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Engineering Multicellular Logic in Bacteria with Metabolic Wires

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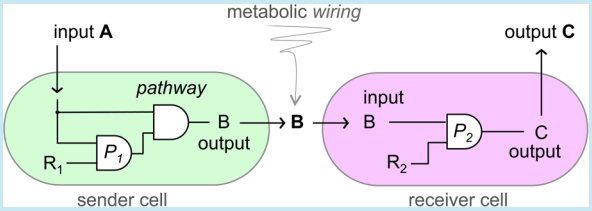
Supporting Information

ABSTRACT: Aromatic biodegradation pathways of environmental bacteria are vast sources of matching trios of enzymes, substrates and regulators that can be refactored to run logic operations through cell-to-cell communication. As a proof of concept, the connection between two *Pseudomonas putida* strains using benzoic acid as the wiring molecule is presented. In this system, a *sender* strain harboring the TOL pathway for biodegradation of aromatics processed toluene as input and generated benzoate as the output signal. Diffusion of such metabolic intermediate to the medium was then sensed by a second strain (the *receiver*) that used benzoate as input for a new logic gate producing a visual output (i.e., light emission). The setup was functional irrespective of whether sender and receiver cells were in direct contact or in liquid culture. These results highlight the potential of environmental metabolic pathways as sources of building blocks for the engineering of multicellular logic in prokaryotic systems.



KEYWORDS: *regulatory networks, regulator-inducer specificity, logic gates, Pseudomonas, biodegradation, TOL system*

One of the most fascinating potential applications of synthetic biology is the reprogramming of cells to perform sophisticated electronic-like computations.[1,2] Most research in this area focuses on the design and implementation of regulatory logic gates as the building blocks for the assembly of more complex circuits.[3−6] Consequently, all 16 Boolean logic gates for two-inputs have been implemented in living cells through a number of different experimental setups.[6−8] While much progress has been made with these relatively simple circuits, the real challenge is to engineer complex synthetic circuits for applications of biotechnological value.[1,2] Technical difficulties stem from the interconnection of many different logic gates in one organism, both in terms of the propagation of noise during circuit operation[9,10] and by the lack of sufficiently different regulatory parts (i.e., promoters and transcription factors) to assemble the system of interest.[11,12] A way to overcome this state of affairs is the engineering of new regulatory elements with well-defined, orthogonal activities suitable for circuit implementation, as recently described.[13,14] An alternative approach is based on the construction of multicellular synthetic circuits implemented such that parts of the system are split between different host strains.[7,15] In these systems, signal computation from the initial strains (those that sense the system inputs) are transmitted to other strains via production of a signaling compound (the *wire*), which is then further processed in the cascade. Diffusible wires used to date include bacterial quorum-sensing molecules[7] and yeast pheromones.[15] This division of labor-type approach could in principle allow the engineering of very sophisticated synthetic cellular programs for biotechnological and biomedical uses.

As multicellular circuit engineering requires the *wiring* of the host cells harboring the system components, the clear problem is the limited number of well-characterized signaling molecules currently available.[16] There is thus a need to expand the number of *molecular wires* available for engineering logic circuits. In this context, we pondered the value of small molecules unrelated to quorum sensing as potential vehicles for assembling multicellular logic gates. Specifically, we focused on the intermediary, diffusible metabolites originating from catabolic pathways for aromatic compounds borne by environmental bacteria.[17−19] Complete genome sequences of such microorganisms (e.g., the Gram-negative soil bacterium *Pseudomonas putida*) have revealed a large repertoire of genes encoding pathways for utilization of aromatic compounds as carbon sources.[20] Diverse substrate-responsive transcription factors are required for expression of these catabolic pathways, each of them with different DNA- and ligand-binding specificity.[18,21,22] Additionally, biodegradation intermediates of aromatic compounds are known to diffuse and be catabolized by different members of the bacterial community,[23] such that communication mediated by metabolic signals has precedents in natural scenarios.

