) are drawn uncollapsed to
402 explain the WENGAN steps.

403

404 **Figure 2:** WENGAN assemblies of the haploid CHM13 genome. A) The barplot shows the contig
405 NG50/NGA50 of WENGAN and other state-of-the-art long-read assemblers, as well as of the current human
406 reference genomes. NG50 is the contig length such that using longer contigs produces half (50%) of the bases of
407 the reference genome. NGA50 is NG50 corrected of assembly errors. NG50 and NGA50 were computed using
408 as genome size the total contig lengths of GRCh38 (2.94Gb). B) Assembly errors predicted by QUAST using as
409 reference GRCh38 (autosomes + X and Y). [Assembly errors overlapping centromeric regions or segmental
410 duplications were excluded from the analysis.](#) C) Consensus quality assessment by alignment of 30 unique BAC
411 sequences to the assembled contigs using the BACVALIDATION tool. D) Gene completeness was determined
412 using the BUSCO tool. E) Segmental Duplications (SD) resolved by the genome assemblies. An SD is
413 considered resolved if the aligned contig extends the SD flanking sequences by at least 50kb (See Methods
414 section). Different CHM13 assemblers are represented using the same color across the five panels of the figure.

415

416 **Figure 3:** BIONANO scaffolding of the WENGAN assemblies of CHM13. We show the largest super-scaffold
417 produced by merging the BIONANO map (BNG) and the WENGAN contigs (WG) generated by combining ultra-
418 long NANOPORE reads (rel3) with PACBIO/HIFI (20kb) or ILLUMINA (2x250 bp) reads. The name of the
419 scaffolded WENGAN contigs is displayed (WSC). Brackets in the contig name indicate that the contig was
420 corrected by the BIONANO map, and the numbers are the start-stop coordinates of the error-free contig region. In
421 parenthesis, we show the contig orientation in the super-scaffold. The white text in the alignments displays the
422 number of nicking matching sites, the total number of nicking sites in the BNG contig, and the length in
423 megabases of the alignment. The blue bar in the BNG contigs shows examples of joins guided by the WENGAN
424 contigs.

425 Figure 4: *De novo* genome assemblies of NA12878 varying the long-read coverage and the short-read
426 technology. A) The *de novo* assemblies were sorted by NG50 at each long-read coverage (lollipop). We
427 computed the NGA50 (which corresponds to the NG50 corrected of assembly errors) of each assembly using
428 QUAST (see Methods section). B) The consensus quality (see Methods section) of each genome assembly as
429 well as the CPU-hours required for the assembly are reported. C) The WENGAN and FLYE assemblies of the
430 complex MHC region located in Chr6:28,477,797-33,448,354 (4.97Mb). The MHC sequence was aligned to the
431 genome assemblies and the aligned blocks ≥ 30 kb with a minimum identity of 95% were kept. The alignment
432 breakpoints (vertical black lines) indicate a contig switch, alignment error or gap in the assembly. The
433 assemblies of the MHC region are displayed in tracks by long-read coverage.

Tables

		NA12878							HG00733			NA24385	
		WenganA	WenganM	WenganD	MasurCA	Canu	Wtdbg2	Flye	WenganD	Shasta	Falcon	WenganD	Shasta
Asm. stats	Contigs (>=50kb)	490	425	364	<u>1,111</u>	798	934	797	387	649	<u>826</u>	270	<u>660</u>
	T. length (Mb)	2,779	2,780	2,823	2,876	2,824	2,701	2,898	2,812	2,802	2,893	2,871	2,819
	NG50 (Mb)	17.24	25.99	35.31	<u>8.43</u>	10.41	11.84	22.91	32.35	<u>21.71</u>	22.33	50.59	<u>20.35</u>
Structural quality	Ref. Covered (%)	94.22	94.30	95.25	95.80	95.05	<u>91.70</u>	95.56	95.12	<u>94.98</u>	96.06	96.36	<u>95.61</u>
	Dup. ratio	1.002	1.002	1.006	1.013	1.008	0.991	<u>1.025</u>	1.004	1.002	<u>1.020</u>	<u>1.011</u>	1.002
	U. length (Mb)	5.21	4.76	8.63	24.68	9.42	<u>32.13</u>	21.29	6.96	6.49	<u>15.41</u>	<u>10.54</u>	6.52
	NGA50 (Mb)	11.82	14.34	16.41	<u>5.69</u>	7.12	7.38	12.36	17.31	<u>12.99</u>	14.61	24.52	<u>14.32</u>
	Max. aln (Mb)	45.66	75.32	72.84	<u>32.62</u>	34.07	70.48	78.99	<u>71.03</u>	78.22	71.68	<u>75.56</u>	75.65
	Asm. errors	153	91	158	<u>275</u>	194	124	177	119	107	<u>198</u>	<u>156</u>	126
C. R	CPU hours (h)	203	725	589	20,000	<u>~150,000</u>	891	5,000	936	<u>~768</u>	<u>20,000</u>	<u>963</u>	<u>~768</u>
	Max. RAM (Gb)	53	45	<u>622</u>	500	-	222	600	644	<u>~966</u>	-	651	<u>~692</u>
Consensus Accuracy													
Indels	Short (Mb)	1.99	1.72	0.85	0.56	0.57	27.16	<u>37.3</u> / 2.65	0.64	<u>3.09</u>	1.19	0.62	<u>3.38</u>
	Rate (bp)	1,381	1,592	3,252	4,966	4,828	98	<u>74</u> / 1,047	4,372	<u>899</u>	2,323	4,499	<u>828</u>
	Medium (Mb)	0.45	0.43	0.29	0.38	0.35	1.85	<u>2.43</u> / 0.74	0.27	<u>0.7</u>	0.28	0.29	<u>0.73</u>
	Rate (bp)	6,049	6,358	9,447	7,335	7,766	1,442	<u>1,142</u> / 3,753	10,161	<u>3,982</u>	10,046	9,608	<u>3,817</u>
	Long (kb)	17.95	18.73	17.74	19.21	<u>45.96</u>	12.64	15.60 / 16.49	<u>22.9</u>	18.13	17.65	<u>24.85</u>	23.05
	Rate (kb)	153	146	157	145	<u>60</u>	211	178 / 169	<u>121</u>	153	157	<u>113</u>	121
	per 100kb	102	90	53	47	55	1,135	<u>1,471</u> / 147	36	<u>141</u>	62	39	<u>152</u>
100-mer comp. (%)	84.24	84.82	87.44	87.54	86.41	29.47	<u>22.47</u> / 81.47	87.45	<u>79.84</u>	86.42	88.53	<u>79.38</u>	
Median QV	27.84	28.41	31.02	27.10	28.79	17.08	<u>16.41</u> / 23.48	26.42	<u>23.36</u>	27.30	-	-	
Gene completeness													
BUSCO	# Complete	3,884	3,893	3,898	3,866	3,882	<u>1,974</u>	2,268 / 3,680	3,907	<u>3,788</u>	3,874	3,904	<u>3,752</u>
	% Complete	94.64	94.86	94.98	94.20	94.59	<u>48.10</u>	55.26 / 89.67	95.20	<u>92.30</u>	94.40	95.13	<u>91.42</u>

