

Cite this: *Polym. Chem.*, 2021, **12**, 50

Received 15th May 2020,

Accepted 29th July 2020

DOI: 10.1039/d0py00710b

rsc.li/polymers

## Boron-rich, cytocompatible block copolymer nanoparticles by polymerization-induced self-assembly†

Lin-Chiang Sherlock Huang,<sup>‡a,b,c</sup> Dao Le,<sup>†a,b,d</sup> I-Lun Hsiao,<sup>e,f</sup> Susanne Fritsch-Decker,<sup>e</sup> Christian Hald,<sup>a,b</sup> Su-Ching Huang,<sup>g</sup> Jen-Kun Chen,<sup>†g</sup> Jih Ru Hwu,<sup>†c</sup> Carsten Weiss,<sup>†e</sup> Min-Hua Hsu,<sup>†h</sup> and Guillaume Delaittre<sup>†a,b,i</sup>

**Core-shell nanoparticles (NPs) with a boron-rich core were synthesized by RAFT-mediated polymerization-induced self-assembly using a new methacrylic boronate ester monomer. Under specific conditions, sub-100 nm spherical NPs could be obtained at high conversions by either emulsion or dispersion RAFT polymerization using poly(oligo(ethylene glycol) methacrylate) (POEGMA) dithiobenzoate-based chain transfer agents. Phenylboronic acid surface-functionalized NPs were obtained using a telechelic POEGMA. Primary data on biocompatibility is provided and suggests suitability as boron delivery agent for boron neutron capture therapy.**

Among the various potential techniques to fight cancer and eliminate tumor cells, boron neutron capture therapy (BNCT) is an attractive binary treatment based on (i) delivery of non-toxic boron drugs into tumor cells and (ii) irradiation with a thermal neutron beam to trigger nuclear fission of boron-10 and subsequent production of high-energy alpha particles.<sup>1</sup>

The key challenge for successful BNCT treatment is the specific accumulation of boron – in any form – in tumor cells. Boronophenylalanine (BPA) has been one of the two major compounds used in BNCT clinical trials for decades, yet requires rather large injected amounts to reach sufficient boron concentrations.<sup>2</sup> The low tumor uptake and selectivity, and short retention of BPA are due to its non-selective tumor-targeting functionality, negative charge, and low molecular weight.<sup>3</sup> Similar issues are encountered with the other major compound used in BNCT, namely sodium borocaptate. To improve the longer circulation of boron agents and therefore facilitate specific tumor accumulation, several types of nanoparticles (NPs) such as liposome, dendrimer, and block copolymer (BCP) NPs have been evaluated as potential delivery system.<sup>4</sup> For instance, boronic acid-containing BCP NPs have been designed and synthesized for BNCT.<sup>5–10</sup> In these examples, boron compounds were either encapsulated in or covalently linked to nanoparticles supposed to accumulate in neoplastic regions *via* the enhanced permeability and retention (EPR) effect.<sup>11,12</sup> While they may improve specific delivery, macromolecular approaches to boron delivery for BNCT still exhibit shortcomings such as low boron content per unit weight, and/or complicated and time-consuming particle synthesis. In the present contribution, we sought to harness polymerization-induced self-assembly (PISA) to prepare boron-rich nanoparticles because this method precisely addresses such shortcomings.

PISA has become a very popular method over the last decade to design core-shell polymeric NPs with specific shapes and controlled diameters.<sup>13–17</sup> Indeed, PISA not only yields colloidal suspensions with homogeneous morphology directly at high concentrations, but also simultaneously gives access to precise macromolecular architecture with high control over functionality,<sup>18,19</sup> with excellent potential for a range of applications.<sup>20–27</sup> We thus anticipated that the PISA-based synthesis of nanoparticles with a boron-rich core and a biocompatible shell in a time-efficient manner could be possible. Note that, while boron-containing polymers have recently

<sup>a</sup>Institute of Biological and Chemical Systems – Functional Molecular Systems (IBCS-FMS), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

<sup>b</sup>Institute for Chemical Technology and Polymer Chemistry (ITCP), Karlsruhe Institute of Technology (KIT), Engesserstrasse 15, 76131 Karlsruhe, Germany

<sup>c</sup>Department of Chemistry, National Tsing Hua University, Hsinchu 30013, Taiwan