In this work, we report the engineering of a simple cell-to-cell communication device in *Pseudomonas putida* using the pathways for toluene and benzoate (Bz) degradation encoded in this organism. Using a series of promoter−reporter fusions, we showed that the extracellular diffusion of Bz during toluene catabolism could be sensed as an input by a reporter strain engineered with a Bz-responsive promoter. The receiver strain was able to further metabolize the released Bz and trigger a second reporter system based on the metabolic intermediate *cis*,*cis*-muconate (2cM). This approach can be expanded to many other characterized catabolic systems.

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As a proof of concept for the utilization of metabolic wires, we generated a simple system based on two different strains. The *sender* strain senses the input and generates an output, and the *receiver* takes the output from the first strain as its input. The general strategy is depicted in Figure 1a. As shown in the figure, input A is processed by the logic circuit (formed by the promoter P_1 and regulator R_1) existing in the *sender* strain to generate output B, which then diffuses to the extracellular medium. Once in the medium, this compound is perceived by the *receiver* strain as an input to its logic circuit (composed by the promoter P_2 and regulator R_2). The outcome of this system, output C, can be a reporter protein as implemented here or could be another signaling molecule that could be further connected to additional strains. The theoretical limitation for the number of steps an entry compound could generate would depend on the number of metabolic intermediates of the pathway that can be sensed by transcription factors. For experimental validation of the system, we focused on catabolic pathways for toluene and Bz from *P. putida*.[24,25] *P. putida* mt-2 is a versatile environmental bacterium that completely metabolizes toluene to generate TCA cycle intermediates.[26] This task is performed by two pathways known as *upper* and *meta* that are encoded in the large catabolic plasmid pWW0 (TOL[24]). The *upper* enzymes perform the first step of toluene metabolism, generating Bz as a metabolic intermediate (Figure 1b). Bz is transformed into TCA intermediates by the *meta* pathway.[24] In the TOL system, induction of the *upper* pathway is activated by the regulator XylR in response to toluene, while induction of *meta* genes is triggered by XylS bound to Bz.[27,28] Additionally, most *Pseudomonas* species have a specific metabolic route for Bz metabolism known as the *ortho* pathway.[25,29] Figure 1c shows the main steps of such *ortho* route as found in *P. putida* KT2440, the pWW0-cured variant of *P. putida* mt-2.[30] A set of three operons (*ben*, *cat* and *pca*) are involved in Bz degradation. These operons are under the regulation of three transcription factors, BenR, CatR and PcaR.[29] Each of these regulators senses specific intermediates (Bz, 2cM and *β*KA) depicted in Figure 1c. Thus, BenR activates *Pb* (*ben* promoter) in response to Bz, while CatR triggers *Pc* (*cat* promoter) in the presence of 2cM.[25,29] Finally, PcaR triggers the induction of the *pca* promoter (*Ppca*) in response to *β*-ketoadipate (*β*KA[25,29])

Taking into account the regulatory and metabolic relationships explained above, we implemented a cell-to-cell communication system where Bz was the metabolic wire between the *sender* and *receiver* strains. In our setup, *P. putida* mt-2 was the *sender* strain, and toluene was the first input to the system. Toluene was sensed by *P. putida* mt-2 and triggered the expression of the *Pu* (*upper* promoter) TOL pathway. The *upper* enzymes converted toluene into Bz. While this compound can be further metabolized by the *meta* pathway, part of the product diffused to the extracellular medium; there it could be sensed by the *receiver* strain (*P. putida* KT *Pb::lux*) harboring the BenR-*Pb-lux* reporter system, which generated a light signal in response to Bz (Figure 2d). Figure 2a highlights the main logic interactions in TOL system of the *sender* cell[31] during the response to toluene as well as the receiver cell logic circuit controlling the production of the reporter output (i.e., light). The truth table of the AND logic gate used to construct the representations is shown in Figure 2b (a systems representation of the two logic circuits is shown in Figure S1, Supporting Information).