435 **Table 1:** WENGAN assemblies of the diploid NA12878, HG00733 and NA24385 genomes. Structural and
436 consensus accuracy was determined as described in detail in the Methods section (Assembly validation). All the
437 assemblies were built by the assembler developers. In particular, all the NA12878 assemblies were generated
438 using the Oxford Nanopore (rel5) plus Illumina data at the assembly or polishing steps (Except WTDGB2). The
439 CANU assembly was hybrid polished with NANOPOLISH x 2, RACON x 2, and PILON x 2. The FLYE assembly was
440 hybrid polished with RACON x 2 and NTEDIT x 3 (Method section). The SHASTA assemblies were polished using
441 only Nanopore reads with HELEN and MARGINPOLISH. The FALCON assembly was polished using only PacBio
442 CLR reads with QUIVER. The WENGAN, MASURCA and WTDGB2 assemblies were not polished by external tools.
443 The reported CPU time does not include the CPU time spent polishing the assembly with external tools. NG50
444 and NGA50 were computed using as genome size the total chromosome lengths of GRCh38 (3.088 Gb).
445 [Assembly errors overlapping centromeric regions or segmental duplications of GRCh38 were excluded from the](#)
446 [analysis](#). The indels were called from aligned blocks ≥ 1 kb at average identity $\geq 99\%$, and were classified
447 according to their length into Short [1-2bp], Medium [3-50bp) and Long [>50 bp]. The indel-rate was computed

448 dividing the amount of assembly sequence aligned by the number of indels called on such alignments. The
449 "indels per 100kb" is computed by QUILT from aligned blocks $\geq 0.5\text{kb}$ with a minimum identity $\geq 80\%$. The
450 100-mers completeness is the fraction of distinct 100-mers in the GRCh38 reference (2.835 Gb) that are
451 captured in the corresponding assembly. Consensus statistics before and after the polishing are included for the
452 FLYE assembly.

453 **Online Methods**

454 **The WENGAN algorithm**

455 **Short-read assembly.**

456 WENGAN can employ MINIA3 [6], ABYSS2 [7] or DISCOVARDENOVO [8] as the *de Bruijn* graph based short-read
457 assembler. All three short-read assemblers are able to assemble a human genome in less than a day. MINIA3 and
458 ABYSS2 were intended for low-memory assembly of large genomes. They are able to assemble human genomes
459 using less than 40Gb of RAM [6,7]. MINIA3 is the fastest method, consuming less than 77 CPU hours to
460 complete a human genome assembly (Supplementary Table 7). Its speed comes from the novel unipath
461 algorithm BCALM2 [40] that uses minimizers [20] to compress quickly and with low memory the *de Bruijn*
462 graph [40]. MINIA3 can be used iteratively to implement a multi-*k*-mer assembly approach. We used *k*-mer sizes
463 of 41, 81 and 121 in all the WENGANM assemblies described (Supplementary Table 7). ABYSS2 uses a Bloom
464 filter and rolling hash function as the main techniques to implement the *de Bruijn* graph-based assembly [7].
465 After filling the Bloom filter, ABYSS2 selects solid reads (that is, reads composed only of solid *k*-mers, namely
466 those for which $\text{frequency}(k) > 2$) as seeds to create the unipaths. These are extended left and right by
467 navigating in the *de Bruijn* graph until a branching vertex or a dead-end is encountered. In our benchmark tests
468 ABYSS2 required on average 481 CPU hours to assemble a human genome (Supplementary Table 7). All the
469 ABYSS2 assemblies were run using a Bloom Filter size of 40Gb ($B=40G$), four hash functions ($H=4$), solid *k*-
470 mer with a minimum frequency of 3 ($kc=3$), *k*-mer size 96, and until the contig step only. DISCOVARDENOVO is
471 a more specialized algorithm designed to assemble a single PCR-free paired-end Illumina library containing
472 ≥ 150 base-pair reads. DISCOVARDENOVO is greedier in terms of memory than MINIA3 and ABYSS2. We
473 observed a memory peak of 650Gb in our human assemblies (Supplementary Table 7). However,
474 DISCOVARDENOVO better leverages the pair-end information and therefore produces the most contiguous short-
475 read assemblies of all three tested assemblers (average contig NG50 69kb, Supplementary Table 7). All the
476 selected short-read assemblers refine the constructed *de Bruijn* graph by removing sequencing errors and
477 collapsing the genomic variants (SNPs, indels) to produce accurate consensus contigs [6-8].

478 **Pair-end pseudo-alignment as building block for genome assembly.**

479 In the same way as *k*-mers are the elemental building blocks of *de Bruijn* graph assemblers; WENGAN relies on
480 pair-end pseudo-alignments as the elemental building blocks for the *de novo* assembly. We recently introduced
481 an alignment-free method called FAST-SG [32] that uses unique *k*-mers to compute a pseudo-alignment of pair-
482 end reads from long or short-reads technologies. Here, we present its successor, which we called FASTMIN-SG,
483 which implements the same ideas of FAST-SG but using minimizers [20] and chaining with the MINIMAP2 API
484 [41]. The uniqueness of the pseudo-alignment is now determined using the MINIMAP2 mapping quality
485 score which gives a higher score to a primary chain when its best secondary chain has a weak pseudo-
486 alignment.

487 To perform a pseudo-alignment of pair-ends from short-read sequencing technologies, we use (10,21)-
488 minimizers for querying and indexing. We discard pair-end pseudo-alignments when one of the mates has a

489 mapping quality score ≤ 30 or covers $\leq 50\%$ of the read bases. For mapping synthetic pair-ends extracted from
490 long-read technologies, we use (5,20)-minimizers and a read length of 250 base pairs. A synthetic pair-end is a
491 fragment of length d for which we have access to the long-read of origin, the position of the fragment in the
492 long-read and the inner long-read sequence between both mates of the synthetic fragment. All the synthetic
493 fragments are extracted from the long-reads using a moving window of 150bp in forward-reverse orientation.
494 We create a spectrum of synthetic mate-pair libraries (Supplementary Fig. 3) by extracting pair-ends at different
495 distances. The range of distances depends on the long-read lengths but go from 0.5kb to a maximum of 500kb
496 with ultra-long nanopore reads. For noisy PacBio reads, we use homopolymer compressed k -mers [41] for
497 indexing and querying the synthetic pair-ends. We discard synthetic pair-end alignments when one of the mates
498 has a mapping quality score ≤ 40 or covers $\leq 65\%$ of the synthetic read bases. The information associated to the
499 long-read of each synthetic pair is stored in the read names for computing approximate long-read alignments
500 later. FASTMIN-SG, like MINIMAP2, uses presets to modify multiple parameters, thus simplifying its usability.
501 Currently, it has presets for raw PacBio reads (pacraw), HiFi reads (pacccs), raw (ontraw) and ultra-
502 long (ontlon) Oxford Nanopore reads, and pair-ends (shortr) from short-read technologies (supporting Illumina
503 or BGI). The pseudo-alignments are reported in SAM format.