<sup>d</sup>Polymer Chemistry Team (ECP), Institut Parisien de Chimie Moléculaire (IPCM), Sorbonne Université and CNRS, UMR 8232, 4 Place Jussieu, 75005 Paris, France

<sup>e</sup>Institute of Biological and Chemical Systems – Biological Information Processing (IBCS-BIP), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

<sup>f</sup>School of Food Safety, College of Nutrition, Taipei Medical University, No. 250, Wuxing St., Taipei 11031, Taiwan

<sup>g</sup>Institute of Biomedical Engineering and Nanomedicine, National Health Research Institutes, No. 35, Keyan Rd., Zhunan Township, Miaoli County 35053, Taiwan

<sup>h</sup>Department of Chemistry, National Changhua University of Education, Changhua 50007, Taiwan. E-mail: minghua@cc.ncue.edu.tw

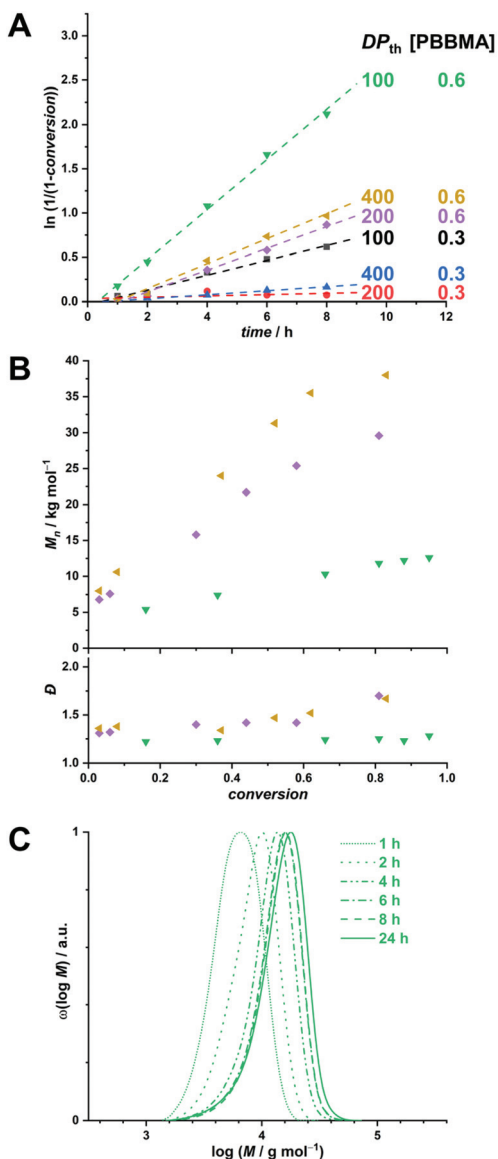
<sup>i</sup>Organic Functional Molecules, Organic Chemistry, University of Wuppertal, Gaußstrasse 20, 42119 Wuppertal, Germany. E-mail: delaittre@uni-wuppertal.de; <http://www.twitter.com/GPRDelaittre>

†Electronic supplementary information (ESI) available. See DOI: 10.1039/d0py00710b

‡These authors have contributed equally to this work.



