Ras activation and symmetry breaking
during *Dictyostelium* chemotaxis

Arjan Kortholt, Ineke Keizer-Gunnink, Rama Kataria, and Peter J.M. Van Haastert§

Department of Cell Biochemistry, University of Groningen, Nijenborgh 7, 9747 AG Groningen, The Netherlands

§Corresponding author:
Tel: (+31)-503634172; Fax: (+31)-503634165; E-mail P.J.M.van.haastert@rug.nl

Running title: symmetry breaking of Ras activation
Key words: chemotaxis, shallow gradients, Ras, amplification, synergy
ABSTRACT

Central to chemotaxis is the molecular mechanism by which a shallow spatial gradient of chemoattractant induces symmetry breaking of activated signaling molecules. Previously we have used Dictyostelium mutants to investigate the minimal requirements for chemotaxis, and identified a basal signaling module providing activation of Ras and F-actin at the leading edge. Here we show that Ras activation follows three phases after application of a pipette releasing the chemoattractant cAMP, each depending on specific GEFs. Initially a transient activation of Ras occurs at the entire cell boundary, which is proportional to the local cAMP concentrations and therefore slightly stronger at the front than in the rear of the cell. This transient Ras activation is present in $g_\alpha 2$-null cells but not in $g_\beta$-null cells, suggesting that $G_\beta_\gamma$ mediates the initial activation of Ras. The second phase is symmetry breaking: Ras is activated only at the side of the cell closest to the pipette. Symmetry breaking absolutely requires $G_\alpha 2$ and $G_\beta_\gamma$, but not the cytoskeleton or four cAMP-induced signaling pathways, PIP3, cGMP, TorC2, PLA2. As cells move in the gradient, the crescent of activated Ras in the front half of the cell becomes confined to a small area at the utmost front of the cell. Confinement of Ras activation leads to cell polarization, and depends on cGMP formation, myosin and F-actin. The experiments show that activation, symmetry breaking and confinement of Ras during Dictyostelium chemotaxis use different G-protein subunits and a multitude of Ras-GEFs and GAPs.
INTRODUCTION

Ras belongs to the family of small G-proteins that function as molecular switches to control a wide variety of important cellular functions. They switch between an inactive GDP-bound and active GTP-bound state. Ras activity is regulated by guanine nucleotide exchange factors (GEFs) that catalyse the exchange of GDP for GTP, thereby activating the Ras protein. GTPase activating proteins (GAPs) stimulate an otherwise low intrinsic GTPase activity by many orders of magnitude, thereby converting the protein back to the inactive GDP-bound form (Bourne et al., 1991; Vetter and Wittinghofer, 2001).

Due to its genetic tractability and high conservation of many important signaling pathways, Dictyostelium has proven to be an excellent model for studying small G-protein signaling (Charest and Firtel, 2007; Kortholt and van Haastert, 2008; Rivero and Somesh, 2002; Sasaki et al., 2004; Weeks, 2005). Genetic studies have shown that Ras proteins are involved in regulation of the cytoskeleton, cell cycle, growth, cell polarity, chemotaxis, and photo- and thermotaxis of multicellular slugs (Chubb et al., 2000; Chubb et al., 2002; Reymond et al., 1984; Sutherland et al., 2001; Weeks, 2005; Wilkins et al., 2000b). RasC and RasG are the best characterized Dictyostelium Ras proteins; both are activated in response to cAMP (Kae et al., 2004), and important for the regulation of the cAMP relay and cAMP-mediated chemotaxis, respectively (Bolourani et al., 2006; Charest et al., 2010; Lim et al., 2001; Lim et al., 2005; Tuxworth et al., 1997).

Gradients of diffusive chemicals give rise to chemotaxis (Hoeller and Kay, 2007; Swaney et al., 2010). Sensitive cells, such as Dictyostelium or neutrophils, can detect very shallow spatial gradients of ~1 % concentration difference across the cell (Mato et al., 1975). Concepts from physics and mathematical models have been employed to understand how cells can detect such minute spatial signals against a large background of mean chemoattractant concentration. These concepts include symmetry breaking to generate a front and rear, signal amplification to enhance spatial differences, and time averaging of spatial information to reduce stochastic noise (Ambrosi et al., 2004; Causin and Facchetti, 2009; Tranquillo et al., 1988; Ueda and Shibata, 2007; van Haastert and Postma, 2007).