504 **Detection and split of chimeric short-read contigs.**

505 The *de Bruijn* graph is complex around repeat sequences, and short-read assemblers can choose wrong paths
506 while traversing such complex regions, thus leading to chimeric contigs (Supplementary Fig. 1). To detect
507 potential chimeric contigs not supported by the short-reads, we map the pair-end reads back to the assembled
508 short-read contigs using FASTMIN-SG (preset shortr). From the pair-end pseudo-alignments, we infer the
509 average \bar{x} and standard deviation σ of the insert-sizes distribution of the genomic library. Then, pair-ends
510 mapped within contigs at the expected orientation and distance ($[\bar{x} - 2.5\sigma, \bar{x} + 2.5\sigma]$) are transformed into
511 physical fragments. For each contig, we create an array of length equal to the contig length, and the contig
512 fragments are used to increase the physical coverage of the contig bases. We then scan the physical coverage
513 array base by base to detect Low Quality Intervals (LQI) that have fragment coverage below a minimum depth
514 threshold (def:7). LQIs are classified according to their contig location as internal, start, end or whole. Finally,
515 contigs are trimmed/split at the boundaries of the LQIs.

516 **The Synthetic Scaffolding Graph (SSG).**

517 We build on top of the work of Huson *et al.* [33] to extend the scaffolding graph formulation and create the
518 Synthetic Scaffolding Graph (SSG). In brief, the contig scaffolding problem was defined by Huson *et al.* [33] as
519 the determination of an order and orientation of a set of contigs that maximizes the amount of satisfied mate-
520 pair links. The scaffolding graph $G=(V,E)$, with vertex set V and edge set E , is a weighted, undirected multi-
521 graph, without self-loops [33]. Each contig C_i is modeled by two vertices (v,w) and an undirected contig-edge
522 (e). The length of e is set to the contig length $l(C_i)$. The contig orientation is represented by associating each of
523 the contig ends to one of the two vertices (*i.e.* $tail(C_i)=v$ and $head(C_i)=w$). Then traversing from
524 $tail(C_i)\rightarrow head(C_i)$ or $head(C_i)\rightarrow tail(C_i)$ implies forward or reverse contig orientation, respectively. Now,
525 consider a pair of mate-reads f and r originated from a synthetic mate-pair library with mean insert size \bar{x} ,
526 standard deviation σ and orientation forward-reverse that uniquely matches two different contigs C_i and C_j . The

527 uniquely mapped mate-pair induces a relative orientation and approximate distance between the two contigs.
 528 Such information is represented by adding a mate-edge e into the graph. The length of the mate-edge e is
 529 computed by subtracting from the expected mate-pair distance (\bar{x}) the amount of overlap that each contig has
 530 with the mate-pair considering the read mapping orientations: $l(e) := \bar{x} - (l(C_i) - pos_{C_i}(f)) - (l(C_j) -$
 531 $pos_{C_j}(r))$. Moreover, the standard deviation $\sigma(e)$ of each mate-edge e is set equal to the standard deviation of
 532 the synthetic mate-pair library. If there is more than one mate-edge e between the same ends of two contigs C_i
 533 and C_j , we can bundle [33] the mate-edge e by computing from the set of mate-edges e_1, e_2, \dots, e_n , the length of
 534 e as $l(e) := p/q$ and its deviation as $\sigma(e) = \sqrt{1/q}$ where: $p = \sum \frac{l(e_i)}{\sigma(e_i)^2}$ and $q = \sum \frac{1}{\sigma(e_i)^2}$ [33]. Additionally,
 535 the weight $w(e)$ of a bundled mate-edge e is set to $\sum_{i=1}^k w(e_i)$, otherwise to 1.

536

537 The **Synthetic Scaffolding Graph (SSG)** is an edge-bundled scaffolding graph $G=(V,E)$, built from a
 538 **spectrum** of synthetic mate-pair libraries, where there is an edge-labelling function (F) that maps the long reads
 539 to the edges through the synthetic mate-pair pseudo-alignments.

540 **Computing approximate long-read overlaps with the SSG.**

541 Since the **SSG** is built from a spectrum of synthetic mate-pair libraries (*i.e.* 1kb to 10kb, Figure 1.3), it contains
 542 mate-edges from the short (1kb) to the long (10kb) range of connectivity (*i.e.* e_1, e_4 , Figure 1.5). Now, consider
 543 a mate-edge e from v to w that are also connected by a transitive path $P = (m_1, c_1, m_2, \dots, m_k)$ of mate-edges
 544 (m_1, m_2, \dots) , contig-edges (c_1, c_2, \dots) and long-read labels $F(P) = (F(m_1), F(c_1), F(m_2), \dots, F(m_k))$. We can
 545 compute the path length $l(P)$ and its standard deviation $\sigma(P)$ as follows [33]: $l(P) = \sum l(m_i) + \sum l(C_i)$ and
 546 $\sigma(P) = \sqrt{\sum \sigma(m_i)^2}$. A mate-edge e from v to w (*i.e.* e_4 , Figure 1.5) can be transitively reduced on the path
 547 P (*i.e.* $P_2 = (tail(c_2), e_3, c_3, e_5, head(c_4))$, Figure 1.6) if e and P have similar lengths and the long-read labels
 548 of e are coherent with every edge e_i of P : $|l(e) - l(P)| \leq 4\max(\sigma(e), \sigma(P))$ and $F(e) \subset F(e_i) \forall e_i \in P$. If
 549 this is the case, then the transitive path P (*i.e.* P_2) is long-read coherent with the mate-edge e (*i.e.* e_i) and
 550 represents an approximate overlap of length $l(P)$ among all the long-reads composing the mate-edge e ($F(e)$).
 551 We store the overlap information by removing e (*i.e.* e_4) from the SSG and incrementing the weight of every
 552 mate-edge m_i in P by $w(e)$ (*i.e.* $w(e_3, e_5) += w(e_4)$, Figure 1.6). Before starting the computation of
 553 approximate long-read overlaps, the repetitive contig-edges are masked, the mate-edges are sorted by ascending
 554 length $l(e)$, and the set of biconnected components of the SSG is computed. The masking of repetitive contig-
 555 edges is performed by estimating the average coverage of unique genomic regions using as proxy the
 556 longest (10%), all likely to be single copy, short-read contigs (\bar{u}). Contig-edges with an average coverage
 557 $\bar{c}\bar{x} > 1.5 * \bar{u}$ are masked by default. This repeat masking procedure is similar to but simpler than the A-statistic
 558 and threshold (~ 1.44) introduced by Myers *et al.* [3]. Transitive long-read-coherent path search takes place
 559 inside each biconnected component. In practice, we use a depth-first search algorithm to enumerate all the long-
 560 read-coherent paths of a given mate-edge e . At each edge extension, we extend the path only if the new added
 561 edge is long-read-coherent with the given mate-edge e ($F(e) \subset F(e_i)$). We stop searching when the size of a
 562 partial path P is larger than 80 vertices or its length is longer than expected ($l(P) > l(e)$ and $|l(e) - l(P)| >$
 563 $4\max(\sigma(e), \sigma(P))$). If there is more than one long-read-coherent path, we choose the path having the maximum
 564 number of hits from the long-reads supporting the given mate-edge e . For very long mate-edges ($l(e) \geq 100kb$),

565 we stop searching if we find more than 100 long-read-coherent paths. All the selected long-read-coherent paths
566 are stored in a path database for later use.

567

568 The final SSG graph is created by performing first bundling and then transitive reduction (approximate
569 long-read overlaps) of mate-edges. From now on, we will refer to this simply as the *reduced SSG*.