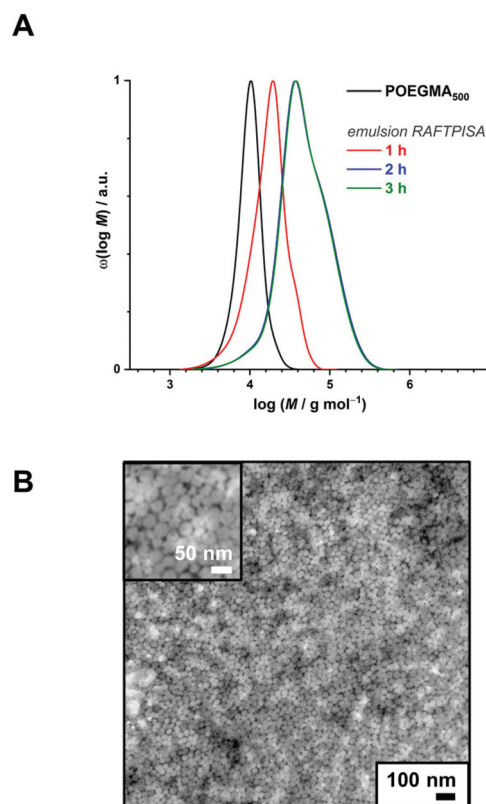




**Fig. 1** RAFT solution polymerization of PBBMA in DMAc at 70 °C. (A) First-order kinetic plots for various  $[PBBMA]$  and  $DP_{th}$ . Dashed lines correspond to linear fits. (B) Evolution of number-average molar mass (top) and dispersity (bottom) with PBBMA conversion for  $[PBBMA] = 0.6$  M at various  $DP_{th}$ . (C) Size-exclusion chromatograms of polymers obtained at different times for  $[PBBMA] = 0.6$  M and  $DP_{th} = 100$ .

ening of the MMD (Fig. 2A). Although the final dispersion contained a homogeneous population of spheres of around 50 nm, as observed by transmission electron microscopy (TEM) (Fig. 2B) and DLS (Fig. S10<sup>†</sup>), a small amount of coagulum was again present. Increasing  $[PBBMA]/[POEGMA_{500}]$  to 200 or 400 at solids contents of 10 or 20 wt% systematically led to early destabilization and low conversions (entries 2, 3, 5, and 6, Table S2<sup>†</sup>).

In order to produce a colloiddally stable PISA system and achieve easy removal of potentially unreacted monomer, we turned to a dispersion process. Methanol was chosen as polymerization medium because (i) PBBMA was found to be

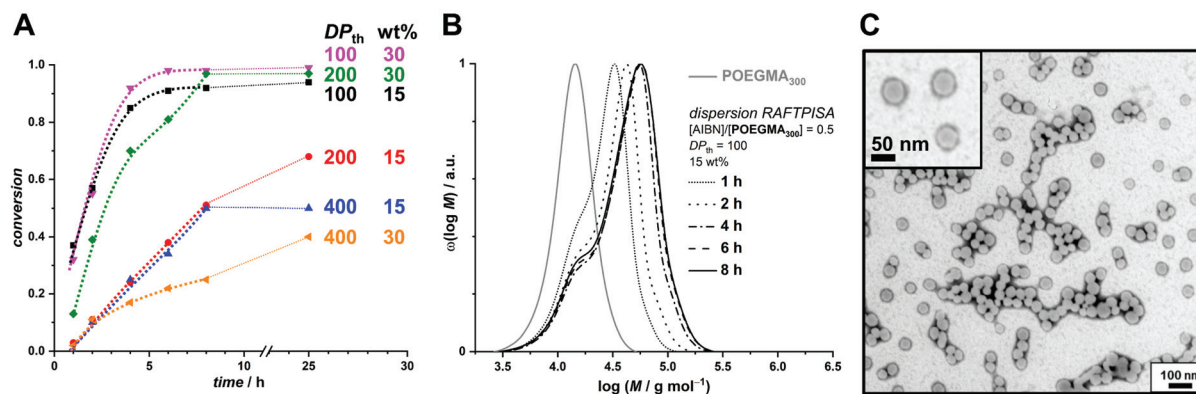


**Fig. 2** (A) Size-exclusion chromatograms of polymers obtained by PBBMA emulsion RAFTPISA in water/ethanol 3 : 1 vol/vol at 70 °C with POEGMA<sub>500</sub> at  $DP_{th} = 100$ , and 20 wt% solids content (entry 4 from Table S2<sup>†</sup>). (B) Transmission electron micrograph of nanoparticles obtained in the conditions mentioned above, after 2 h.

