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1 **Engineered toxin-intein antimicrobials can selectively target and**  
2 **kill antibiotic-resistant bacteria in mixed populations**

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21 **Targeted killing of pathogenic bacteria without harming beneficial members of host**  
22 **microbiota holds promise as a strategy to cure disease, and limit both antimicrobial-**  
23 **related dysbiosis and development of antimicrobial resistance. We engineer toxins**  
24 **that are split by inteins and deliver them by conjugation into a mixed population of**  
25 **bacteria. Our toxin-intein antimicrobial is only activated in bacteria that harbor**  
26 **specific transcription factors. We apply our antimicrobial to specifically target and kill**  
27 **antibiotic resistant *Vibrio cholerae* in complex populations gathering various bacterial**  
28 **species. We found that 100% of antibiotic resistant *V. cholerae* receiving the plasmid**  
29 **were killed. Escape mutants were extremely rare (10<sup>-6</sup>-10<sup>-8</sup>). We demonstrate that**  
30 **conjugation and specific killing of targeted bacteria is functional in the microbiota of**  
31 **zebrafish and crustacean larvae, which are natural hosts for *Vibrio* spp. Toxins split**  
32 **with inteins could form the basis of a range of precision antimicrobials which would**  
33 **kill both Gram – and Gram + pathogens.**

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36 With the advent of the antibiotic era, infectious diseases were thought to be under  
37 control, but worldwide emergence of antibiotic-resistant bacteria has occurred, owing to the  
38 widespread unchecked use of antibiotics. Further, it is now estimated that antibiotic resistant

39 bacteria could be the main cause of death by 2050<sup>1</sup> unless new classes of antimicrobials are  
40 developed.

41 Broad spectrum antimicrobials indiscriminately kill bacteria which can result in  
42 microbiota dysbiosis and concomitant health sequelae. Moreover, antibiotic that have non-  
43 specific targets can select for antibiotic resistance, which is mainly acquired by horizontal  
44 gene transfer among bacteria in communities<sup>2</sup>. Alternatives to broad spectrum antibiotics  
45 include bacteriocins, which kill a subset of bacterial species or strains, and will not provoke a  
46 superinfection<sup>3</sup>. Other targeted antimicrobials have also been reported, including CRISPR-  
47 Cas antimicrobials<sup>4-6</sup>, phage therapy<sup>7</sup> and local release of toxins<sup>8</sup>.

48 We set out to design antimicrobials to specifically kill antibiotic-resistant *Vibrio*  
49 *cholerae*. To mediate bacterial killing we chose the toxin component of type II bacterial toxin-  
50 antitoxin (TA) systems, which are involved in stabilization of plasmids, prophages and  
51 superintegrans<sup>9</sup>. Type II toxin and antitoxins are proteins<sup>9</sup>. The toxin targets conserved  
52 bacterial cellular functions which reduces the potential for development of resistance. Each  
53 antitoxin is highly specific for the cognate toxin, and nonspecific toxin-antitoxin interactions  
54 are counterselected<sup>10</sup>. Our antimicrobial design relies on the regulation of type II TA  
55 transcription by highly specific transcription factors (TF). This means that activation of the  
56 toxin, and concomitant killing, of individual members of mixed bacterial populations is  
57 feasible if a targeted bacterial species expresses the Type II toxin-regulating transcription

58 factor. We validated our approach by showing that we could selectively kill antibiotic-  
59 resistant *V. cholerae* present in mixed populations.

60 *V. cholerae* causes between 21 000 and 143 000 deaths from cholera per year<sup>11</sup>.

61 The most recent cholera pandemics involved the O1 and O139 serogroups. Virulence in *V.*  
62 *cholerae* is coordinated by the master transcriptional activator ToxR, which regulates the  
63 ToxR regulon<sup>12</sup>, which includes the cholera toxin genes. Cholera epidemics are associated  
64 with antibiotic resistance owing to resistance genes present on an integrative and  
65 conjugative element (ICE) named SXT (from sulfamethoxazole and trimethoprim resistance).  
66 SXT can carry genes that confer resistance to sulfamethoxazole (*sul2*), trimethoprim (*dfrA1*  
67 and *dfr18*), streptomycin (*strB*), chloramphenicol (*floR*) and tetracycline (*tetA*) and was first  
68 described in *V. cholerae* serogroup O139<sup>13</sup>. SXT also encodes functions promoting its  
69 excision, dissemination by conjugation, and integration, as well as the transcription factors  
70 that control expression of these functions<sup>13</sup>.

71 Our previous experience with type II toxins<sup>14,15</sup> taught us that basal expression of a  
72 full-length toxin gene from P<sub>BAD</sub> is sufficient to kill the *E. coli* host. To avoid this, we  
73 designed a genetic module containing a toxin split by an intein, and in our module the split  
74 toxin-intein can only be activated by ToxR. Inteins are protein sequences embedded into a  
75 host protein (extein) from which they are autocatalytically excised in a process called protein  
76 splicing. During protein splicing the intein ligates the extein extremities and allows the

77 reconstitution of the mature protein. In nature, a few examples of split inteins also exist  
78 allowing the assembly of a single protein from two genes<sup>16</sup>. We split the type II toxin gene  
79 *ccdB* (Plasmid pToxInt, Supplementary Fig. 1) into two parts, each of which is associated  
80 with half of a split intein. Split inteins have been used in several biotechnological tools<sup>17</sup> and  
81 enable control of toxic protein functions *in vivo*<sup>18</sup>. We used the split intein DnaE, which is  
82 present in the *dnaE* gene of *Nostoc punctiforme*. DnaE is well characterized and has a high  
83 rate of trans-splicing<sup>19</sup>. Using inteins enables strict control of toxin production, and avoids  
84 toxicity due to basal expression<sup>14,15</sup> (Supplementary Fig. 1).

85         First, we cloned full –length gyrase inhibiting toxin CcdB from *Vibrio fischeri*<sup>15</sup> into a  
86 plasmid (pTOX Supplementary Table 1) and transformed the toxin construct into a *E. coli*  
87 XL2 blue (Supplementary Table 1) that constitutively expresses a genomic copy of the  
88 cognate antitoxin (data not shown). We showed that *ccdB* was bactericidal (Supplementary  
89 Fig. 2) and that the intein-mediated splitting strategy led to more stable retention of the toxin-  
90 harboring plasmid under repression conditions compared with a construct harboring a whole  
91 *ccdB* toxin gene (Supplementary Fig. 1). We also evaluated whether three other type II  
92 toxins belonging to different toxin families (ParE2, HigB2 and RelE4<sup>14</sup>) could tolerate a  
93 splitting and stay functional, We selected intein insertion points by inspection of 3D structure  
94 predictions for toxins made in Phyre2<sup>20</sup>, a tool for modeling protein structure (Supplementary  
95 Fig. 3a). Each toxin was divided into N- and C-terminal portions (Supplementary Fig. 3b)

96 which were fused in-frame to the N- or C-parts of the split intein *dnaE* gene (102 and 36  
97 amino acids long), respectively. N- and C-terminal toxin-intein fusions were cloned in  
98 separate, compatible plasmids (N or C plasmids, respectively Supplementary Table 1) and  
99 were under the control of different promoters (Fig. 1a). We validated reconstitution of the  
100 active toxin by intein protein splicing in *E. coli* (Supplementary Fig. 4). For all five tested split  
101 toxins, we found that under inducing conditions bacteria containing N and C plasmids died,  
102 whereas bacteria with either the N or the C plasmid survived. N and C toxin-intein complex  
103 toxicity was tested using mutations known to prevent splicing. When splicing didn't occur,  
104 reconstitution of the toxin did not take place, and bacteria survived (Supplementary Fig. 4).