570 **Generation of the assembly backbone with the SSG.**

571 Computation of approximate long-read overlaps allows to solve the scaffolding problem using all the synthetic
572 mate-pair libraries simultaneously. Given the reduced SSG, our goal is to determine an optimal set of vertex
573 disjoint paths covering all the contig-edges with a maximum total weight of the mate-edges. Since this
574 optimization problem is NP-hard, we use Edmond's maximum weighted matching approximation algorithm that
575 guarantees to find an optimal solution with a worst-case performance ratio $r = W(S)/W(G) > 2/3$ [34]. The
576 matching algorithm implementation is based on an extensive use of priority queues, leading to an $O(V E \log(V))$
577 time complexity [42, 43]. All the contig-edges, as well as the mate-edges associated to repetitive contigs or
578 having a weight smaller than 5, are masked during the matching cover step. After computing the matching
579 cover, all the contig-edges are added to the matching cover solution and we use a depth-first-search approach to
580 detect simple cycles. If such cycles are found, the set of biconnected components of the graph is computed and
581 simple cycles are destroyed by removing the mate-edge of lowest weight in each biconnected component. In
582 practice, the matching cover solutions contain few cycles (< 10 on human genomes) and we observed
583 performance-ratios higher than $r > 0.8$. The set of optimal simple paths (lines or scaffolds) is what we call the
584 *assembly backbone*.

585 **Validation of the assembly backbone with the SSG.**

586 We validate the assembly backbone using the physical genomic coverage obtained from the computation of the
587 approximate long-read overlaps. The key idea is to identify suspicious mate-edges e (corresponding to
588 potentially incorrect joins) not supported/covered by long-read overlaps longer than O (by default $O \geq 20kb$).
589 We first assign genomic coordinates to each line $L_i = (c_1, m_2, \dots, m_{k-1}, c_k)$ from 1 to $l(L_i)$, taking into account
590 the orientation of the contig-edges and the ordering and distance provided by the matched mate-edges. In a
591 second step, all the contig-edges are converted into physical genomic fragments as well as the mate-edges
592 spanned by long-reads longer than O . In a third step, if the vertices v, w of a reduced mate-edge e belong to the
593 same line L_i and the length of $l(e)$ is longer than O , we create a new simple path pf that goes from v to w in the
594 line L_i . The new simple path pf is converted into a physical genomic fragment f only if the length of pf is similar
595 to the length of the reduced mate-edge e , that is, if $|l(e) - l(pf)| \leq 4\max(\sigma(e), \sigma(pf))$. If that is the case, the
596 simple path pf increases the physical genomic coverage of the line L_i . In a fourth step, once the physical genomic
597 coverage of all the lines L_i have been computed, we look for all the intervals inside a scaffold having a lack of
598 physical coverage at the mate-edge locations and we tag such mate-edges as potentially erroneous joins. A line
599 L_i is split at potential error joins only if the number of long-reads supporting the suspicious mate-edge e is less
600 than $m_l r$ (default $m_l r \leq 4$). In practice, we observe that the physical path coverage of human assemblies is around
601 20X (30X long-read coverage), thus usually less than 200 mate-edges are removed.

602 **Gap filling with the SSG.**

603 A property of the SSG is that all the mate-edges are spanned by at least one long-read. Therefore, after
604 construction and validation of the assembly backbone, we proceed to create a consensus sequence for each of
605 the matched mate-edges. We start by ordering the lines by decreasing length, which imposes a global order to
606 the mate-edges and consequently to the long-read sequences. For each mate-edge e , we select the N best long-
607 reads (default: 20) spanning e . The long-read selection is done by counting, with the edge-labeling function
608 $F(e)$, the number of synthetic mate-pairs contributed by the long-read l_i to compose the mate-edge e . This
609 means that, the more synthetic mate-pairs are contributed by long-read l_i , the greater is the confidence that the
610 long-read l_i spans e . All the selected long-read sequences are sorted according to the mate-edges order using an
611 external merge sort algorithm to create a long-read sequence database. Following the long-read database
612 creation, we build a consensus sequence for each mate-edge using the partial order alignment graph [35]. For
613 each mate-edge, we select the long-read contributing the most synthetic mate-pairs as consensus template, then
614 the remaining long-reads spanning e are aligned to the template using a fast implementation of Myers bit-vector
615 algorithm [36]. The long-read alignments are scanned to partition the long-reads into non-overlapping windows
616 of size w (by default 500bp) on the template sequence. The long-read chunks that have an average identity
617 lower than 65% are removed from the corresponding windows. The purpose is to use high-quality alignments to
618 build the template consensus. For each window w , we call the consensus sequence using a SIMD accelerated
619 implementation of the partial order alignment graph [17]. The mate-edge consensus is built by joining the
620 window sequences. Finally, the corresponding contig-ends are aligned (using once again Myers bit-vector
621 algorithm) to the mate-edge consensus sequence to determine the correct mate-edge sequence boundaries, thus
622 filling the gap between the two contig-edges.

623 **Polishing with the SSG.**

624 Since not all the contig-edges are part of the assembly backbone (as is the case for the contig-edges related to
625 repeats or short sequences), we can use them to improve the consensus base accuracy of the mate-edge
626 sequences. To this end, we use two polishing strategies, one based on the SSG and a second based on pairwise
627 alignments. The graph polisher uses the reduced SSG to find transitive long-read-coherent paths as before, but
628 masking the contig-edges composing the assembly backbone. Since now we navigate on more complex parts of
629 the SSG (unmasked repeat sequences), we limit the path search to a maximum of 5 million iterations on each
630 mate-edge. Once a long-read-coherent path has been found, we align the contig-edges (with the proper
631 orientation) to the mate-edge sequence using Myers bit-vector algorithm [36]. Then, the alignments are
632 trimmed as a function of the average long-read-depth of the mate-edge consensus sequence. We thus expect a
633 minimum identity between 80% and 99% when the average long-read-depth of the consensus sequence is
634 between 1 and 20, respectively. If a contig-edge maps with an identity higher than the expected and the
635 alignment covers at least 75% of the contig-edge, we replace the corresponding mate-edge aligned sequence by
636 the contig-edge aligned sequence, thus polishing the mate-edge sequence. The alignment polisher searches for
637 matches between the singleton contig-edges and all the mate-edge consensus sequences. In brief, we first index
638 all the mate-edge consensus sequences using (5,17)-minimizers [20]. Minimizers are stored in a hash table and
639 the ones having a frequency higher than 1000 are excluded. The (5,17)-minimizers of the contig-edges are
640 scanned on the mate-edge sequence index to collect HSPs or exact (5,17)-minimizer matches. HSPs are sorted

641 by mate-edges and hits are identified by finding the longest strictly increasing subsequence (co-linear chain)
642 between the contig and the mate edges. After collecting all the hits, we use a greedy algorithm to determine a
643 layout of contig-edge hits along the mate-edge sequence. The greedy algorithm starts by sorting the contig-edge
644 hits by number of minimizer matches and then adds the hits to the layout only if there is no overlap with a
645 previously added hit. We then proceed as in the graph polisher to align and polish the mate-edge sequence using
646 the best-hit layout. Finally, WENGAN outputs the sequence of each line plus the sequence of contig-edges (>5kb)
647 not used in the polishing steps.