highly soluble in it as opposed to its polymer – which is a requirement for PISA – and (ii) because it is considered a green solvent.<sup>42</sup> As the thermoresponsive character of POEGMAs with shorter oligoethylene glycol side chains becomes irrelevant in methanol, we chose to start our investigation on dispersion RAFTPISA with POEGMA<sub>300</sub>, because this is also a more practical polymer in terms of purification (*i.e.*, separation of residual monomer). A series of experiments was performed by varying  $DP_{th}$  (100, 200, and 400) and the total solids content (10, 15, and 30 wt%). With the previously employed  $[\text{initiator}]/[\text{CTA}]$  ratio of 0.2, far-from-complete monomer conversions were obtained after 24 h (Table S3, entries 1–6, as well as Fig. S11<sup>†</sup>). Increasing  $[\text{initiator}]/[\text{CTA}]$  to 0.5 allowed a nearly full PBBMA conversion for  $DP_{th} = 100$  at 15 and 30 wt%. In those cases, as well as for  $DP_{th} = 200$  at 30 wt%, more than 90% PBBMA was polymerized within 6–8 h and nearly full conversion was eventually reached (Fig. 3A). Molar masses increased with time and conversion, with however a significant apparent amount of remaining macroCTA, and therefore increasing  $D$  (Fig. 3B). Nevertheless, particle size increased with conversion and retained a homogeneous character (Table S4<sup>†</sup>). As observed by TEM, pure spherical NPs were obtained with  $DP_{th} = 100$  at 15 wt%







**Fig. 3** (A) Conversion vs. time plots for PBBMA dispersion RAFTPISA with POEGMA<sub>300</sub> at [AIBN]/[POEGMA<sub>300</sub>] = 0.5 at various solids contents and DP<sub>th</sub>. (B) Size-exclusion chromatograms of polymers obtained by PBBMA dispersion RAFTPISA in methanol at 70 °C with POEGMA<sub>300</sub> at [AIBN]/[POEGMA<sub>300</sub>] = 0.5, DP<sub>th</sub> = 100, and 15 wt% solids content (entry 7, Table S3†). (C) Transmission electron micrograph of nanoparticles obtained after 25 h under conditions corresponding to B (entry 7, Table S3†).

(Fig. 3C). Importantly, the hydrodynamic diameters of the NPs remained essentially unchanged when transferred to water with no sign of aggregation (Table S4†). At higher target DP<sub>th</sub> and/or solids content, PISA syntheses gave more condensed jelly-like solution or gel sedimentation indicating possible formation of worm-like filomicelles/nanofibers (entries 5, 6, and 9, Table S3†). At higher DP<sub>th</sub> and solids content, *i.e.*, 200–400 and 30 wt%, control was lost both in terms of MMDs ( $D > 2$ ) and colloidal stability (precipitation). When POEGMA<sub>300</sub> was replaced with POEGMA<sub>500</sub> (Table S5†), kinetics remained similar (Fig. S14†). For DP<sub>th</sub> = 100 at 15 wt%, a colloidal stable dispersion was obtained, however with conversion-dependent evolution of the dispersion characteristics, following classic observations made in PISA formulations leading to higher-order morphologies: first, fluid dispersions of small nanoparticles; then, gel with large heterogeneous particle size distribution (PSD); finally, viscous dispersions with homogeneous PSD (Fig. S15 and Table S6†). As of now, we have not investigated all these samples departing from classic core-shell spheres in depth, since BNCT has so far typically required spherical nanoparticles. Nevertheless, note that other PISA morphologies, particularly anisotropic structures, could be interesting as well.<sup>43</sup>