105         Next we chose the gyrase poison CcdB, which is likely the most extensively  
106 characterized type II toxin, to design a toxin-intein antimicrobial specific for pathogenic *V.*  
107 *cholerae*. In *V. cholerae* one of the ToxRS-regulated genes encodes a membrane porin,  
108 OmpU<sup>21</sup>. We cloned the N fusion of CcdB-intein downstream of the *ompU* promoter  
109 (regulated by ToxRS), and the C fusion under P<sub>BAD</sub> in the same plasmid (pU-BAD,  
110 Supplementary Fig. 5a). The functionality of pU-BAD was tested in an *E. coli* DH5α strain  
111 expressing the *V. cholerae* *toxRS* operon from a second plasmid (pRS, Supplementary Fig.  
112 5a). Upon arabinose-mediated induction of *toxRS* expression, only bacteria containing both  
113 pU-BAD and pRS plasmids died (Supplementary Fig. 5b). We replicated cell killing in  
114 MG1655 (data not shown). We then tested pU-BAD activity in pathogenic *V. cholerae* strains

115 O1 and O139 (Supplementary Fig. 6a). We observed constitutive expression of the N-fusion  
116 due to the presence of chromosomal *toxRS*. However, toxicity due to basal expression from  
117 P<sub>BAD</sub> (Supplementary Fig. 6a) led to pU-BAD plasmid instability in *V. cholerae*. A *V. cholerae*  
118 mutant lacking *toxRS* ( $\Delta toxRS$ ) displayed normal growth and pU-BAD stability in the  
119 presence of arabinose (Supplementary Fig. 6a). This suggested that P<sub>ompU</sub> could be used to  
120 regulate CcdB-intein fusion expression for targeted killing of *V. cholerae*.

121 In order to develop a conjugative CcdB-intein-based antimicrobial to specifically kill  
122 pathogenic *V. cholerae* in microbial communities, we cloned a split-toxin-intein operon under  
123 the control of *ompU* promoter in a plasmid, and added an origin of transfer (*oriT*) to render it  
124 conjugative (plasmid pPW, Supplementary Fig. 6b, Supplementary Table 1). Conjugation is  
125 carried out from donor strain *E. coli*  $\beta$ 3914, an MG1655  $\Delta dapA$  which contains the RP4  
126 conjugative machinery integrated into its chromosome. pPW was introduced by conjugation  
127 into *V. cholerae* strains O1, O139 and an O1- $\Delta toxRS$  mutant (Supplementary Fig. 6b), but  
128 only the  $\Delta toxRS$  strain was able to grow after transfer of the pPW plasmid, demonstrating  
129 that it kills only *Vibrio* expressing ToxR.

130 We next tested whether pPW could kill specific strains in a mixed bacterial population  
131 (Fig. 1b). Different recipient bacteria in this population could be distinguished in the  
132 presence of X-gal: *V. cholerae* O139 (blue) and *E. coli* DH5 $\alpha$  (white) (Fig. 1c). We  
133 conjugated pPW and two control plasmids (non-toxic N fusion containing pN<sub>ctrl</sub> plasmid, and



134 the pTox<sub>ctrl</sub> plasmid, which carries the P<sub>BAD</sub>-regulated toxin-intein operon) into this mixture.  
135 After conjugation of pPW from *E. coli* β3914 and selection for transconjugants, pPW killed *V.*  
136 *cholerae* O139 (blue bacteria) and we were only able to detect *E. coli* DH5α transconjugants  
137 (white) on media containing XGal. Similarly, after plasmid conjugation into *V. cholerae* O1  
138 and *E. coli* strains (MG1655), we only obtained *E. coli* transconjugants (Supplementary Fig.  
139 7a).

140         Specific killing by pPW relies on expression of the regulator *toxR*, which is present in  
141 all *Vibrio* genera<sup>22</sup>. However, the ToxR regulon has evolutionarily diverged among the  
142 different *Vibrio* species, so we analyzed pPW action in two other *toxRS*-containing *Vibrio*  
143 species (Fig. 1d). We found that pPW can kill *Vibrio mimicus* but not *Vibrio vulnificus*, which  
144 is more phylogenetically distant from *V. cholerae*, and despite harboring a ToxR ortholog,  
145 does not activate *ompU* expression<sup>23</sup>. Additionally, we showed that our system is highly  
146 specific to ToxR, since conjugation into other γ-proteobacteria, such as *Salmonella*  
147 *typhimurium* and *Citrobacter rodentium*, did not result in killing (Supplementary Fig. 7b).

148         Next we evaluated whether a split-intein toxin could kill antibiotic resistant bacteria  
149 present in a community. The SXT ICE family in *V. cholerae* includes various antibiotic  
150 resistance genes<sup>13</sup>. The SXT chassis encodes several TFs that regulate SXT transmission  
151 including the SetR repressor<sup>13</sup>. We designed a module to detect SXT carriage and kill SXT-  
152 harboring bacteria by implementing an additional component into our antimicrobial: the *ccdA*

153 gene, which encodes the antitoxin partner of CcdB. *ccdA* was cloned downstream of the  
154 SXT PL promoter, which is controlled by the SetR repressor, in a plasmid also containing the  
155 *ccdB*-intein operon regulated by the P<sub>BAD</sub> promoter (pPLA plasmid, Supplementary Fig. 8a,  
156 Supplementary Table 1). We tested whether pPLA could kill antibiotic resistant *E. coli* SXT  
157 (Supplementary Fig. 8b) and *V. cholerae* O139 (Fig. 2a). Both bacteria contain an SXT  
158 element integrated at *prfC*. Only SXT carrying bacteria from both species were killed. All  
159 bacteria lacking SXT, including *V. cholerae* O1 and *E. coli* DH5 $\alpha$ , survived (Fig. 3a and  
160 Supplementary Fig. 8b). In order to develop a conjugative antimicrobial to kill antibiotic  
161 resistant bacteria we added an *oriT* to pPLA to produce pABRW (Supplementary Table 1,  
162 Fig. 2). pABRW was tested by conjugation into a mixed population of *E. coli* MG1655 (blue)  
163 and *E. coli* SXT (white). Selection for pABRW yielded only *E. coli* MG1655 transconjugants,  
164 demonstrating that pABRW specifically kills bacteria containing SXT (Fig. 2b). The same  
165 result was obtained after conjugation of pABRW into *V. cholerae* O139 mixed with *V.*  
166 *cholerae* O1- $\Delta$ *lacZ* (Fig. 2c), confirming that pABRW plasmid specifically kills ABR bacteria  
167 in a heterogeneous population.