The signal transduction cascade for chemotaxis consists of surface receptors, heterotrimeric and small G-proteins, and numerous signaling enzymes, leading to the local activation of the cytoskeleton, predominantly F-actin at the front and myosin filaments at the side
and the rear of the cell. In *Dictyostelium*, a shallow gradient of cAMP induces the activation of cAMP receptors and their associated G-proteins $G_{\alpha2\beta\gamma}$ in a manner that is approximately proportional to the steepness of the gradient (Elzie et al., 2009; Jin et al., 2000; Xiao et al., 1997). In contrast, activation of Ras is much stronger in the front than in the rear of chemotaxing cells (Charest et al., 2010; Kortholt et al., 2011; Sasaki et al., 2004; Sasaki and Firtel, 2006; Zhang et al., 2008). Several studies have shown that inactivation of both *rasC* and *rasG* results in defected cAMP mediated chemotaxis (Bolourani et al., 2006; Kortholt et al., 2011). Four signaling enzymes, PI3K, TorC2, PLA2 and sGC, have been implicated in chemotaxis (Chen et al., 2007; Kamimura et al., 2008; Liao et al., 2010; Veltman et al., 2008). Cells lacking all four enzyme activities show normal Ras activation in cAMP gradients, and can exhibit chemotaxis, but only in steep cAMP gradients (Kortholt et al., 2011). These observations suggest that symmetry breaking during chemotaxis occurs at the level of Ras activation, and that activation of downstream signaling pathways is not essential for Ras activation and chemotaxis.

*Dictyostelium* Ras activation occurs downstream of heterotrimeric G-protein signalling (Kae et al., 2004; Sasaki et al., 2004), but the exact mechanism is not well understood. Here we used a sensitive assay to visualize Ras activation in cells in defined gradients of cAMP. We show that Ras activation follows three phases after application of a stable cAMP gradient. Initially a transient activation of Ras occurs at the entire cell boundary, which is proportional to the local cAMP concentrations and therefore slightly stronger at the front than in the rear of the cell. The second phase is symmetry breaking: Ras is activated only at the side of the cell closest to the pipette. During the third phase the crescent of activated Ras in the front half of the cell becomes confined to a small area at the utmost front of the cell. Mutant studies revealed that activation, symmetry breaking and confinement during *Dictyostelium* chemotaxis use different G-protein subunits and a multitude of RasGEFs and GAPs. Together these experiments provide a conceptual framework to explain the exquisite sensitivity of cells to sense shallow gradients of chemoattractants.
RESULTS

A sensitive assay for Ras activation at the cell boundary

Ras proteins are localized approximately uniform at the plasma membrane of Dictyostelium cells (Sasaki et al., 2004; Sasaki and Firtel, 2009). Stimulation of cells with cAMP does not change the localization of Ras, but locally stimulates the conversion of Ras from the inactive Ras-GDP state to active Ras-GTP (Sasaki et al., 2004; Sasaki and Firtel, 2009). The RBD domain of mammalian Raf binds specifically to the GTP-form of Ras. Ras-activation can therefore be observed as the translocation of RBD-Raf-GFP from the cytoplasm to the cell boundary (Kortholt et al., 2011; Sasaki et al., 2004; Sasaki and Firtel, 2009). Since boundary pixels also contain cytoplasm, translocation assays are fundamentally insensitive (Bosgraaf et al., 2008). Here, we used a more sensitive assay to detect Ras-GTP by co-expressing cytosolic-RFP with RBD-Raf-GFP. In each boundary pixel (i) the fluorescence intensity of cytosolic RFP (cRi) refers to the volume of cytosol in that pixel (see methods). The fluorescence intensity of RBD-Raf-GFP specifically bound to Ras-GTP at the membrane in that pixel (Ψ) is the total GFP fluorescence intensity (Gi) minus the fluorescence intensity of RFP. For direct comparison among different cells and strains, data are presented as the level of RBD-Raf-GFP at the cell membrane relative to the average level of RBD-Raf-GFP in the cytosol, Ψ = (Gi – cRi)/<Gc>.