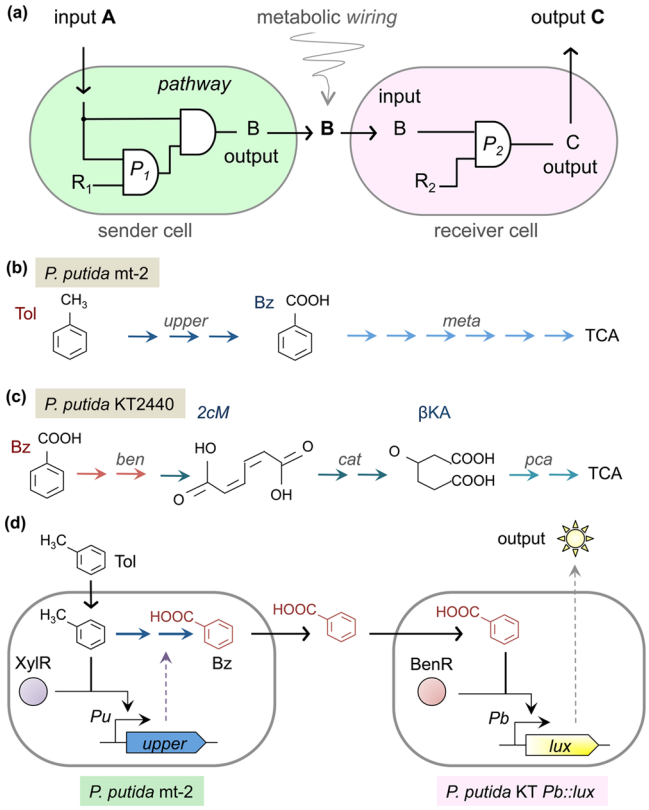

Figure 1. Overall strategy of metabolic wiring. (a) In this system, an entry input A controls a set of logic interactions in the *sender* strain. P_1 and P_2 represent promoters regulated by transcriptional factors R_1 and R_2, respectively. These regulators are the sensors of inputs A and B. As a result of the computation performed by this circuit, input A is converted to B, which diffuses to the extracellular media. Once this compound accumulates in the outside, it is sensed by the *receiver* strain, where it serves as an input signal for next logic circuit. In this way, the two logic circuits are wired through the intermediate metabolite. (b) In *P. putida* mt-2, toluene is degraded in two steps via the *upper* and *meta* pathways of the TOL network.[24] In the first step, toluene (Tol) is converted to benzoate (Bz) by the *upper* enzymes. The enzymes are expressed from the *Pu* promoter when activated by XylR in response to toluene. Next, Bz is metabolized to generate TCA cycle intermediates through the action of the *meta* enzymes. In this case, the *meta* operon is expressed from the *Pm* promoter when activated by XylS bound to the inducer Bz. (c) In the *ortho* pathway of *P. putida* KT2440, three sets of enzymes (*ben*, *cat* and *pca*) are necessary to completely break down Bz. The compound *cis,cis*-muconate (labeled as 2cM) generated during this process acts with CatR to stimulate the activation of the *cat* operon, while *β*-ketoadipate (*β*KA) is sensed by the PcaR regulator to trigger production of the *pca* enzymes. (d) In the implemented system, *P. putida* mt-2 works as the *sender* strain and *P. putida* KT *Pb::lux* as the receiver. When toluene is present in the media, it is sensed by *P. putida* mt-2, which activates the complex TOL network.[31] One of the outcomes of this circuit is production of *upper* enzymes that convert toluene to Bz. As the *upper* enzymes start to produce high amounts of Bz from toluene, the compound diffuses to the extracellular medium and is then sensed by the receiver strain, where it triggers the activation of the BenR regulator. Active BenR binds the *Pb* promoter and stimulates the production of the *lux* operon, leading to bioluminescent emission.