168 We next combined the pPW and pABRW modules in a single plasmid. We replaced  
169 the operator sequence O4 of PL with O1 (see online Methods) to increase SetR repression  
170 to yield pFW (Supplementary Table 1, Fig. 3), which efficiently kills *V. cholerae* O139 (Fig.  
171 3c). In order to test whether non-replicative-conjugative plasmids (which would not spread

172 toxin-intein fusions and/or antibiotic resistant genes) could harbor our killing module, we  
173 changed the pSC101 replication origin to a *pir*-dependent R6K origin (Supplementary Fig.  
174 9). R6K origin can be activated in a host expressing an ectopic *pir* gene in the chromosome.  
175 After conjugation of pPW-R6K and pFW-R6K into bacteria that lack the *pir* gene, CFU/ml  
176 were reduced by 60% compared with controls (Supplementary Fig. 9b). This suggests that  
177 even if the plasmid cannot actively replicate once transferred in the targeted bacteria,  
178 expression of the toxin is sufficient to kill these bacteria, while the use of such R6K  
179 derivatives is limiting the risk of unnecessary propagation of the killing plasmid.

180         We moved onto evaluate whether our split-intein toxin could target specific bacteria  
181 in natural microbiomes. We tested killing of *V. cholerae* O139 in three niches, each of which  
182 is a natural habitat for this pathogen<sup>24</sup>: water, tropical zebrafish and a crustacean. We first  
183 tested the versatility of *E. coli*  $\beta$ 3914 which is auxotrophic for the diaminopimelic acid (DAP)  
184 for delivering conjugative plasmid pNctrl, in absence of DAP and found no difference in  
185 conjugation rates (Supplementary Table 2). Although conjugation efficiency decreases 300  
186 fold in water, *V. cholerae* transconjugants were obtained with the control plasmid pN<sub>ctrl</sub>  
187 (Supplementary Table 2), while using pFW, no transconjugants were detected (data not  
188 shown). These results indicate that in these conditions too when receiving the pFW, *V.*  
189 *cholerae* was killed. These preliminary data suggest that our method using pFW might hold  
190 potential in bioremediation of *Vibrio*-contaminated water.

191 We also tested pNctrl and pFW using a zebrafish infection model<sup>25</sup> (Supplementary  
192 Fig. 10a). Analysis of the microbiota composition using 16S rRNA analysis on 4 days post  
193 fertilization zebrafish larvae detected less than 30 different bacterial species, mostly aerobic  
194 including several *Aeromonads*, *Pseudomonads* and *Stenotrophimonads* (JBB and JMG,  
195 unpublished). First we tested localization of both *E. coli* and *V. cholerae*, in the gut of  
196 zebrafish larvae. We infected four-day-post-fertilization zebrafish larvae with fluorescently  
197 tagged *V. cholerae* O1-GFP and *E. coli*-RFP. Fluorescence microscopy revealed co-  
198 localization of both *V. cholerae* O1-GFP and *E. coli*-RFP in the digestive tract  
199 (Supplementary Fig. 10a). We then tested specific killing in larvae infected with *V. cholerae*  
200 O139 (Fig. 4a, Supplementary Fig. 11b,c). The only *V. cholerae* O139 transconjugants  
201 obtained were from conjugation with pN<sub>ctrl</sub> plasmid. No *V. cholerae* O139 transconjugants  
202 were obtained using pFW. Therefore, pFW kills *V. cholerae* O139 in zebrafish larvae (Fig. 4a  
203 and Supplementary Fig. 11b). We assessed dysbiosis using observation after plating on  
204 different media and didn't find any macroscopic change (Supplementary Fig. 11a). We also  
205 used a mixture of 1:1 *V. cholerae* O1 and O139 for larval infection and then infected with *E.*  
206 *coli*  $\beta$ 3914 (pNctrl) or  $\beta$ 3914 (pFW). We detected pN<sub>ctrl</sub> transconjugants in both O1 and O139  
207 serogroups, but O1 transconjugants only were obtained after conjugation with pFW (Fig. 4a  
208 and Supplementary Fig. 11c). Therefore pFW specifically killed the O139 serogroup.

209 We also tested pFW in the crustacean *Artemia salina* model which is used for fish  
210 feeding and commonly found to carry various *Vibrio* species<sup>26</sup> (Fig. 4b and Supplementary  
211 Figs. 10b, 12). We detected co-localization of *V. cholerae* O1-GFP and *E. coli*-RFP in the  
212 gut of *A. salina* (Supplementary Fig. 10b) and conjugation with pFW plasmid did not provoke  
213 visible change in the *A. salina* microbiota, after sampling of the aerobic species on plates  
214 (data not shown). Transconjugants of *V. cholerae* O139 were only detected after  
215 conjugation with pN<sub>ctrl</sub>, but not with pFW, showing that pFW kills *V. cholerae* O139 in *A.*  
216 *salina* larvae (Fig. 4b and Supplementary Fig. 12a). We also infected *A. salina* with a 1:1 mix  
217 of *V. cholerae* O1 and O139 and detected pN<sub>ctrl</sub> transconjugants in O1 and O139  
218 serogroups, but only detected O1 pFW transconjugants (Fig. 4b and Supplementary Fig.  
219 12b).

220 Our split toxin-intein method can be applied to specifically kill selected bacteria  
221 subtypes. We anticipate that our system could be fine-tuned to trigger toxin activation in  
222 response to various environmental cues<sup>27</sup> including temperature, salt or pH by adding a  
223 conditional protein splicing intein<sup>28</sup>. Inteins are functional in eukaryotic cells<sup>29</sup>, so toxin-intein  
224 combinations might also be developed for targeted killing of tumor cells. The specificity of  
225 our system requires identification of a species-specific transcriptional regulator, and such  
226 TFs are widespread in pathogenic and antibiotic-resistant bacterial pathogens<sup>30-31</sup>. The  
227 Achilles' heel of precision antimicrobials is delivery into complex communities. Antimicrobials

228 delivered by conjugation e.g. RNA-guided nucleases<sup>5</sup> have reduced targeted bacterial  
229 populations by 2- to 3-log even with a ratio of donor:recipient bacteria of 340:1<sup>5</sup>. In our  
230 experiments, using 1:1 ratios were detected a decrease in targeted bacteria (*V. cholerae*) of  
231 10%, which is equivalent to the conjugation rate. We were able to kill  $\approx$  90-95% of the ABR  
232 *E. coli* after the conjugation of pABRW by increasing ratios of donor to recipient to 10:1  
233 (Supplementary Fig. 13). Phage delivery might be useful<sup>5</sup>, but phage have other  
234 disadvantages<sup>32</sup>, including narrow host range and rapid emergence of phage resistance.  
235 One advantage of our system compared with others<sup>4,5,33</sup> is that escape mutants are less  
236 frequent (below  $10^{-6}$  -  $10^{-8}$ ; Supplementary Table 3). Analysis of escape clones  
237 (Supplementary Table 4), when targeting ABR bacteria revealed that between 63 and 90%  
238 of these clones had lost the SXT element, and were not ABR (Supplementary Table 5). One  
239 of the reasons for the lower chance of escape might be that toxin resistance has not been  
240 observed. A different synthetic kill switch based on TA systems was also stable due to  
241 minimal escape rates *in vivo*<sup>34</sup>. The dual regulatory system in the Final Weapon (Fig. 3a)  
242 functions as an AND-logic gate, increasing effectiveness in the control of toxin production,  
243 which only happens when both inputs (pathogenicity and ABR) are present. If delivery of  
244 mobilizable antimicrobials can be optimized, appearance of resistant bacteria would be rare.  
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333

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352

353 **AUTHOR CONTRIBUTIONS**

354 D.M. and R.L.-I designed the experiments. J.B.-B and R.L.-I designed and performed the *in*  
355 *vivo* experiments. J.B.-B. performed the microscopy experiments and statistic analysis.