648 **WENGAN assemblies of CHM13**

649 The WENGAN (HiFi+UL) assembly of the haploid CHM13 genome was generated using the WENGANM mode.
650 The PacBio/HiFi reads were assembled with MINIA3 using an iterative multi-*k*-mer approach with the following
651 *k*-mer sizes: 41, 81, 121, 161, 201, 251, 301, and 351. The PacBio/HiFi reads were then included in all the
652 subsequent WENGANM steps (Figure 1). The WENGAN (ILL+UL) assembly was generated using the WENGAN
653 mode. The specific commands to reproduce both WENGAN assemblies are provided in the Supplementary
654 Material (Subsection 1.2).

655 **Assembly validation.**

656 Genome assemblies generated by WENGAN and other assemblers were assessed by whole genome alignment to
657 the human reference genome using the QUAST [37] (Version: 5.0.2) tool. QUAST was run with the options "--
658 large --min-identity 80 --fragmented" using the GRCh38 (patch 19) reference (autosomes plus X and Y).
659 Additionally, we ran a QUAST analysis using as reference the curated CHM13 assembly (chm13.draft_v0.7,
660 2.9384 Gb) generated by the T2T consortium [30] for all the CHM13 assemblies (Supplementary Table 4).
661 Several assembly metrics (*i.e.* NG50, NGA50, largest alignment block, indels per 100kb, genome fraction, and
662 others) were collected from the QUAST report. [QUAST assembly errors overlapping centromeric regions or
663 segmental duplications annotated in GRCh38 were excluded from the analysis using the script and annotation
664 files provided by Shafin *et al.* \[19\] \("quast_sv_extractor.py -s empty -d GRCh38_masked_regions.bed -c
665 centromeres.bed -q quast_all_alignments.tsv"\). The procedure masked a total of 610Mb of the GRCh38
666 reference. \[Assembly errors before and after the masking of highly repetitive regions are reported.\]\(#\) The consensus
667 quality was determined by computing a more stringent alignment allowing a maximum of 1% divergence using
668 MINIMAP2 \[41\] program \(MINIMAP2 options: cxasm10 --cs -r2k\), then contig-to-reference alignments longer
669 than 1kb were scanned by PAFTOOLS \(option call -l1000 -L1000\) to call Single Nucleotide Variants, insertions
670 and deletions. Additionally, we used the 100-mers completeness analysis to assess with an alignment-free
671 method the consensus quality of the genome assemblies using the KMC \[44\] *k*-mer counter \(Version 3.1.0\). The
672 GRCh38 \(patch 19\) reference genome has a total of 2,835,070,131 distinct 100-mers and those were intersected
673 with the 100-mers of the genome assemblies using the KMC_TOOLS utility \(option intersect -ci1 -cx1000\). The
674 gene completeness of the genome assemblies was assessed with the BUSCO \[45\] program \(Version 3.0.2\) using
675 the MAMMALIA ODB9 gene set \(4,104 BUSCO groups\). The single plus duplicated complete BUSCO gene counts
676 are reported. The consensus quality of the genome assemblies was determined by aligning orthogonal BAC or
677 Fosmid sequences data \(Supplementary Table 16\). The statistics were computed considering fully resolved
678 BAC/Fosmid only. The BAC/Fosmid consensus quality analysis was performed using the BACVALIDATION tool](#)

679 (<https://github.com/skoren/bacValidation>). The amount of Segmental Duplication (SD)
680 resolved by the genome assemblies of CHM13, HG00733, NA12878 and NA24385 was determined using
681 SEGDUPLLOTS [38] (<https://github.com/mvollger/segDupPlots>). SEGDUPLLOTS aligns the
682 assembled contigs to GRCh38 and considers an SD as resolved when the aligned contig extends the SD flanking
683 sequences by at least 50kb. The sequence of the T2T-X chromosome was repeat-masked with the
684 REPEATMASKER program (version 4.1.0, search engine: HMMER v3.2.1, options: "-species human -gff -xm")
685 using the DFAM(v3.1) database. The contigs of the CHM13 assemblies were anchored to the T2T-X
686 chromosome using MASHMAP (version v2.0) and then masked with REPEATMASKER using the aforementioned
687 options. Finally, the WENGAN assemblies of CHM13 were validated and scaffolded using the hybridScaffold.pl
688 program (BIONANO Solve3.4_06042019a) (with the options -c hybridScaffold_DLE1_config.xml -B 2 -N 2)
689 and the BIONANO map assembled by the T2T-consortium [30].

690 **Hybrid polishing of FLYE assemblies**

691 We polished the FLYE assemblies of NA12878 using the same sequencing reads employed in the WENGAN
692 assemblies. We used two rounds of long-read polishing with RACON [17] followed by three rounds of short-read
693 polishing with NTEdit [24]. The commands executed as well as the consensus quality improvement after each
694 round of polishing are provided in the Supplementary Material (Supplementary Tables 10 and 14).

695 **Genome sequencing of NA12878.**

696 The genomic DNA from the GM12878 human cell line was purchased from the Coriell Institute (cat. no.
697 NA12878, RRID:CVCL_7526).

698 **MGI sequencing**

699 Library preparation for the NA12878 sample was performed with the MGIEasy DNA Library Prep Kit V1.1
700 (MGI, 940-200022-00) following the manufacturer's instructions. Briefly, 1 µg of genomic DNA at a
701 concentration of 12.5ng/µL was fragmented with an E220 Covaris program optimized to yield fragments of
702 450bp average length. A double-sized selection was performed with AMPure XP beads (Beckman Coulter) at
703 0.52X ratio followed by a 0.15X ratio as recommended by MGI. A total of 50ng of fragmented DNA was used
704 for the end repair and A-tailing reaction following the manufacturer's instructions. A set of adapters with 8
705 barcodes were ligated to the repaired DNA for one hour at 23°C. After purification with AMPure XP beads
706 (Beckman Coulter) at a 0.5X ratio, the DNA was subjected to PCR enrichment following the manufacturer's
707 instructions. A total of 330ng of PCR product was hybridized with the Split Oligo (MGI, 940-200022-00) for
708 the circularization step followed by digestion. Circularized ssDNA was purified with Library Purification Beads
709 (MGI, 940-200022-00) and quantified with an ssDNA assay on a Qubit 3 fluorometer (Thermo Fisher). For the
710 linear amplification to generate DNA nanoballs (DNBs), 75fmol of circularized ssDNA were used. The DNB
711 library was loaded in a single lane and sequenced on a MGISEQ-2000 instrument with a paired-end modus and
712 read length of 150bp with the MGISEQ-2000RS High-throughput Sequencing Set PE150 (MGI, 1000003981)
713 according to (DNBs) manufacturer's instructions.

714 **Illumina sequencing**

715 Library was prepared using the TruSeq DNA PCR-Free Library Prep kit (Illumina, FC-121-3001) following the
716 TruSeq DNA PCR-free reference guide (Illumina, 1000000039279v00). Briefly, 1 µg of genomic DNA was
717 used for fragmentation on an E220 Covaris to yield insert sizes of 350bp. The DNA was end-repaired,
718 adenylated and subjected to adapter ligation as described in the reference guide. The library was quantified
719 using the KAPA Lib Quantification Kit (Roche, LB3111) and dsDNA HS assay (Qubit). The average fragment
720 size was estimated with a HS DNA kit (Agilent) on a 2100 Bioanalyzer (Agilent). A S2 flow cell was loaded
721 with 2.2nM on a NovaSeq6000 instrument to generate 2x151 paired-end reads.