Cells in buffer exhibit intrinsic symmetry breaking of active Ras

In buffer, RBD-Raf-GFP seems to be localized approximately uniform in the cell with little detectable enhanced localization at the boundary. However, after subtraction of RBD-Raf-GFP in the cytoplasm using cytosolic RFP, it appears that boundary pixels retain a significant amount of RBD-Raf-GFP (Fig. 1A and movie 1). RBD-Raf-GFP is clearly present at the cell membrane in the extending pseudopods, but is also detectable at the plasma membrane of other parts of the cell (Fig. 1A). RBD-Raf-GFP at the membrane (Ψ) was measured around the circumference of 14 cells (Fig 1B). The front of the cell is defined by the center boundary point of the extending pseudopod; RBD-Raf-GFP at the membrane in this point is Ψ = 0.53 ± 0.07 (i.e. RBD-Raf-GFP at the membrane is 53 ± 7% relative to RBD-Raf-GFP the cytoplasm; mean ± SD, n = 14 cells). The membrane at the rear of the cell contains RBD-Raf-GFP at a level of Ψ = 0.10 ± 0.05, about 5 fold less than in the pseudopod. The experiments demonstrate that cells in buffer exhibit...
intrinsic symmetry breaking of activated Ras. The front half of the cell contains about 3-fold more activated Ras than the rear-half of the cell.

How do cAMP gradients influence the local accumulation of activated Ras?

**Multiple phases of Ras activation in cAMP gradients**

Wild-type cells expressing RBD-Raf-GFP and RFP were stimulated with a micropipette releasing cAMP (Fig. 2). The actual cAMP concentration around the cells was determined in control experiments using the fluorescent dye Alexa in the pipette. The cAMP concentration rapidly increases; at a distance of 50 µm from the pipette cAMP reaches half-maximal levels at about 3.2 s. At 60 µm from the pipette the cAMP concentration is not only lower, but also half-maximal levels are reached about 1 s later. Thus a cell at this position receives at the upgradient side of the cell stronger and faster cAMP signals than at the down-gradient side. The measured cAMP concentration was used to calculate the local occupancy of the cAMP receptors with the known affinity of the receptor (Postma and van Haastert, 2009).

All cells exposed to a steep cAMP gradient (5000 pM/µm at a mean cAMP concentration of 150 nM) exhibit a strong and synchronous response (Movie 2 and Fig. 2), which allows detailed kinetic analysis of the translocation of RBD-Raf-GFP from the cytoplasm to the membrane (Fig. 3). Upon application of the cAMP gradient, RBD-Raf-GFP rapidly depletes from the cytoplasm, followed by a return to the cytoplasm around 15 s (Fig. 3A). In uniform cAMP RBD-Raf-GFP remains in the cytoplasm, but in a cAMP gradient RBD-Raf-GFP returns to the membrane, but only at the upgradient side of the cell (Figs. 2, 3B). This shows that Ras activation in cAMP gradients consist of three phases, which we first will describe for cells exposed to a steep cAMP gradient inducing strong chemotaxis and subsequently analyze these phases in cells exposed to different cAMP gradients.