356 D.M., R.L.-I and A.R.-P participated in the conception of the project. R.L.-I and D.M.

357 prepared the manuscript and wrote the article with large participation of J.B.-B, J.-M.G. and

358 A.R.-P.

359

360 **COMPETING FINANCIAL INTERESTS**

361 The authors declare no competing financial interests.

362

363 **DATA AVAILABILITY STATEMENT**

364 The data, plasmids and strains generated for this study, that support our findings are

365 available upon request to the corresponding author.

366

367 **Figure Legends:**

368 **Figure 1. Specific killing of pathogenic *V. cholerae* in mixed population of**  
369 **bacteria mediated by toxin-intein strategy.** (a) Schematic representation of the  
370 active toxin production from plasmids encoding split toxin (red) combined with split  
371 intein (blue) inside a bacterium. The first half of the toxin is fused with N-terminal split  
372 intein gene (N plasmid) under the control of  $P_{BAD}$  promoter and the second half of the  
373 toxin is fused with the C-terminal intein gene (C plasmid) and it is controlled by  $P_{LAC}$ .  
374 Expression of these fusions is activated by the addition of arabinose and IPTG,  
375 respectively. Recognition of the protein fusions takes place by the intein module,  
376 which carry out the splicing process, which lead to toxin reconstitution, provoking cell  
377 death. (b) Mode of action of the genetic weapon spreading through conjugation in  
378 mixed population of bacteria and killing of targeted harmful bacteria. (c) Mixed  
379 population of *V. cholerae* O139 (blue) and *E. coli* DH5 $\alpha$  (white) as recipients for  
380 conjugation using  $\beta$ 3914 as donor strain containing  $pN_{ctrl}$ ,  $pTox_{ctrl}$  or  $pPW$  plasmids.  
381 The *ompU* promoter activated specifically by ToxRS from *V. cholerae* is represented  
382 by a circled (+) pink-symbol. Transconjugants were selected in MH + Spectinomycin  
383 (Sp), X-gal for color development and arabinose for induction of  $P_{BAD}$ . (d)  
384 Conjugation of  $pN_{ctrl}$ ,  $pTox_{ctrl}$  and  $pPW$  plasmid using  $\beta$ 3914 as donor strain in *Vibrio*  
385 *mimicus* and *Vibrio vulnificus*. Transconjugants were selected in MH media + Sp and  
386 arabinose for induction of  $P_{BAD}$ . Pictures are representative of three independent  
387 experiments.

388

389

390 **Figure 2. Specific killing of antibiotic resistant bacteria (containing SXT).** (a)

391  $pPLA$  plasmid that contains CcdB-intein fusion operon under  $P_{BAD}$  control expression

392 and *ccdA* antitoxin under PL promoter (symbolized by an orange circled -) which is  
393 repressed by SetR. Growth test of *V. cholerae* O1 or O139 containing pPLA plasmid  
394 in MH media + Sp and supplemented with glucose (GLU) or arabinose (ARA). (b)  
395 Mixed population of *E. coli* MG1655 (blue) and *E. coli* SXT (white) as recipients for  
396 conjugation using  $\beta$ 3914 as donor strain containing pN<sub>ctrl</sub>, pTox<sub>ctrl</sub> or pABRW  
397 plasmids. Transconjugants were selected on MH + Sp, X-gal for species  
398 identification and arabinose for induction of P<sub>BAD</sub>. (c) Mixed population of *V. cholerae*  
399 O139-SXT (blue) and *V. cholerae* O1 (white) as recipients for conjugation using  
400  $\beta$ 3914 as donor strain containing pN<sub>ctrl</sub>, pTox<sub>ctrl</sub> or pABRW plasmids as described in  
401 b). Pictures are representative of three independent experiments.

402

403

404 **Figure 3. Design, tuning and assay of the final weapon pFW, obtained by**  
405 **putting together the pathogenicity and antibiotic resistance (ABR) modules in**  
406 **a single conjugative vector.** (a) Schematic representation of the specific killing of  
407 *V. cholerae* O139 after pFW conjugation (left). Schematic display of the  
408 corresponding AND-logic gate (right). (b) Conjugation from  $\beta$ 3914 of either pN<sub>ctrl</sub> or  
409 pFW, of *V. cholerae* serogroup O139 (blue) and O1 (white) as recipient mixed  
410 population. Transconjugants were selected on MH + Sp (plasmid marker). pFW  
411 plasmid was obtained after change in RBS sequence of *ompU* promoter to increase  
412 translation of toxin-intein fusion and substitution of the O4 operator sequence by O1  
413 operator sequence (see online methods) to increase SetR binding affinity to the PL  
414 promoter, and consequently increase repression. Only *V. cholerae* serogroup O1  
415 that is devoid of SXT in its genome was detected after pFW conjugation,  
416 demonstrating the specific killing of serogroup O139, which contain both  
417 chromosomally encoded ToxR and SetR the chosen indicators of pathogenicity and

418 antibiotic resistance, respectively. Pictures are representative from three  
419 independent experiments.

420

421

422 **Figure 4. Specific killing of pathogenic and ABR *V. cholerae* O139 in the**  
423 **zebrafish larvae and *Artemia salina* nauplii models.** (a) Four-day-postfertilization  
424 zebrafish larvae were exposed to water containing  $10^4$  CFU/ml *V. cholerae* O139 or  
425 a mixed population containing  $10^5$  CFU/ml *V. cholerae* O139 + *V. cholerae* O1, and  
426 then infected (see methods) with  $10^7$  (O139) or  $10^6$  (mix *Vibrio*) CFU/ml of  $\beta$ 3914 as  
427 donor strain of either pN<sub>ctrl</sub> or pFW plasmids. Five larvae were fished and mashed to  
428 analyze its microbiota. Transconjugants were selected in MH media with Sp and X-  
429 gal. Transconjugants were only detected after conjugation with pN<sub>ctrl</sub> plasmid for  
430 O139 and not after pFW conjugation as expected from the specific killing. Confirming  
431 pFW specificity, pFW transconjugants were detected for *V. cholerae* O1, which should  
432 not be killed by this plasmid. Data for O139 represent transconjugants obtained from  
433 15 larvae fished in three independent experiments (n=3, mean  $\pm$  s.d), and data from  
434 the mix of *Vibrio* represent transconjugants obtained from 10 larvae in two  
435 independent experiments (n=2, mean  $\pm$  s.d). (b) *Artemia salina* stage nauplii were  
436 infected with  $10^7$  CFU/ml *V. cholerae* O139 or a mix of  $10^7$  CFU/ml *V. cholerae* O139  
437 + *V. cholerae* O1 (see methods). Then exposed to  $10^7$  CFU/ml  $\beta$ 3914 as donor strain  
438 of either pN<sub>ctrl</sub> or pFW plasmids. Transconjugants were selected in MH media with  
439 Sp and X-gal. As in zebrafish, transconjugants were only detected after conjugation  
440 with pN<sub>ctrl</sub> plasmid for O139 and not after pFW conjugation. As expected, *V.*  
441 *cholerae* O1 pFW transconjugants were also detected in this in vivo model. Data  
442 numbers were calculated from four independent experiments (n=4, mean  $\pm$  s.d).