722

723 **Oxford Nanopore sequencing**

724 Three flow cells were run with the sample NA12878. One flow cell was loaded with a library prepared from
725 unsheared genomic DNA. For the additional two sequencing runs, [14 µg of] NA12878 genomic DNA was
726 mechanically sheared with Megaruptor 3 (Diagenode) [at a concentration of 70 ng/µL in a volume of 200 µL]
727 with manufacturer's recommended speed to get sheared DNA with an average fragment length of 30Kb. Size
728 selection was performed with Blue Pippin™ (Sage Science) to remove fragments shorter than 10Kb using a
729 0.75% agarose cassette, the S1 marker and a high-pass protocol (Biozym, 342BLF7510). A further clean-up
730 with AMPure XP beads (Beckman Coulter) on the size-selected DNA was performed at a 1X ratio for one
731 library. Fragment size was assessed with the gDNA 165kb Analysis Kit on a FemtoPulse (Agilent) and the
732 concentration of DNA was assessed using the dsDNA HS assay on a Qubit 3 fluorometer (Thermo Fisher). For
733 each of the three sequencing runs, one library was prepared with the SQK-LSK109 Ligation Sequencing kit
734 (ONT) per flow cell following the instructions of the 1D Genomic DNA by Ligation protocol from Oxford
735 Nanopore Technologies. Briefly, 1.1 to 1.3 µg of genomic DNA was used for the DNA repair reaction with
736 NEBNext Ultra II End Repair/dA-Tailing Module (New England Biolabs, E7546S) and NEBNext FFPE DNA
737 Repair Module (NEB, M6630S). Upon clean-up with AMPure XP beads (Beckman Coulter) at 1X ratio, the
738 end-repaired DNA was incubated for one hour at room temperature with Adapter Mix (ONT, SQK-LSK109),
739 Ligation Buffer (ONT, SQK-LSK109) and NEBNext Quick Ligation Module (NEB, E6056S). The ligation
740 reaction was purified with AMPure XP beads (Beckman Coulter) at a 0.4X ratio and L Fragment Buffer (ONT,
741 SQK-LSK109). A total of 600ng (25fmol) of the generated libraries were loaded into the flow cell (FLO-
742 PR002) on a PromethION instrument (ONT) following the manufacturer's instructions. The Nanopore reads
743 were base-called using GUPPY (v3.0.3) with the high accuracy FLIP-FLOP model.

744 **Data availability**

745 All sequence datasets and *de novo* genome assemblies described in the manuscript are publicly available
746 through the corresponding repositories. Specific hyperlinks for the four human datasets are provided in the
747 Supplementary Material: Supplementary Table 1 provides hyperlinks for all the long-read datasets;
748 Supplementary Table 2 provides hyperlinks for all the short-read datasets; Supplementary Table 3 provides
749 hyperlinks for all the *de novo* assemblies used in the benchmark; Supplementary Table 16 provides hyperlinks
750 for the BAC/Fosmid sequences used for consensus quality assessment. The BIONANO data of CHM13 is
751 available at <https://github.com/nanopore-wgs-consortium/CHM13>. Specific hyperlinks for the

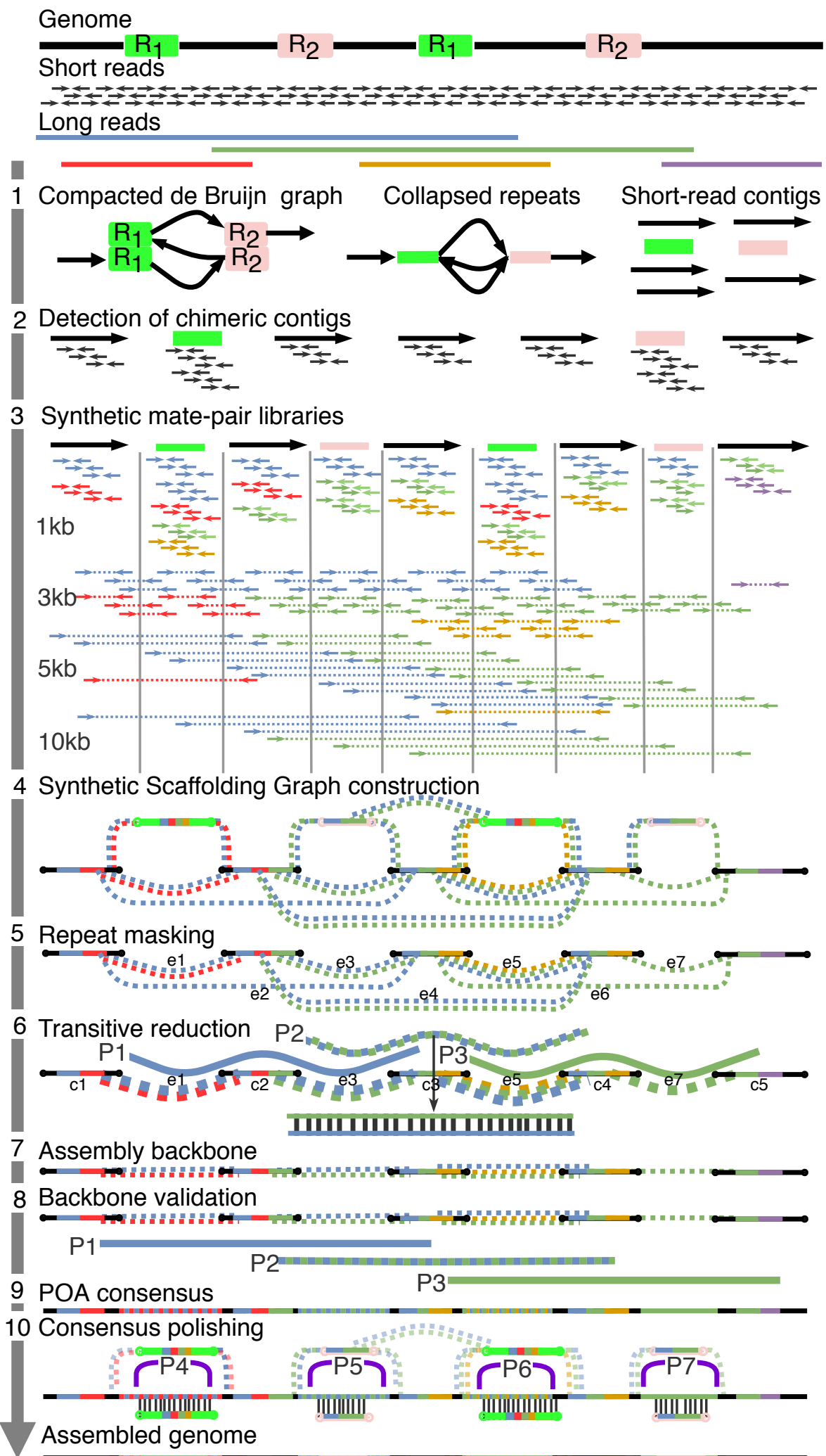
752 non-human datasets are provided in the Supplementary Table 17. The supplementary files, including all the
753 WENGAN assemblies described in the present manuscript, are available through Zenodo at
754 <https://zenodo.org/record/3779515>. The specific commands for each WENGAN assembly are
755 provided in the Supplementary Material (Subsection 1.2). The NovaSeq6000, MGISEQ-2000RS and
756 PromethION sequence data of NA12878 were submitted to the Sequence Read Archive (SRA) under the
757 BioProject PRJNA603060.