**Initial “uniform” response: excitation and adaptation of Ras activation**

At about 6 seconds after application of a steep gradient of cAMP, RBD-Raf-GFP exhibits maximal translocation from the cytoplasm to the entire membrane in what appears as a uniform response (Figs 2, 3A). However, detailed measurement of the local levels of RBD-Raf-GFP at the membrane reveals a gradient of RBD-Raf-GFP at the membrane that is similar to the gradient of cAMP (Fig. 3E). Although these gradients are said to be steep for chemotaxis (20% concentration
difference across the cell induces very strong chemotaxis) the differences in receptor occupancy between upgradient and downgradient sides of the cell are actually relatively small; the initial Ras activation exhibits a similarly small difference across the cell (Fig. 3E). After the initial translocation of RBD-Raf-GFP to the entire membrane, RBD-Raf-GFP starts to dissociate from the membrane. This dissociation is observed at the downgradient side of all cells; it occurs with a half-time of 4-6 seconds (Fig. 3B), is completed after ~30 seconds, and never reoccurs in the stable cAMP gradient. In contrast, at the upgradient side of the cells the dissociation of RBD-Raf-GFP from the membrane is followed by a return of RBD-Raf-GFP at the membrane (Fig. 3B). The response is more heterogeneous than at the downgradient side of the cell. In some cells dissociation of RBD-Raf-GFP from the membrane is nearly complete before it starts to return, while in other cells RBD-Raf-GFP starts to return at the membrane sooner, long before dissociation could be completed. The fraction of cells that exhibit late reappearance of RBD-Raf-GFP at the membrane was used to estimate the dissociation kinetics of RBD-Raf-GFP from the membrane at the upgradient side of the cell, which appeared to be not statistically different from that at downgradient side of the cell (downgradient: t1/2 = 5.8 ± 1.1 s; upgradient: t1/2 = 5.5 ± 1.3 s , n = 4 cells).

**Symmetry breaking**

As mentioned above, RBD-Raf-GFP starts to return to the membrane at the upgradient side of the cell at about 12 to 24 seconds after application of the pipette. Interestingly, when measured as the depletion of RBD-Raf-GFP from the cytoplasm, this recovery of RBD-Raf-GFP from cytoplasm to the membrane is completed after 30 seconds (Fig. 3B), but continues till 90 seconds when measured as the membrane level of RBD-Raf-GFP at the front of the cell (Fig. 3C), suggesting that activation of Ras at the leading edge may be complex. Figures 3D and 3F reveal that at 30 seconds after stimulation, Ras activation occurs at a relatively large crescent of 15.6 +/- 1.4 μm, comprising ~40 % of the circumference of the cell. At 90 seconds after stimulation the crescent is much smaller (8.3 +/- 0.7 μm) with a concomitant increase of the intensity at the utmost leading edge of the cell. This suggests that gradient sensing comprises two processes: symmetry braking to induce Ras activation at the upgradient half of the cell, followed by confinement of activated Ras into a smaller crescent. Figure 3C reveals that in steep gradients Ras activation in the upgradient half of the cell is about 10-fold larger than in the downgradient half of the cell. This
symmetry breaking starts at ~16 seconds after application of the cAMP gradient, reaches half-maximal levels in ~6 seconds, and is complete at 30 seconds after stimulation (Fig. 3G).

*Confinement*

The confinement of Ras activation into a smaller crescent in steep gradients is the slowest process. It starts at 20 seconds, has a half-time of 24 seconds and reaches a final level at about 2 minutes after stimulation (Fig. 3D, G). Between 30 and 90 seconds after stimulation, the crescent reduces about 2-fold in length, which is accompanied by a ~2-fold increase of intensity of RBD-Raf-GFP at the leading edge of the cell Fig. 3F. Thus the notion of constant depletion levels of RBD-Raf-GFP in the cytoplasm whereas the intensity at the leading edge increases (Fig. 3B, C) is caused by symmetry breaking to form a crescent of activated Ras and the confinement of activated Ras into a smaller crescent.