443



## 1 ONLINE METHODS

2

### 3 **Strains and culture conditions.**

4 Unless otherwise noted, bacterial cultures were grown at 37°C with Luria-Bertani (LB)  
5 medium (Lennox) or Mueller-Hinton (MH) solid media supplemented when appropriate,  
6 with the following antibiotics: 50 µg/ml kanamycin (Kan), 50 µg/ml chloramphenicol  
7 (Cm), 100 µg/ml carbenicillin (Carb), 50 or 100 µg/ml spectinomycin (Sp) for *E. coli* and  
8 100 µg/ml Sp for *Vibrio cholerae*. Selection of transconjugants was carried using 100  
9 µg/ml Sp in all cases, except for *V. mimicus* and *V. vulnificus* where we used 50 µg/ml  
10 Sp. Bacterial strains used in this study are listed in Supplementary Table 1. Other  
11 molecules were added to the media with the following concentrations: 40 µg/ml 5-  
12 bromo-4-chloro-3-indolyl-beta-D-galactopyranoside (Xgal), 0.3 mM Diaminopimelic acid  
13 (DAP), 1% glucose and 0,2% arabinose.

14

### 15 **Plasmid construction.**

16 Plasmids are listed in Supplementary Table 1 and primers in Supplementary Table 6.  
17 All plasmid sequences were verified through sequencing.  
18 To generate the N and C plasmids for each toxin-intein fusion, the N- and C-terminal  
19 toxin regions were amplified with primers F-toxin-EcoRI/R-toxin-intein and F-toxin-  
20 intein/R-toxin-Xbal, respectively. N-and C-terminal intein regions were amplified with  
21 primers F-intein-toxin/R-intein-Xbal and F-intein-EcoRI/R-intein-toxin, respectively. As  
22 DNA templates for toxins we used chromosomal DNA from *V. cholerae* in all cases and  
23 *V. fischeri* for *ccdB*. Intein amplification was done with chromosomal DNA from the  
24 cyanobacteria *Nostoc punctiforme*. PCR products of N- and C-terminal regions were  
25 fused by Gibson assembly<sup>35</sup>. Each toxin-intein fusion was then digested with  
26 EcoRI/Xbal (Thermo Fisher) and then cloned in EcoRI/Xbal digested pBAD43<sup>36</sup> and  
27 pSU38<sup>37</sup> (or pSU18) plasmids, respectively (Supplementary Table 1). To generate the

28 mutated version of N-terminal plasmid (n\*) whole plasmids were amplified using  
29 primers F-Int-tox-mut/R-int-tox-mut.

30 To assemble the pU-BAD plasmid (Supplementary Fig. 5) we first cloned the C-  
31 terminal CcdB-Npu fusion into a pBAD18 plasmid (EcoRI-XbaI). An *ompU* promoter  
32 was inserted upstream the N-terminal ccdB/Npu fusion in N plasmid by PCR. The  
33 *ompU* promoter region was amplified using F-PompU-1/R-PompU-dB (size=352 bp).  
34 This promoter was chosen based on previous work<sup>21</sup> that showed its high induction in  
35 the presence of ToxR. A region containing the pSC101 origin was amplified using R-  
36 BAD43-BAD18/F-4126 primers and the N-terminal CcdB-Npu plasmid as template. A  
37 second region containing the N-terminal fusion was amplified using 4217/R-BAD43-  
38 BAD18 primers and N-terminal plasmids also as templates. Other regions containing  
39 the C-terminal fusion and Kan resistance gene were amplified using R-BAD18-  
40 BAD43/F-BAD18-BAD43 primers and the C-terminal CcdB-Npu pBAD18 plasmid as  
41 template. PCR products were then fused by Gibson assembly<sup>35</sup> producing the pU-BAD  
42 plasmid.

43 To generate the pRS plasmid, (Supplementary Fig. 5) the *toxRS* operon from *V.*  
44 *cholerae* O1 was amplified using F-toxR-SacI/R-toxS-XbaI primers, digested with SacI  
45 and XbaI and ligated with SacI-XbaI digested plasmid pBAD30. The native RBS  
46 sequence of *toxR* was kept.

47 To assemble the toxin-intein N and C-terminal fusions as an operon (pToxInt plasmid),  
48 N- and C-fusions were amplified using F-CcdB-EcoRI/R-Int-N-Int-C and F-Int-C-Int-  
49 N/R-Int-XbaI primers and then ligated by Gibson assembly<sup>35</sup>, digested with EcoRI/XbaI  
50 and cloned into a pBAD43-EcoRI/XbaI digested plasmid. The fusion contains the  
51 following sequence: 5' TGATAAAGGAGGTAACATATG 3' between the N and C genes.  
52 This sequence contains the RBS sequence necessary for translation of the C-terminal  
53 fusion. The pTox plasmid was created by amplification of the *ccdB* toxin gene from *V.*  
54 *fischeri* DNA with F-CcdB-EcoRI/R-CcdB-XbaI primers, EcoRI/XbaI digestion and  
55 ligation into a pBAD43-EcoRI/XbaI digested plasmid. *E. coli* XL2blue strain that

56 contains F' plasmid integrated in the chromosome (containing the *ccdB/ccdA* TA  
57 system and conferring resistance to CcdB), was used to transform with this ligation in  
58 order to obtain positive clones.

59 To assemble the pPW genetic weapon, the *ompU* promoter was amplified as  
60 previously described and ligated by Gibson assembly<sup>35</sup> with the product of pToxInt  
61 plasmid PCR using F-dB-PompU/R-BAD-PU1 primers.

62 The pPLA plasmid was constructed first by amplifying by PCR the PL promoter<sup>38</sup> using  
63 DNA from *V. cholerae* O139 and F-PL-plasmid/R-PL-*ccdA* as primers. Then, the *ccdA*  
64 antitoxin gene was amplified using the F-*ccdA*-PL/R-*ccdA*-plasmid primers and *V.*  
65 *fischeri* DNA. Finally, the pTox-Int plasmid was also amplified using F-plasmid-dA/R-  
66 plasmid-PL primers. Ligation by Gibson assembly<sup>35</sup> of the three PCR products resulted  
67 in the pPLA plasmid.