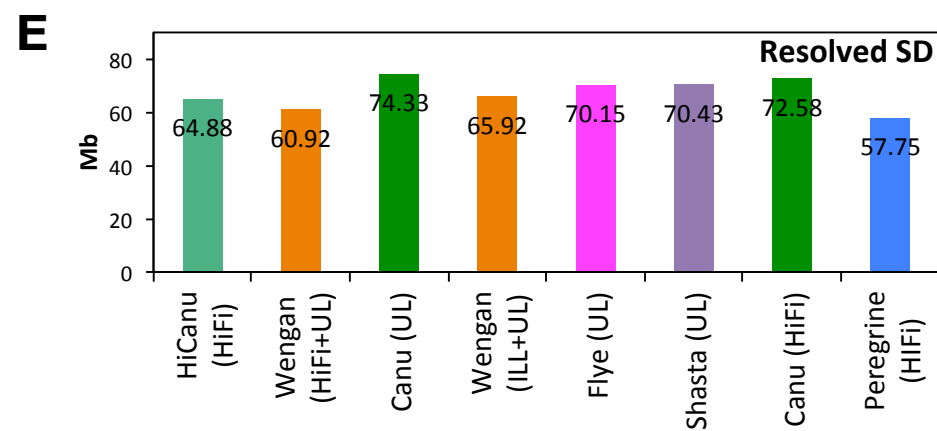
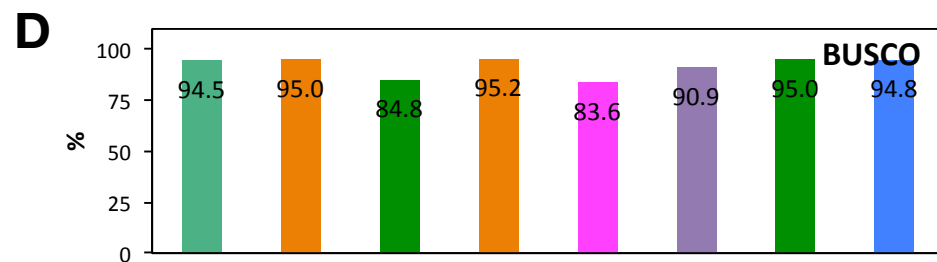
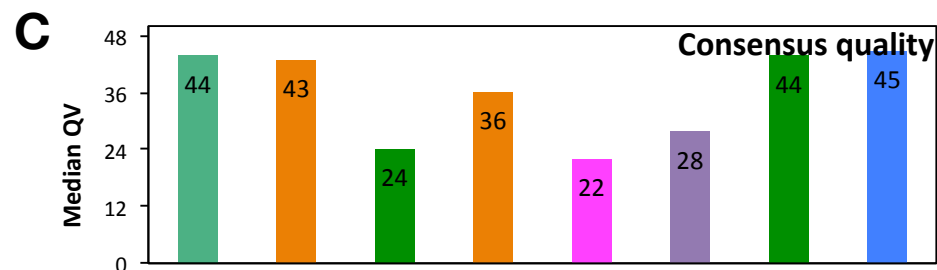
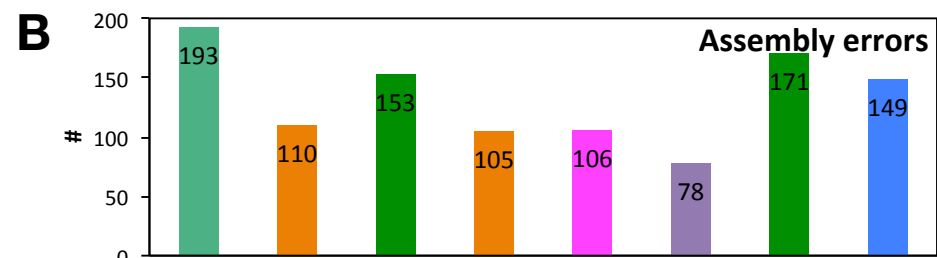
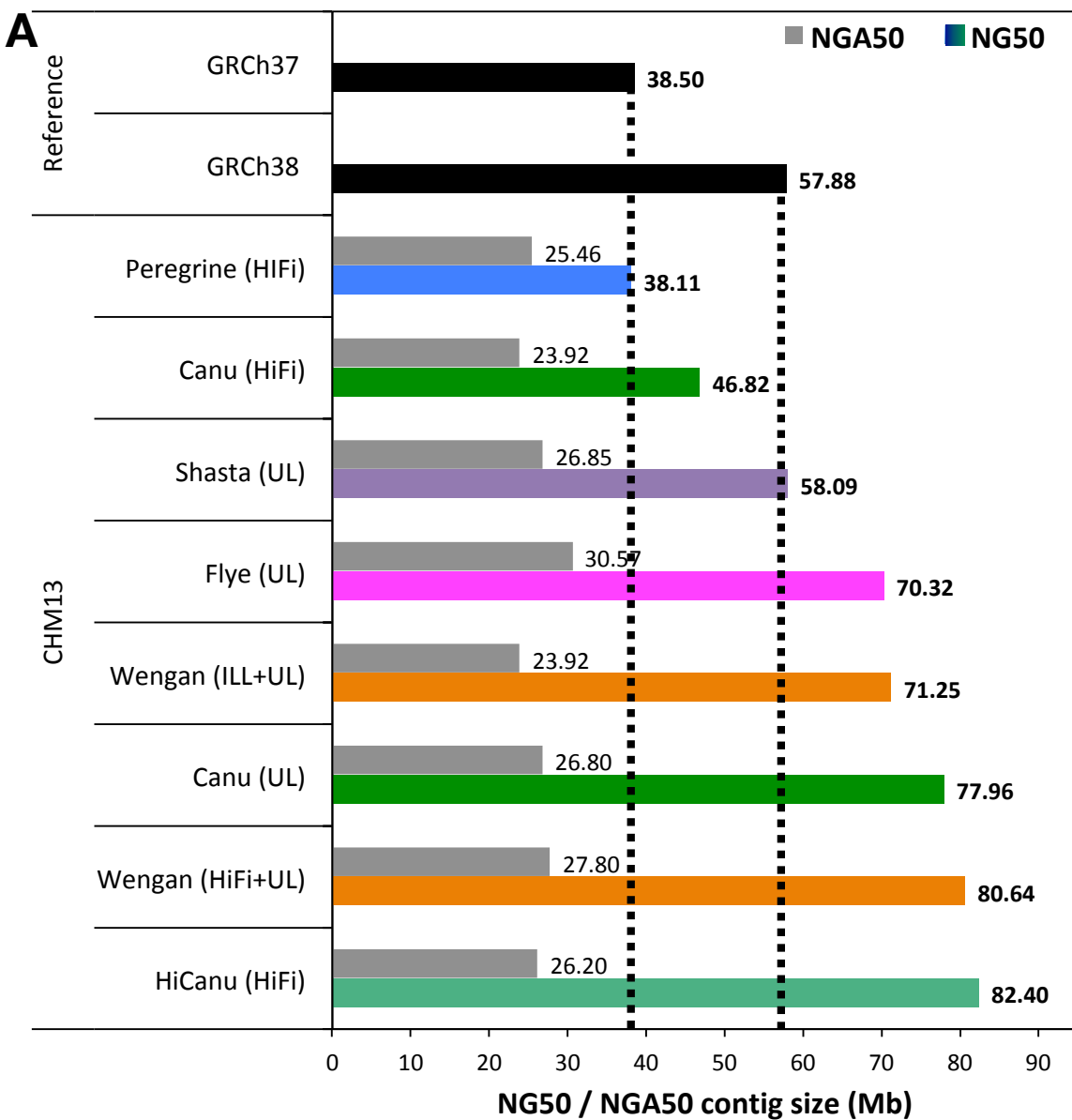
758 **Code availability**

759 The WENGAN code (version 0.2) used in this manuscript is freely available at
760 <https://github.com/adigenova/wengan> and is distributed under the MIT open source license.