For the construction of the metabolically wired logic system, we used two different *receiver* strains as shown in Figure 3a,b. The first was the above-mentioned BenR-*Pb-lux* reporter strain that directly sensed Bz[32] (Figure 3a). For the second system, we used a reporter strain based on the CatR-*Pc* system (*P.*

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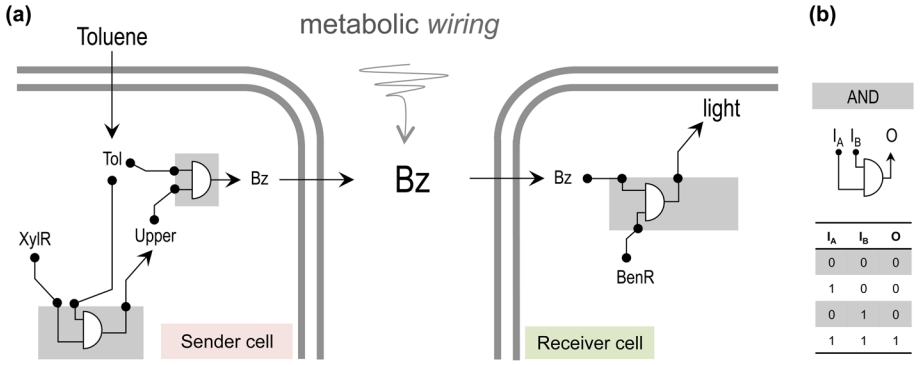

Figure 2. Logic circuits of *P. putida sender* and *receiver* strains. (a) To the left, the logic circuit that converts toluene (input) into Bz (output) is composed of the regulatory *xylR* gene and the *upper* metabolic operon. To the right, the logic interactions involving the receiver strain are shown. In this case, the transcriptional factor BenR and one external signal (Bz) are used as inputs for the control of light emission. (b) The AND logic gate used to construct the circuits along with its truth table.