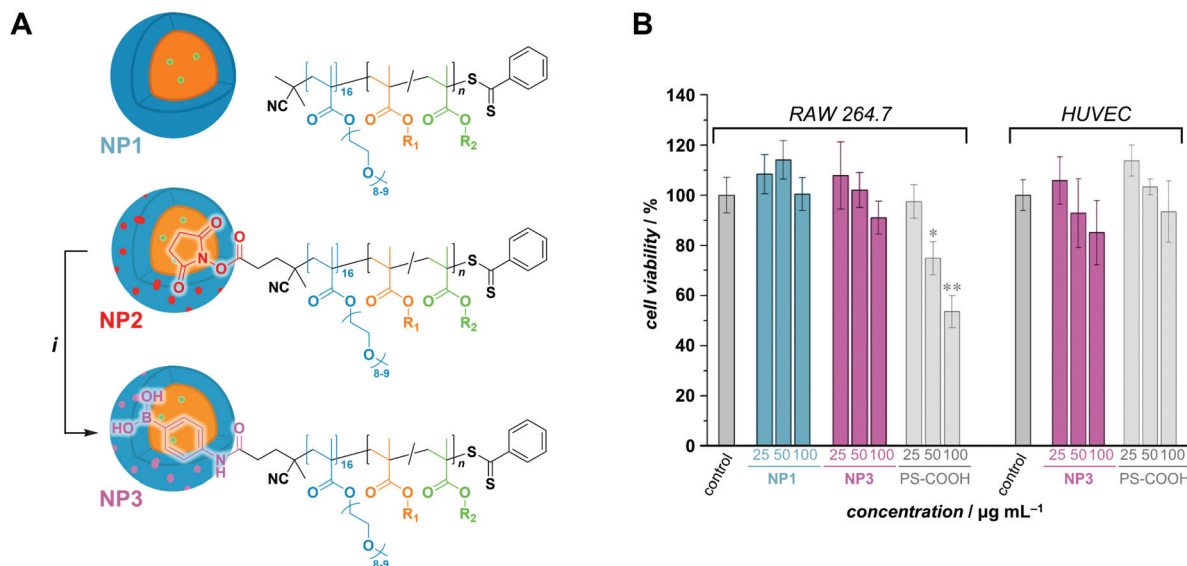
In most dispersion RAFTPISA experiments, the dispersity of the resulting block copolymers was relatively high, with the presence of a low-molar-mass tail in MMDs. While this tail is not uncommon and is typically attributed to a fraction of residual macroCTA, its relatively high intensity was puzzling. We and others did not observe this in the RAFTPISA of BzMA or 2-hydroxypropyl methacrylate with similar macroCTAs.<sup>38,44,45</sup> We postulated that some interactions with the SEC stationary phase arising from moieties not present in those previous systems could be responsible for the observed MMD distortions in the present case. In fact, when we incubated PBBMA in methanol at 70 °C, we found that a steady amount of free pinacol (13–14 mol%) was instantaneously formed (Fig. S17†). To investigate this, we added free pinacol

to a dispersion RAFTPISA in order to shift the equilibrium between boronate ester on the one hand and boronic acid and pinacol on the other hand towards the former. POEGMA<sub>500</sub>-mediated RAFTPISA of PBBMA with pinacol (20 mol% with regards to PBBMA) was slightly accelerated (Fig. S18A†), with final nanoparticles very similar in size (see Fig. S19†). More importantly, SEC analysis of final block copolymer evidenced narrower MMDs with a noticeable decrease of the aforementioned tail signal (Fig. S18B†), which is an indirect proof of possibly interference of hydrolyzed boronate ester moieties with a neat RAFTPISA. A possible solution to this issue would be the use of dry methanol.

The motivation of this study being the development of a potential boron delivery agent for BNCT, we sought to preliminarily assess the biocompatibility of the RAFTPISA-made POEGMA-*b*-PPBMA NPs. For imaging purposes, fluorescent NPs were prepared by adding a small amount of fluorescein methacrylate (FMA) to a PISA recipe.<sup>46</sup> Briefly, nanoparticles NP1 and NP2, without and with surface functional groups, respectively, were obtained from POEGMA<sub>500</sub> and POEGMA<sub>500</sub>NHS, respectively (see ESI†). NHS ester-surface-functionalized NP2 were subsequently reacted with 3-aminophenylboronic acid to produce NP3 with specific targeting agent for sialylated epitopes (Fig. 4A), as mentioned earlier. Successful surface modification to obtain NP3 was confirmed by the appearance of aromatic signals in deuterated polar media, in which the core is invisible (Fig. S20†). The NP dispersions were dialyzed against MeOH, then water, to remove unreacted monomer and switch the dispersant, respectively. Their colloidal characteristics in cell culture media are collated in Table S7.† The fluorescent nature of the NPs was confirmed by fluorescence spectroscopy with  $\lambda_{em,max} = 515$  nm (Fig. S20†).