*Gradient-dependent activation of Ras.*

Movie 3 shows the localization of RBD-Raf-GFP at the membrane before and after introduction of a micropipette producing a shallow cAMP gradient (28 pM/µm at a mean background concentration of 2.5 nM). Cells move towards the pipette with a chemotaxis index of 0.5, i.e. with a small directional bias relative to the movement in buffer. The localization of RBD-Raf-GFP in these cells suggests a series of responses that is qualitatively similar as in steep gradients, but smaller in magnitude. Figure 2B presents typical images of RBD-Raf-GFP at the membrane in a shallow gradient. Upon application of a shallow cAMP gradient, RBD-Raf-GFP translocates from the cytoplasm to the boundary of the cell. As in steep gradients, translocation is maximal at ~6 seconds, and recovers by adaptation. The kinetics of adaptation are nearly identical in shallow and steep gradients (t1/2 = 7.6 ± 1.7 s and t1/2 = 5.7 ± 1.1 s in shallow and steep gradients, respectively; Fig. 3G). Following this activation and deactivation of Ras, RBD-Raf-GFP at the membrane starts to reappear at the upgradient half of the cell at a level that is about 5-fold more than at the downgradient half of the cell. This symmetry breaking in a shallow cAMP gradient follows the same kinetics as in a steep gradient and reaches a steady state at about 40 seconds after application of the gradient (Fig. 3C, G). The spatial activation of Ras is shown in Fig. 3D revealing that RBD-Raf-GFP is localized at the membrane in a wide crescent. In contrast to a steep gradient, this large area of Ras activation does not confine in time to a smaller crescent with
higher intensity. In summary, in a shallow cAMP gradient, initial activation and adaptation, as well as symmetry breaking are smaller but follow the same kinetics as in steep cAMP gradients. In contrast, confinement of Ras activation, and it’s induced polarization, does not occur in shallow cAMP gradients.

To determine the gradient-dependent activation of Ras, the experiments were repeated with pipettes containing different cAMP concentrations and cells were observed at different distances from the pipette. This provides a series of experimental conditions with gradients of different steepness of the cAMP concentration. The chemotaxis indexes of cells in these gradients are presented in Figure 4D. To accommodate intrinsic Ras symmetry breaking as well as gradient-induced symmetry breaking, we defined the front of the cell as the area from which a pseudopod is extended. In all these experiments we observed no significant changes of RBD-Raf-GFP levels at the membrane in the rear half of the cell, which is about 10% of the level of RBD-Raf-GFP in the cytoplasm ($\Psi = 0.10 +/- 0.01$).

In buffer the front half of the cell contains ~3-fold more activated Ras compared to the rear half of the cell (Fig. 4A). cAMP gradients up to ~30 pM/µm induce only a slight increase of activated Ras in the front half of the cell compared to cells in buffer. Ras activation at the front of the cell increases with increasing steepness of the gradient, until a level that the front half of the cell contains ~8-fold more activated Ras than the rear half of the cell. Data are best fitted with a Hill plot that yields a Hill coefficient of $n = 0.73$ and the gradient inducing half-maximal Ras activation at the front of $K_{0.5} = 220$ pM/µm (Fig. 4A). Confinement of the crescent of activated Ras upon longer exposure of cells to a cAMP gradient does not occur in shallow gradients below ~50 pM/µm (Fig. 4B). Also these data are best fitted with a Hill plot that yields a Hill coefficient of $n = 0.75$ and the gradient inducing half-maximal crescent confinement of $K_{0.5} = 890$ pM/µm (Fig. 4B). The combination of symmetry breaking and confinement of the crescent in steep gradients leads to a ~5-fold increase of the intensity of RBD-Raf-GFP at the utmost front of the cell (Fig. 4C). Due to the negative cooperativity (Hill coefficient <1) and the differences in $K_{0.5}$ for symmetry breaking and confinement of the crescent, this increase of Ras activation at the utmost front of the cell occurs over 4 decades of the cAMP gradient (Fig. 4C).