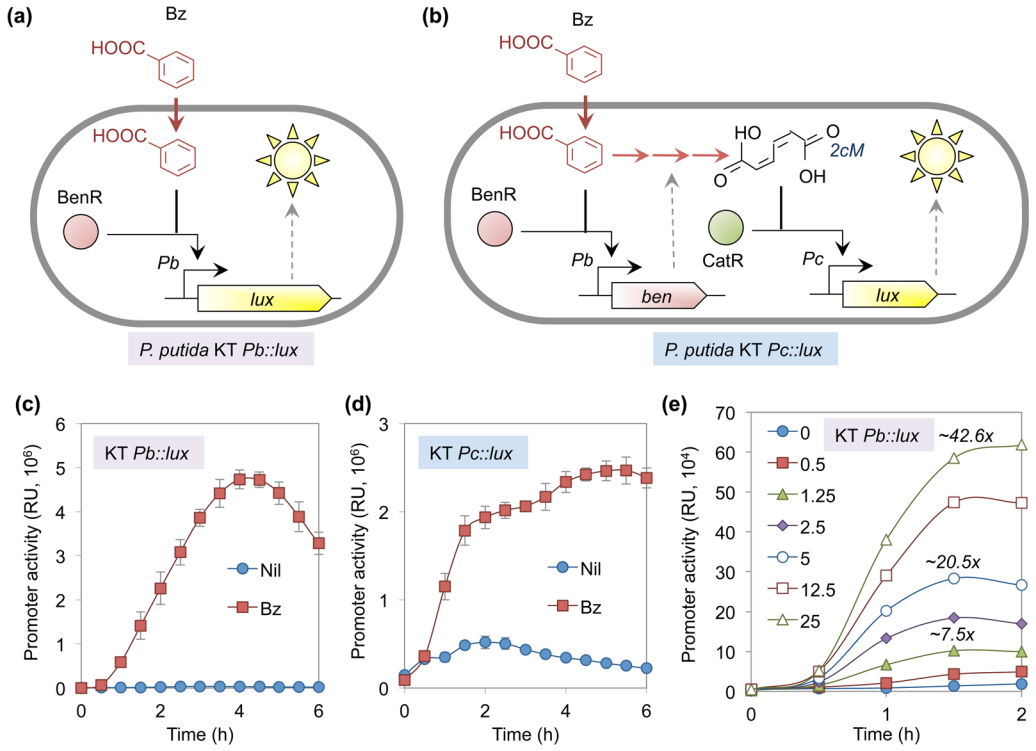

Figure 3. Individual characterization of the transcriptional response of receiver strains. (a) *P. putida* KT *Pb::lux* with the regulatory system controlling *lux* expression. (b) In *P. putida* KT *Pc::lux*, Bz induces expression of the *ben* enzymes that convert this compound to *cis,cis*-muconate (2cM). This compound is then sensed by CatR to activate the *Pc::lux* reporter fusion. (c) Transcriptional response of *Pb::lux* fusion induced with 1 mM Bz. Briefly, overnight cultures were diluted 1:20 in fresh minimal media supplemented with or without (control; Nil) the inducer. Samples were loaded into a plate reader, and at 30-min intervals, the bioluminescence and the OD_{600} were measured. RU are relative units calculated as bioluminescence/OD_{600} at each time point. Vertical bars are the standard deviation (SD) calculated from at least four technical replicates. (d) Transcriptional response of *Pc::lux* fusion induced with 1 mM Bz. Experiments were performed as in (c). (e) Induction kinetics of *Pb::lux* fusion in response to micromolar concentrations of Bz. For these experiments, overnight cultures were diluted 1:20 in fresh minimal media supplemented without (control; Nil) or with different concentrations of Bz (0.5, 1.25, 2.5, 5, 12.5, and 25 μM). Promoter activities were assayed as in (c). In each experiment, the calculated SD was less than 15% (not shown). In the graph, the changes in expression at concentrations of 1.25 (7.5×), 5 (20.5×) and 25 μM (42.6×) are shown.

putida KT *Pc::lux*; Figure 3b) that is triggered by the metabolic intermediate 2cM produced during Bz degradation by the *ortho* pathway (Figure 1c). This strain only produces output signal if Bz is metabolized by enzymes encoded by the *ben* genes. The use of two different receiver strains was important to ensure that the levels of Bz released to the medium could induce expression of enough *ben* enzymes capable to convert this metabolite to 2cM, which in turn could trigger the CatR-*Pc* system. To evaluate the response of these two sensor bacteria to the inducer Bz, we assayed the promoter activity in liquid medium where each strain was exposed separately to 1 mM of this compound. Overnight cultures were diluted in fresh medium with the inducer and incubated for several hours in a plate reader. At 30-min intervals, light emission and optical density at 600 nm (OD_{600}) were recorded and used to calculate the promoter activity as described in the Methods section.

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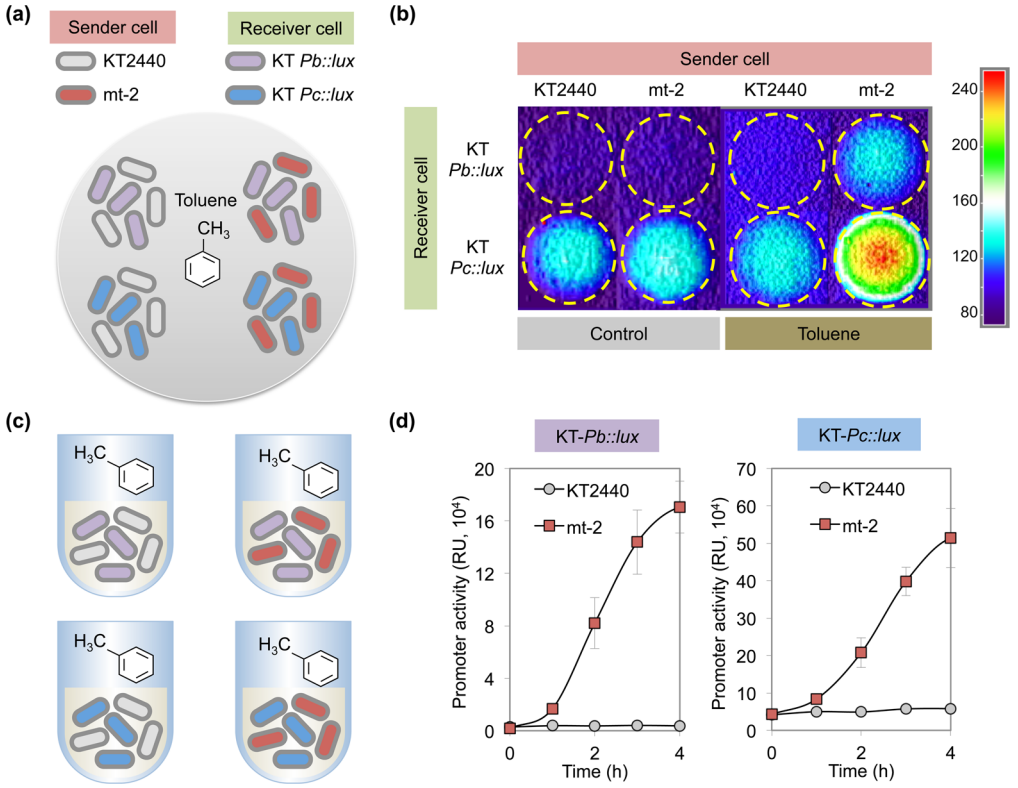