Next, we analyzed interactions of the NPs with scavenger cells. Indeed, clearance by the reticuloendothelial system (RES) typically accounts for the poor delivery of nanomedicines to target tissues.<sup>47</sup> Therefore, uptake and cytocompatibility of NP1 and NP3 were tested in RAW 264.7 and HUVEC cells,<sup>48</sup>





**Fig. 4** (A) Modification of NHS ester-functionalized PEOGMA<sub>500</sub>NHS-*b*-PPBMA nanoparticles. R<sub>1</sub> = 4-phenylboronate pinacol ester; R<sub>2</sub> = fluorescein. *i*: 3-aminobenzeneboronic acid, triethylamine, ambient temperature. (B) Cell viability of boron-containing PISA-made nanoparticles NP1 and NP3 in RAW 264.7 cells and HUVECs. Data are representative of 2 independent experiments, each performed in triplicates and shown as means ± SEM. \*Significantly different from control group (\**p* < 0.05, \*\**p* < 0.01).

which are widely used as model systems in nanotoxicology and represent macrophages and endothelial cells, respectively, belonging to the RES.<sup>45</sup> Fluorescein-labeled, carboxylated polystyrene (PS-COOH) NPs were included as a reference polymeric nanomaterial.<sup>49</sup> As seen in Fig. 4B, nanoparticles NP1 and NP3 were non-toxic up to the concentration of 100 µg mL<sup>-1</sup> over 24 h of exposure. Note that NP1 could not be assessed with HUVECs because large agglomerates were formed in the corresponding M200/LSGS cell medium (Table S7†) and interfered with image analysis. Compared to PS-COOH NPs, non-functionalized NP1 were taken up at very low amounts in macrophages and adhered to endothelial cells (presumably due to agglomeration). However, 3-aminophenylboronic acid-functionalized NP3, intended for targeting selected cells of interest, did not accumulate in macrophages and endothelial cells (Fig. S21–S23†). Hence, future investigations on clearance of these NPs *in vivo* as well as their potential to target specific cell types are warranted. The difference in colloidal stability between NP1 and NP3 in these conditions remains to be elucidated. Nevertheless, functional nanoparticles NP3 appear to be promising for BNCT.

While their stealth core-shell architecture and their ease of functionalization with targeting moieties or labels confer decisive advantages over boronophenylalanine (BPA) – the classic BNCT agent – it is particularly interesting to put into perspective the “solubilizing effect” of the present NPs with the maximum solubility of BPA. The latter is indeed soluble at physiological pH only up to about 6 mg mL<sup>-1</sup>, that is, 0.031 wt% of boron.<sup>50</sup> Considering the best working systems here (entries 4 and 7 of Tables S2 and S3,† respectively), boron mass concentrations with one order of magnitude higher are achieved (0.42 and 0.33 wt%, respectively), within non-opti-

mized systems (see calculations in ESI†). At the same time, the boron concentration per mass unit of compound remains in the same range: 5.2 wt% for BPA *vs.* 2.8 and 2.2 wt%, respectively.

## Conclusions

In this communication, we described for the first time the synthesis of amphiphilic diblock copolymer nanoparticles with a boron-rich core by polymerization-induced self-assembly (PISA). A new methacrylic monomer with a pinacol boronate ester was synthesized with good yields from commercially available and cheap reagents in two steps. Its efficient RAFT polymerization was demonstrated for limited degrees of polymerization, both in homogeneous and heterogeneous systems. Using hydrophilic macromolecular transfer agents, PISA could be carried out to obtain sub-100 nm spherical nanoparticles using both emulsion and dispersion polymerization in (hydro)alcoholic media. While they may not be useful for the envisioned application, *i.e.*, boron-neutron capture therapy (BNCT), typical PISA higher-order morphologies such as nanorods/fibers and nano/microvesicles were not investigated, yet could be part of further investigations. Future work should also be directed to refining the optimal block copolymer composition (DP of 1<sup>st</sup> block *vs.* DP of 2<sup>nd</sup> block) to increase the relative boron concentration within the nanoparticles. Finally, encouraged by the preliminary results on biocompatibility reported here, implementation of the new nanoparticles in BNCT, first *in vitro*, then possibly *in vivo*, should be performed.



## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

L-C. S. H. thanks the Ministry of Science and Technology of the Republic of China (MOST) and the German Academic Exchange Service (DAAD) for his DAAD-MOST Sandwich fellowship. D. L. thanks the Alexander von Humboldt Foundation for his postdoctoral fellowship. J. R. H. and M.-H. H. thank MOST (Grant No. 109-2634-F-007-023) as well. The Macroarc group (ITCP, KIT) and the Levkin lab (IBCS-FMS, KIT) are gratefully acknowledged for access to SEC and DLS instruments, respectively.

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