*A predominant role for RasG in response to cAMP*
Thus far five *Dictyostelium* Ras proteins have been characterized in detail, and they all appear to have important and distinct roles in cell physiology; RasB is essential for cytokinesis, RasD regulates phototaxis and thermotaxis of multicellular slugs, RasS is important for the switch between eating and moving, and RasC and RasG together regulate all cAMP mediated signalling in early development (Chubb et al., 2000; Chubb et al., 2002; Reymond et al., 1984; Sutherland et al., 2001; Weeks, 2005; Wilkins et al., 2000b). Although RasG is the predominant Ras protein detected by our marker, the RBD domain of mammalian Raf also binds with lower affinity to active RasC and most likely all other *Dictyostelium* Ras proteins (Kae et al., 2004; Sasaki and Firtel, 2009). We here have used our sensitive assay to determine the specific contribution of RasC and RasG to the three cAMP mediated activation phases. Cells with a deletion of rasC have only a slight defect in the uniform response and confinement, and show almost normal Ras activation at the leading edge of cells moving in a cAMP gradient (Fig 5, Table 1). Several studies have shown that disruption of both rasC and rasG results in severe growth, developmental and chemotaxis defects (Bolourani et al., 2006; Kortholt et al., 2011). In the contrary, a recent study showed that rasC/rasG-null cells are not essential for chemotaxis to both folate and cAMP (Srinivasan et al., 2013). Since the cause of these conflicting data are unknown, but might due to compensation by other pathways or upregulation of other Ras proteins, we instead used cells expressing dominant negative RasGS17N from a tightly controlled doxycycline-inducible promoter (Veltman et al., 2009b). Wild-type cells expressing RasGS17N have reduced chemotaxis (chemotaxis index is 0.65 ± 0.07) compared to wild-type cells (chemotaxis index is 0.88 ± 0.10), exhibit a more than two fold reduced uniform response, show strong defects in symmetry breaking, and have no confinement. (Fig 5, Table 1). Furthermore, rasC-null cells expressing RasGS17N have strongly impaired chemotaxis (CI = 0.22 +/- 0.14), do not show a significant change in the localization of RBD-Raf-GFP, neither to uniform cAMP nor in a cAMP gradient (Fig 5, Table 1, Movie S4). Together these results confirm previous genetic studies (Bolourani et al., 2006), and show that RasG is the key Ras protein in the regulation of cAMP mediated chemotaxis. However, rasC-null cells expressing RasGS17N show a strongly reduced, but significant, RBD-Raf-GFP translocation in response to uniform folate (Table S2), suggesting that also other Ras proteins contribute to folate chemotaxis.

**Different roles of G-protein subunits**
The cAMP receptor activates the heterotrimeric G-protein Gα2βγ (Jin et al., 2000; Xiao et al., 1997). Mutant cells with a deletion of the single gβ gene do not show any changes in the localization of RBD-Raf-GFP, neither to uniform cAMP nor to a cAMP gradient (Fig. 6A). Cells also do not exhibit chemotaxis, confirming that Gβγ is essential for chemotactic signal transduction (Sasaki et al., 2004; Wu et al., 1995). Surprisingly, cells with a deletion of gα2 do show a very significant translocation of RBD-Raf-GFP to the cell boundary in response to uniform cAMP (Fig. 6A). Expression of RasG(S17N) in gα2-null cells completely inhibits this RBD-Raf-GFP response, indicating that the detected Ras activation in gα2-null cells is completely dependent on RasG (Table 1). The RBD-Raf-GFP response is less pronounced in gα2-null cells compared to wild-type cells, and requires ~10-fold higher cAMP concentrations (Fig. 6C). The rate of Ras activation is initially the same in gα2-null and wild-type cells (Fig. 6B). However, in gα2-null cells Ras activation stops after 3.8 ± 0.7 s, while in wild-type cells activation continues till 6.0 ± 0.9 s after stimulation with uniform cAMP (means ± SD, n = 8).

As mentioned above for wild-type cells, a cAMP gradient initially induces a “uniform” transient translocation of RBD-Raf-GFP to the cell boundary, which is followed by Ras activation at the side of the cell facing the cAMP gradient (movie 1). Also in gα2-null cells, the cAMP gradient induces a short transient uniform Ras activation, but in contrast to wild-type cells, the specific upgradient response never occurs (Fig. 6A); in addition, gα2-null cells do not exhibit any directional movement towards cAMP.

Vegetative Dictyostelium cells respond to the chemoattractant folate, which activates many signaling pathways in a way that is similar to their activation by cAMP in starved cells. Folate chemotaxis requires activation of Gα4βγ (Hadwiger et al., 1994) and Ras at the leading edge (Lim et al., 2005). Whereas cells lacking gβ don’t show any folate stimulated Ras activation, gα4-null cells still have a normal Ras response to uniform folate. As observed for cAMP in gα2-null cells, cells lacking gα4 don’t show the specific upgradient response or directional movement in a folate gradient (Kataria et al., 2013).