Figure 4. Implementation of multicellular circuits through metabolic wiring. (a) Solid media experiments. *P. putida* KT2440 or *P. putida* mt-2 were used as *sender* strains, while *P. putida* KT *Pb::lux* or *P. putida* KT *Pc::lux* were the receivers. Equal amounts of overnight cultures were mixed in agar plates in the indicated *sender*/*receiver* combinations. Cells were exposed to toluene vapors phase and incubated for 4 h. After induction, light emission from each mixture was analyzed using a CCD camera as described in the Methods. (b) Bioluminescence of mixed cells after 4 h of induction. Cells were incubated in the absence (control) or presence of toluene. (c) Liquid media experiments. Overnight cultures were diluted 1:20 in 1× PBS buffer in the combinations indicated. Cells were exposed to saturating amounts of toluene for 20 min, after which samples were loaded into a plate reader and assayed for bioluminescence emission. (d) Promoter activity of mixed cultures in liquid media. RU refers to relative units calculated as bioluminescence/OD_{600} at each time point. Vertical bars are the standard deviation (SD) calculated from at least four technical replicates.

Uninduced cultures were used as controls to calculate basal promoter activities. As shown in Figure 3c,d, both reporter systems were highly responsive to Bz. The BenR-*Pb*-based strain showed a higher induction than its CatR-*Pc* counterpart (152.5- vs 9.8-fold, respectively). This result was mainly due to the higher basal activity observed for *P. putida* KT *Pc::lux* (Figure 3d). We next investigated the sensitivity of *P. putida* KT *Pb::lux* in low concentrations of Bz. *P. putida* KT *Pb::lux* was assayed as before except that cells were exposed to Bz concentrations ranging from 0.5 to 25 μM. As shown in Figure 3e, strain *P. putida* KT *Pb::lux* was highly sensitive to the inducer; as little as 1.25 μM triggered 7.5-fold promoter induction. The highest concentration resulted in 43-fold induction. Taken together, these results revealed the high sensitivity of the *P. putida* KT *Pb::lux* reporter strain at micromolar concentrations of the inducer Bz, making it a suitable for the cell-to-cell wired system.