761 **Methods-only references**

40. Chikhi, R., Limasset, A. & Medvedev, P. Compacting de Bruijn graphs from sequencing data quickly and in low memory. *Bioinformatics* **32**, i201–i208 (2016).
41. Li, H. Minimap2: pairwise alignment for nucleotide sequences. *Bioinformatics* **34**, 3094–3100 (2018).
42. Galil, Z., Micali, S. & Gabow, H. An $O(EV \log V)$ Algorithm for Finding a Maximal Weighted Matching in General Graphs. *SIAM J. Comput.* **15**, 120–130 (1986).
43. Dezsó, B., Jüttner, A. & Kovács, P. LEMON - an Open Source C++ Graph Template Library. *Electronic Notes in Theoretical Computer Science* **264**, 23–45 (2011).
44. Kokot, M., Dlugosz, M. & Deorowicz, S. KMC 3: counting and manipulating k-mer statistics. *Bioinformatics (Oxford, England)* **33**, 2759–2761 (2017).
45. Simão, F. A., Waterhouse, R. M., Ioannidis, P., Kriventseva, E. V. & Zdobnov, E. M. BUSCO: assessing genome assembly and annotation completeness with single-copy orthologs. *Bioinformatics* **31**, 3210–3212 (2015).

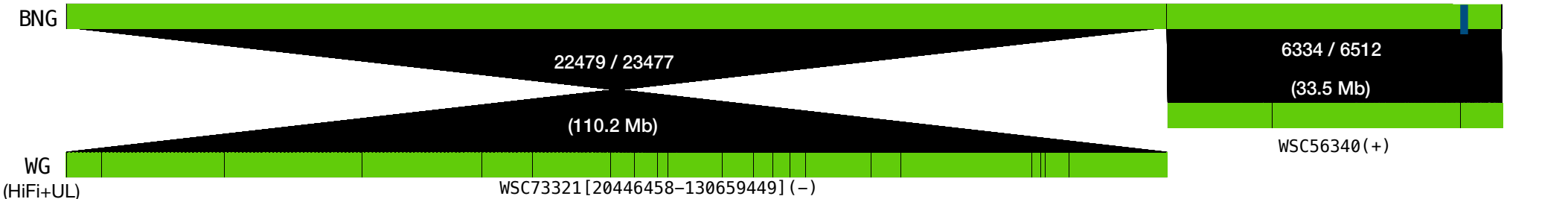




Super-Scaffold_2896

Wengan (HiFi + UL)

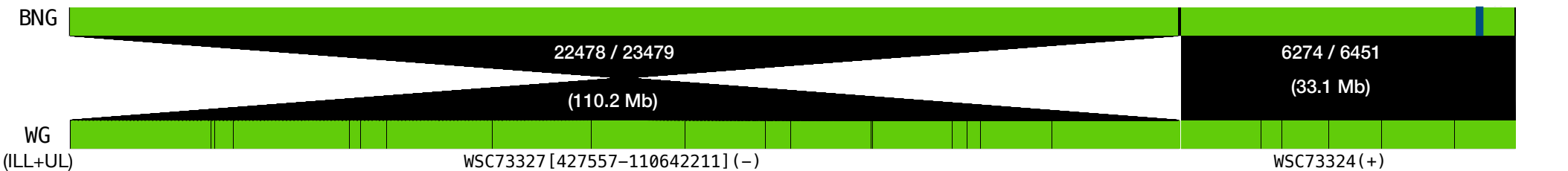
0 9.5 19.1 28.7 38.3 47.9 57.4 67.0 76.6 86.2 95.8 105.3 114.9 124.5 134.1 143.7 Mb

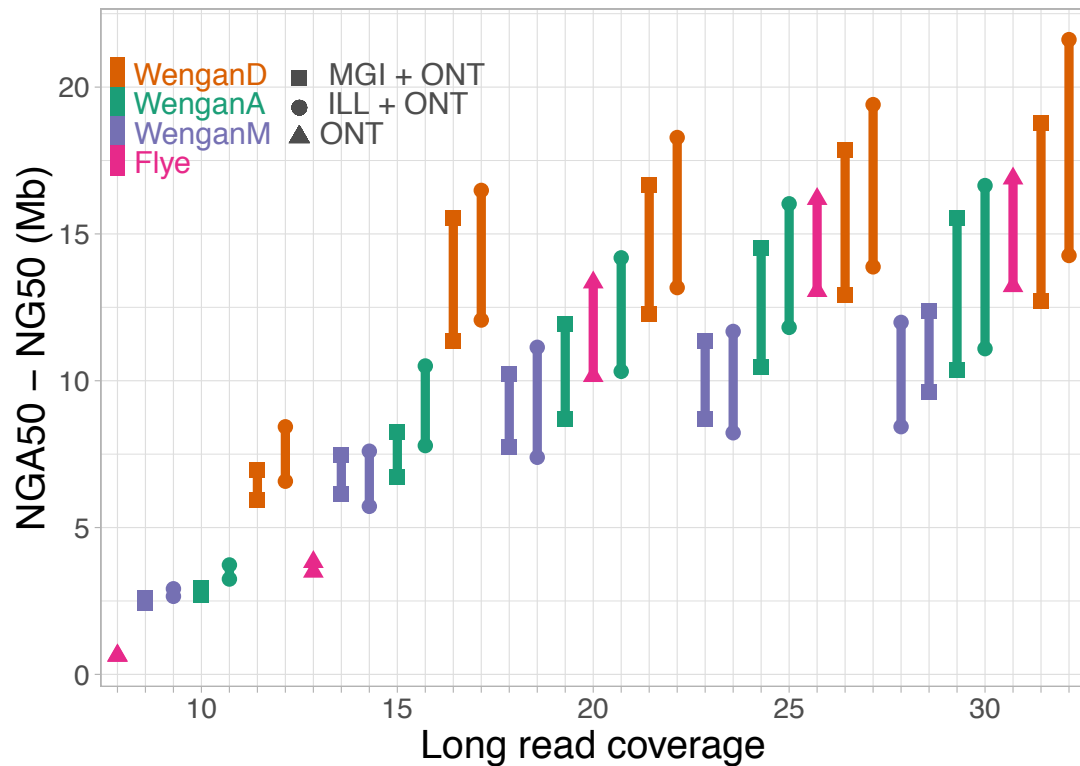


Super-Scaffold_1631

Wengan (ILL + UL)

0 9.5 19.1 28.7 38.3 47.9 57.4 67.0 76.6 86.2 95.8 105.3 114.9 124.5 134.1 143.7 Mb



A**C****B**