68 Mobilizable genetic weapons were created by amplifying the origin of transfer *oriT* RP4  
69 using F-pSW23-BAD/R-oriT-BAD43 primers and the plasmid pSW23T<sup>39</sup> as template.  
70 Then, the *oriT* PCR product was ligated through Gibson assembly<sup>35</sup> with the amplified  
71 plasmid using F-BAD-pSW/R-BAD43-oriT primers and the weapon or control plasmids  
72 as template.

73 To assemble the Final Weapon we the plasmid pFW (Figure 3) as follow. The *ompU*  
74 promoter-1 was ligated into the pABRW plasmid as previously described for the pU-  
75 BAD construction. In order to fine-tune the RBS of *ompU* in this plasmid as well as the  
76 PL promoters,, PCRs were performed using F-*ccdB*-SD-OK/R-PU-SD-OK and F-PL-  
77 SD-T/R-PL-SD-T primer pairs, respectively. Finally, to generate the pFW plasmid, an  
78 operator O1 sequence (see <sup>38</sup>) was added into the PL promoter by PCR amplification of  
79 the pFW2 plasmid using F-PL-O1/R-PL-O1 primers.

80 To generate the pPW-R6K, pFW-R6K and pNctrl-R6K plasmids we first amplified the  
81 R6K replication origin using F-R6K-weapon/R-R6K-weapon primers and the pMP7<sup>40</sup>  
82 plasmid as template. Then, the pPW, pFW and pNctrl plasmids were amplified using F-

83 weapon-R6K/R-weapon-R6K primers. Finally, PCR fragments were ligated by Gibson  
84 assembly<sup>35</sup>.

85

#### 86 **$\Delta$ toxRS strain construction**

87 DNA regions 500 bp upstream and downstream of the *toxRS* operon were amplified  
88 using F-toxRup-p7/R-toxRups and F-toxSdow/R-toxSdow-p7, respectively. The  
89 amplified fragments were ligated by Gibson assembly<sup>35</sup> and then cloned into an R6K  $\gamma$ -  
90 *ori*-based suicide vector, pSW7848<sup>40</sup> that encodes the *ccdB* toxin gene under the  
91 control of an arabinose-inducible promoter, P<sub>BAD</sub>. For conjugal transfer of plasmids into  
92 *V. cholerae* strains, *E. coli*  $\beta$ 3914 was used as the donor. Clones where integration of  
93 the entire plasmid in the chromosome by single crossover occurred were selected.  
94 Elimination of the plasmid backbone resulting from a second recombination step was  
95 selected as described ref 39.

96

#### 97 **Transformation assays**

98 DH5 $\alpha$  chimiocompetent cells (Invitrogen) were transformed with 150 ng of pTox,  
99 pToxInt or pN plasmids (Supplementary Fig. 1a). Transformants were then tested in Sp  
100 containing media with glucose or arabinose to analyze toxin integrity. 10 to 12% of  
101 pTox-transformed clones from were able to grow in the presence of arabinose. Four  
102 independent clones were analyzed by sequencing and they all carried an insertion  
103 sequence in the *ccdB* toxin gene. These clones were responsible for pTox  
104 transformation rate decrease in comparison with the pToxInt and pN plasmids.

105 DH5 $\alpha$  cells (Invitrogen) were co-transformed with two plasmids simultaneously. Both  
106 plasmids were then simultaneously selected (Supplementary Fig.4).

107 Transformation of the donor strain  $\beta$ 3914 was performed in the presence of DAP.

108

#### 109 **Growth tests**

110 Eighteen independent clones from DH5 $\alpha$  transformation were inoculated in p96  
111 microplates containing LB media with Sp and glucose. The TECAN Infinite 200  
112 microplate reader (TECAN, Männedorf, Germany) was used to determine growth  
113 curves, with absorbance (620nm) taken at 6-minute intervals for a period of 12 h. The  
114 obtained OD values were plotted as seen on Supplementary Fig. 1b.

115 In Supplementary Fig. 2 for analysis of bactericide effect of CcdB toxin: *V. cholerae*  
116 O139 was co-transformed with antitoxin-*ccdA* (pBAD24-*ccdA*) and pPW plasmids in  
117 the presence of arabinose allowing the antitoxin to be expressed. pPW plasmid  
118 contains the toxin-intein under the control of *ompU* promoter, which is always active in  
119 *V. cholerae*. Bacteria culture supplemented with antibiotics for maintaining both  
120 plasmids and arabinose, were diluted at OD=0.5 (time 0h). Then bacteria were washed  
121 three times with MH media with antibiotics and glucose, in order to switch off antitoxin  
122 expression, and incubated for 4h at 37°C. Total bacteria were calculated by the CFU/ml  
123 at time 0h and 4h present in MH media with antibiotics and with glucose (1%) or  
124 arabinose (0,2%). Data numbers were calculated from four independent experiments  
125 (n=4).

126

### 127 **Conjugation assays.**

128 Overnight cultures of donor and recipient strains were diluted 1:100 in culture media  
129 with antibiotic and grown at 37°C for 2-3 hours. Then, cultures were diluted to an OD<sub>600</sub>  
130 = 0.5. The different conjugation experiments were performed by a filter mating  
131 procedure described previously<sup>41</sup> with a donor/recipient ratio of 1::1. When the  
132 recipients were composed of a mixed population the donor/mixed-recipient ratio was  
133 1::0.5-0.5. Before mixing the different bacteria, cultures were washed three times with  
134 fresh media to remove antibiotics. In Supplementary Table 2 bacteria were mixed in  
135 different proportions (2:1 and 3:1) to test whether this would impact conjugation  
136 efficiency. Conjugation was performed during 4h at 37°C on filter in MH plates

137 supplemented with DAP (and containing NaCl until 332mM final concentration in the  
138 case of *V. vulnificus*).

139

#### 140 ***In vivo* conjugation in zebrafish larvae and *Artemia salina***

141 All animal experiments described in the present study were conducted at the Institut  
142 Pasteur according to European Union guidelines for handling of laboratory animals  
143 ([http://ec.europa.eu/environment/chemicals/lab\\_animals/home\\_en.htm](http://ec.europa.eu/environment/chemicals/lab_animals/home_en.htm)) and were  
144 approved by the Institut Pasteur Animal Care and Use Committee and the Direction  
145 Sanitaire et Veterinaire de Paris under permit #A-75-1061. Conjugative killing was  
146 assessed as follow. Four-day-postfertilization zebrafish larvae were exposed to water  
147 containing 10<sup>4</sup> CFU/ml of *V. cholerae* O139 for 2 hours at 27°C (Figure 4a) or a 1::1  
148 mixed population containing 10<sup>5</sup> CFU/ml *V. cholerae* O139 + *V. cholerae* O1 (Figure  
149 5a, mix *Vibrio*) for 2 hours at 27°C. Then, larvae were washed in sterile water three  
150 times and then placed into a well containing 10<sup>7</sup> or 10<sup>6</sup> CFU/ml (Figure 4a, *V. cholerae*  
151 O139 and mix *Vibrio*, respectively) of the *E. coli* β3914-Δ*dap* donor strain containing  
152 either the pN<sub>ctrl</sub> or pFW plasmid for 24 hours at 27°C. In Supplementary Fig. 11b and  
153 11c, infection dose for *Vibrio* was the same than for Fig. 4a. Larvae were transferred to  
154 bacteria-free wells, washed in sterile water three times and then placed into a well  
155 containing Tricaine (Sigma-Aldrich #E10521) at 200 mg/ml to euthanize them. Finally,  
156 they were transferred to a tube containing calibrated glass beads (acid washed, 425  
157 um to 600 um, Sigma-Aldrich #G8722) and 500 μl of water. Five larvae were mashed  
158 using FastPrep® Cell Disrupter (BIO101/FP120 QBioGene) for 45 seconds at  
159 maximum speed (6,5 m/sec) to analyze their microbiota (Supplementary Fig. 11) in MH  
160 Media + X-gal or TCBS media for selection of *V. cholerae*. Blue bacteria corresponding  
161 to *V. cholerae* O139 were detected in MH media. Transconjugants selection was done  
162 into MH Media + X-gal and Sp and then, replication of these MH plates were done on  
163 TCBS media to specific identify *V. cholerae*. Strain identity was confirmed through