After characterization of the individual receiver strain, we validated the synthetic approach for metabolic wiring by mixing *P. putida sender* and *receiver* strains and exposing the cells to toluene. As sender strains, we used either *P. putida* mt-2 or *P. putida* KT2440, a variant of the former lacking the TOL plasmid. Because *P. putida* KT2440 is unable to metabolize toluene, it serves as a control where the *sender* and *receiver* strains do not communicate. The receiver strains were *P. putida* KT *Pb-lux* and *P. putida* KT *Pc-lux*, described above. Initially, we assayed the wiring between the strains in solid media. Each individual strain was grown as described in the Methods. After pregrowth, 10 μL of the cultures were added to the surface of 1.6% agar plates in the following four combinations of *senders*/*receivers*: (i) *P. putida* KT2440/*P. putida* KT *Pb-lux*; (ii) *P. putida* KT2440/*P. putida* KT *Pc-lux*; (iii) *P. putida* mt-2/*P. putida* KT *Pb-lux*; and (iv) *P. putida* mt-2/*P. putida* KT *Pc-lux*. These combinations are represented in Figure 4a. Toluene was entered in medium in the form of saturating vapors as described in the Methods section. The plates were sealed airtight and incubated for 4 h. After incubation, bioluminescence was analyzed using a CCD camera in a VersaDoc Imaging System (Bio-Rad). As shown in Figure 4b, after exposure to toluene vapors, both *P. putida* KT *Pb-lux* and *Pc-lux* *receiver* strains mixed with the *P. putida* mt-2 *sender* generated higher light emission than the controls where *P. putida* KT2440 was used as the *sender*, while control conditions (where no toluene was added) failed to enhance luminescence of the sensors. This result showed that Bz production from toluene by *upper* enzymes was indeed detected by the reporter strains.

To further characterize the transmission of Bz from the *sender* to the *receiver*, quantitative experiments were performed in liquid media. Overnight cultures were diluted 1:10 in 1× PBS buffer in similar combinations as in the solid media experiments (Figure 4c). Mixed cells were exposed to toluene vapors for 20 min and loaded onto a plate reader. At 1-h intervals, bioluminescence and OD_{600} were measured and used to calculate promoter activity. As shown in Figure 4d, promoter

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activity in the receiver strains was highly stimulated by toluene when *P. putida* mt-2 was used as the *sender* strain. In contrast, when *P. putida* KT2440 was used as the *sender*, the *receiver* strains only produced low-level basal promoter activity. These results confirmed that Bz produced by *P. putida* mt-2 was specifically sensed by the *receiver* strains and was sufficient to induce the *Pb* and *Pc* promoters in these hosts.

In conclusion, these results accredit catabolic pathways for aromatic compounds as reliable sources of synthetic wiring devices between different bacterial strains. We thus advocate their exploitation for engineering multicellular logic circuits. Furthermore, metabolically wired cells could be in principle connected to additional strains, through linking the generation of the output C (Figure 1a) to the production of, e.g., quorum sensing molecules, which could use these compounds as inputs. Also, well-characterized regulatory elements (such as LacI, TetR, AraC, etc.) could be merged to such metabolic devices from catabolic pathways for implementing complex circuits in the same cell. Note that when placed in a different host many of such pathways are altogether alien to the endogenous metabolism,[18,20,33] and therefore, the logic gates composed of small molecule-enzyme-regulator trios that could be built upon them would be orthogonal. This is because catabolic pathways for recalcitrant and xenobiotic compounds used to reside in specific types of organisms,[18,22] so that no crosstalk would be expected with the endogenous metabolic networks of distant hosts. In combination with standard tools available for circuit engineering in bacteria,[34,35] we anticipate that a number of environmentally relevant logic circuits could be easily assembled in different hosts of interest. On these bases we encourage adoption of similar approaches for circuit engineering with other well characterized catabolic pathways of environmental microorganisms (such as the *nah*, *tfd*, *bph*, *tod*, etc.[18,20]).

METHODS

Bacterial Strains and Growth Conditions. *E. coli* strain CC118 was used as the host organism for plasmid constructs.[36] *E. coli* strain HB101 (pRK600) was utilized as a helper strain for triparental mating, which was performed as described.[36] *P. putida* KT2440[30] and *P. putida* mt-2[26] were used as *sender* strains. Unless otherwise indicated, *E. coli* cells were grown in Luria−Bertani (LB) medium at 37 °C, while *P. putida* strains were grown in M9 minimal medium[37] supplemented with 2 mM $MgSO_4$ and 10 mM of succinate as the sole carbon source. When required, kanamycin (Km, 50 μg/mL) or chloramphenicol (Cm, 30 μg/mL) was added to the media. The aromatic compounds used as inducers (toluene and benzoate) were all purchased from Sigma-Aldrich.

Construction of the *Receiver* Strains. We constructed reporter fusions in receiver strains by cloning the target promoter in a broad-host range plasmid pSEVA226 (a RK2 derivative with a Km resistance marker) that harbors the *luxCDABE* operon[38] downstream of a pUC18-like multiple cloning site.[34] Briefly, PCR reactions were performed using *P. putida* KT2440 DNA, *Pfu* DNA polymerase (Promega), and primers for the *Pb* promoter as follows: PBF (5′-TGG ATG AAT TCG ACA GTA CCC TCC-3′) and PBR (5′-GCG CGG ATC CGG CCA GGG TCT CCC TTG-3′). For *Pc* promoter amplification, primers PCF (5′-GAG AGA ATT CAG GCC CAG TTC CAG CTC G-3′) and PCR (5′-GCG CGG ATC CTG TTG CCA GGT CCC GTC AG-3′) were used. These primers introduced *Eco*RI and *Bam*HI sequences at the 5′ and 3′ ends, respectively (restriction sites are underlined in the primer sequences). After purification of the PCR products, fragments were digested with *Eco*RI/*Bam*HI enzymes (New England Biolabs) and ligated into a pSEVA226 vector that was previously digested with the same enzymes. Ligations were used to transform chemically competent *E. coli* CC118 cells, and the resulting Km^R clones were selected. After confirmation of the correct insertion of the promoters, the resulting plasmids were named pSEVA226-*Pb* and pSEVA226-*Pc*. Cloned promoters were verified by DNA sequencing. The reporter constructs were transferred to *P. putida* KT2440 by triparental mating,[36] generating strains *P. putida* KT *Pb::lux* (*P. putida* KT2440 with pSEVA226-*Pb*) and *P. putida* KT *Pc::lux* (*P. putida* KT2440 with pSEVA226-*Pc*), which were used as *receivers* in the experiments below.

Promoter Activity Assays. For testing promoter induction in solid media, overnight cultures of *sender* and *receiver P. putida* strains were mixed in different combinations as shown in Figure 4a, spotted on M9/succinate agar plates and exposed to saturating vapors of 1 M toluene dissolved in DMSO. Plates were sealed with parafilm and incubated for 4 h. After induction, nondisruptive monitoring of promoter output was carried out with a VersaDoc Imaging System (BioRad), and results were processed with ImageJ software (http://rsbweb.nih.gov/ij/). To analyze promoter activity quantitatively, single colonies of *P. putida* were used to inoculate 5 mL of M9 minimal medium supplemented with 10 mM of succinate. Cultures were grown for 16 h and diluted 1:20 into fresh minimal media containing different effectors. To quantify promoter responses in different inducer concentrations, benzoate was used at 0.5, 1.25, 2.5, 5, 12.5, and 25 μM. For single concentration experiments, benzoate was used at a 1 mM final concentration. Diluted cells were placed in 96-well microplates (Optilux, BD Falcon) and analyzed in a WallacVíctor II 1420 Multilabel Counter (Perkin-Elmer). Every 30 min, the optical density at 600 nm (OD_{600}) and the bioluminescence were recorded. Strains harboring an empty vector (pSEVA226) were used as a control, and background production of the lux genes was subtracted from the assayed promoters. To assay receiver induction in the wiring experiments, overnight cultures were mixed as in Figure 4c in 1× PBS buffer at 1:10 dilutions. Mixed cultures were exposed to saturating vapors of toluene for 20 min. After this pre-exposure, cells were transferred to 96-well microplates (Optilux, BD Falcon), which were loaded in a plate reader. Every hour, the optical density at 600 nm (OD_{600}) and the bioluminescence were recorded. Promoter activities were calculated in relative units (RU, bioluminescence/OD_{600}) by normalizing bioluminescence to cell density.

ASSOCIATED CONTENT

Supporting Information

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Author Contributions

R. Silva-Rocha performed experiments and drafted the manuscript. V. de Lorenzo directed the project and wrote the paper.

Notes

The authors declare no competing financial interest.

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