164 yellow color development in TCBS *Vibrio* specific media. The amoeba *Tetrahymena*  
165 *thermophila* (*T. thermophila*) was added to feed larvae during the experiment.

166

167 Groups of 225±15 larvae of *Artemia salina* stage nauplii suspended in 1ml volume of  
168 seawater were washed using sterile cell strainer Nylon filters 100 µm pore size  
169 (Falcon) and three times with the same volume (3x1ml) of sterile PBS (D8537, Sigma).  
170 Nauplii were suspended in 1ml PBS and then infected with 10<sup>7</sup> *V. cholerae* O1 or a mix  
171 of 10<sup>7</sup> *V. cholerae* O1 and O139 for 2 hours in agitation at 27°C. Then nauplii were  
172 washed as previously described and exposed to 10<sup>7</sup> of β3914 -Δ*dap* bacteria with  
173 pN<sub>ctrl</sub> or pFW plasmid for 4 hours at 27°C. These experiments were repeated four times  
174 independently. The microbiota from 1ml containing 225±15 nauplii were analyzed as  
175 previously described for zebrafish. In the case of *Artemia*, we have used M63B1  
176 minimal media where *Artemia* feel asleep and then put them on ice, previous the use of  
177 fast-prep (FastPrep® Cell Disrupter (BIO101/FP120 QBioGene) for 45 seconds at  
178 maximum speed (6,5 m/sec)). Transconjugants were selected from 225±15 nauplii  
179 after pN<sub>ctrl</sub> or pFW conjugation treatment into MH media with Sp and X-gal  
180 (Supplementary Fig. 12a,b). For the identification of *V. cholerae* in the mix of both  
181 serogroups (Fig. 4b and Supplementary Fig. 12b), replication of these MH plates were  
182 done into TCBS media to specifically identify *V. cholerae*. Strain identity was confirmed  
183 through yellow color development in TCBS *Vibrio* specific media.

184

185 **Co-localization of *E. coli* and *V. cholerae* in the zebrafish larvae and *A. salina* by**  
186 **Microscopy.**

187 Co-localization of *E. coli* and *V. cholerae* in the zebrafish larvae was assessed as  
188 follow. Four-day-postfertilization zebrafish larvae were exposed to water containing 10<sup>6</sup>  
189 CFU/ml *V. cholerae* O1-GFP for 2 hours at 27°C. Then washed in sterile water three  
190 times and then placed into a well containing 10<sup>7</sup> CFU/ml of *E. coli*-RFP for 24 hours at  
191 27°C. Larvae were removed from the well and then placed into a well containing

192 Tricaine for euthanize them. Infected and non-infected larvae were visualized by  
193 fluorescence microscopy (EVOS FL microscope-Life technologies) using appropriate  
194 wavelength conditions enabling or not the visualization of GFP and RFP. Fluorescence  
195 was only detected in infected larvae and more precisely into the gut where both  
196 bacteria are co-localized.

197 In the case of *A. salina* stage nauplii the microscopy experiment was done using  $10^7$  *V.*  
198 *cholerae*-GFP for 2 hours in agitation at 27°C. Then nauplii were washed as previously  
199 described and exposed to  $10^7$  of *E. coli*-RFP strain for 2 hours. Microscopy conditions  
200 were performed as for zebrafish experiment.

201

## 202 **Statistics**

203 In Supplementary Fig. 9, one-way ANOVA with Dunnett's Multiple Comparison Test  
204 was performed. PNcontrol-R6K vs pPW-R6K, Mean Diff. = 2.383e+008, q = 4.183,  
205 \*\*P<0.05, 95% CI of diff = (8.937e+007 to 3.871e+008). PNcontrol-R6K vs pFW-R6K,  
206 Mean Diff. = 2.308e+008, q = 4.227, \*\*P<0.05, 95% CI of diff = (9.187e+007 to  
207 3.896e+008).

208 In Supplementary Fig. 13, one-sided t-test Mann Withney was performed. *E. coli* SXT  
209 vs *E. coli* MG1655. P value = 0.0143. \*P < 0.05.

210

## 211 **References**

212

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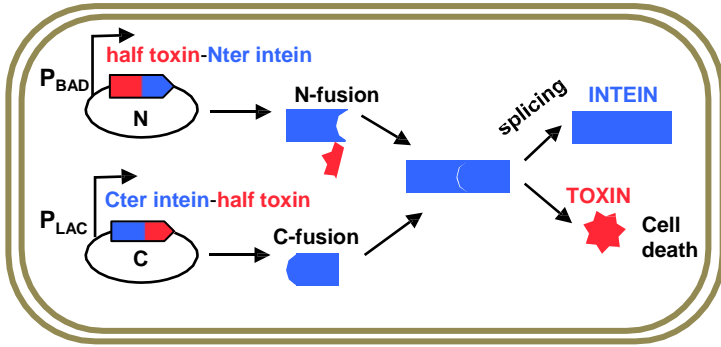
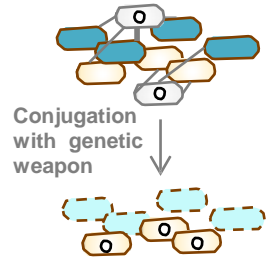
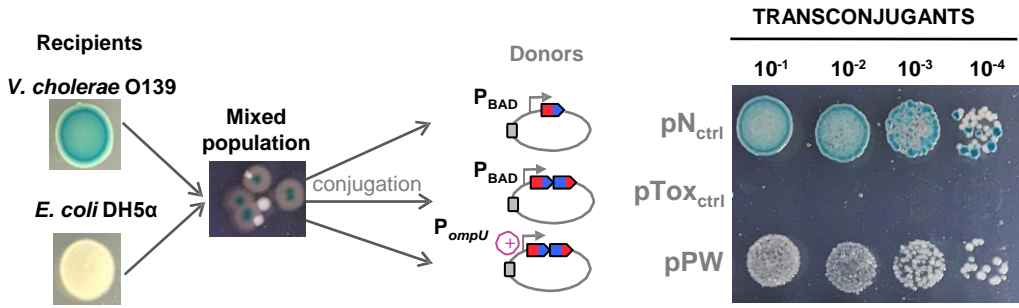
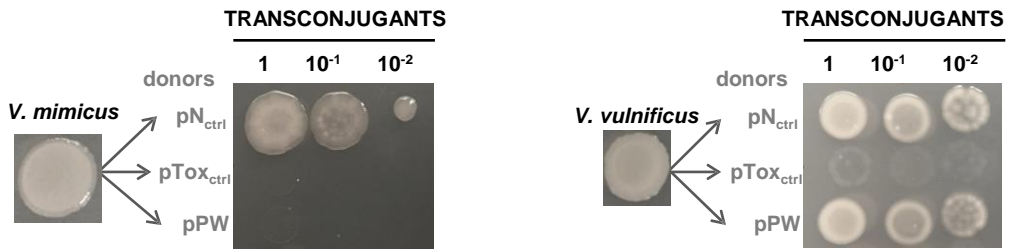
**a****b****c****d**

Figure 1

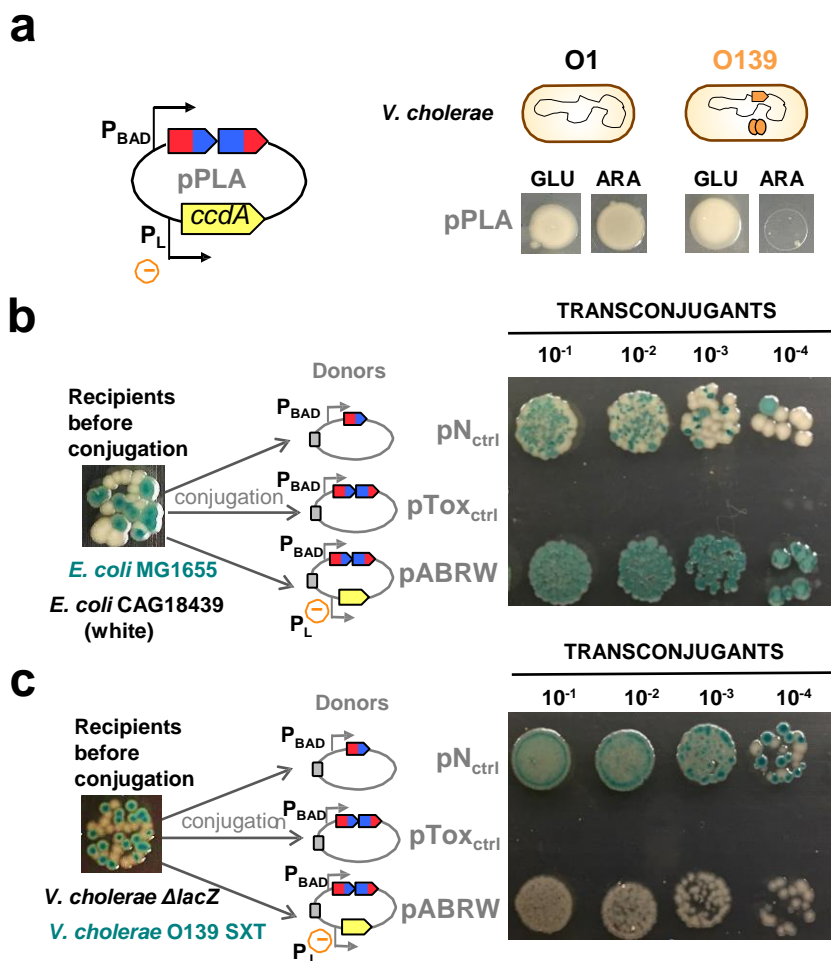


Figure 2

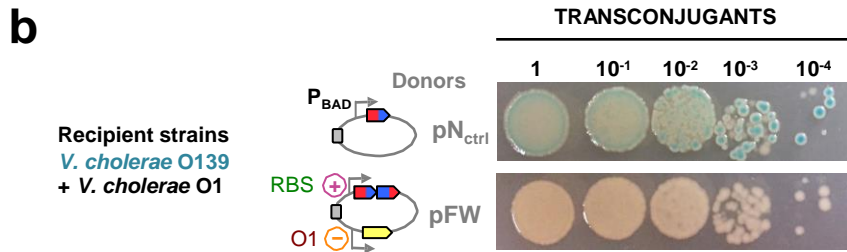
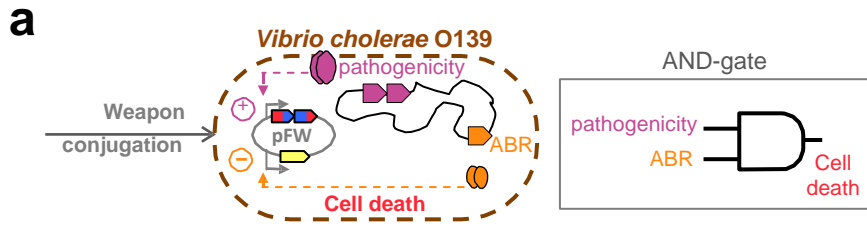


Figure 3

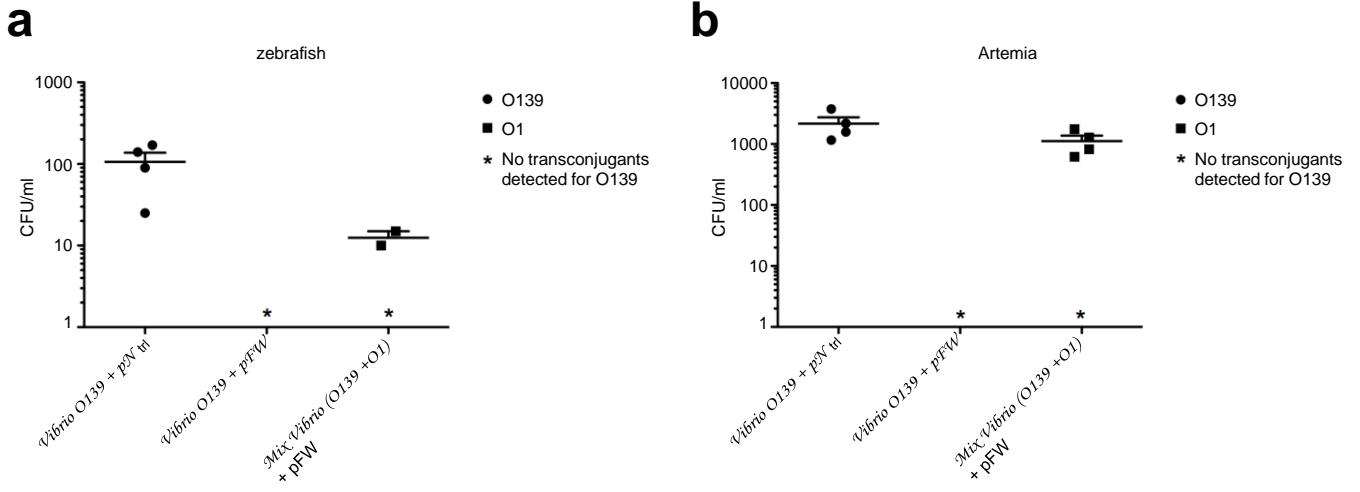


Figure 4