These results indicate different roles for Gβγ and Gα2/Gα4 during chemotaxis. The experiments with wild type, gα2-null and gα4-null cells suggest that Gβγ induces Ras activation, which is completely transient, even in a cAMP or folate gradient. Ras activation by uniform folate is about equal in wid-type and gα4-null cells, suggesting that Gα4 provides little contribution to
Ras activation. However, a comparison of Ras activation by uniform cAMP between wild-type and \( g\alpha2\)-null cells suggests that \( G\alpha2 \) contributes to Ras activation by which the response to uniform cAMP is prolonged. More importantly, in a cAMP or folate gradient, \( G\alpha2 \) or \( G\alpha4 \) mediates symmetry breaking by which Ras activation re-occurs at the side of the cell facing the chemoattractant, and cells move towards cAMP or folate.

**Role of GEFs and GAPs**

The genome of *Dictyostelium* contains 25 genes encoding for GEFs and 17 genes encoding for GAPs that potentially activate and inactivate Ras, respectively. Many of these genes have been inactivated by homologous recombination, without very severe effects on chemotaxis (Kortholt and van Haastert, 2008; Weeks, 2005; Wilkins et al., 2005). We have used the sensitive assay to measure Ras activation in 9 mutants (Table I). Recently it has been shown that the GAP NfA regulates RasG activity during chemotaxis (Sasaki and Firtel, 2009); consistently \( nfaA\)-null show strongly reduced symmetry breaking and lack confinement (Table 1). The reduced symmetry breaking is the combined result of reduced Ras activation at the upgradient half and increased Ras activation at the downgradient half of the cell. All tested GEF mutants, with the exception of \( gefL\)-null cells, exhibit strongly reduced symmetry breaking, from ~8-fold in wild-type cells to only ~3-fold in the mutants. In all GEF mutants this defect in symmetry breaking is caused by reduced Ras activation at the upgradient half of the cell. It should be noted that symmetry breaking is not absent in any mutant, suggesting that in wild type cells symmetry breaking is mediated by multiple Ras-GEFs.

The confinement of the crescent still occurs in mutants with a deletion of \( gefB\), \( C\), \( G\), \( L\) and \( M\), but is essentially absent in mutants lacking \( gefD\) and \( gefE\). This suggests that a specific subset of GEFs and GAPs may be involved in restricting Ras activation to the utmost front of the cell. To investigate the role of confinement of Ras activation in a small crescent for cell shape, we have measured cell elongation defined as the ratio of the cell’s length and width. The results (see Table S1, Fig. S2) indicate that there is no correlation between cell elongation and the Ras responses. For instance, \( gefD\)-null and \( gefE\)-null cells are both defective in confinement, but the \( gefD\)-null mutant is more elongated whereas \( gefE\)-null cells are far less elongated than wild-type cells.
The signalling pathways and cytoskeleton are important for confinement

Previously it has been shown that the formation of F-actin and the four signalling pathways, PI3K, TorC2, PLA2 and sGC, are not required for Ras activation by uniform cAMP or in a cAMP gradient (Kortholt et al., 2011). These data were obtained for Ras localization at the leading edge in a stable cAMP gradient. Table I shows the data for the different phases of Ras activation upon application of the pipette releasing cAMP for wild-type, cells with a deletion/inhibition of all four signalling pathways, and myosin-null cells, all in the absence or presence of the F-actin inhibitor LatA. All cell lines exhibit a similar “uniform” translocation of RBD-Raf-GFP to the membrane at ~6 second after application of the pipette, the subsequent dissociation of RBD-Raf-GFP from the membrane, and the reappearance of RBD-Raf-GFP at the leading edge. Symmetry breaking (ratio of Ras activation in the upgradient half versus the downgradient half of the cell) is essentially identical in all these cell lines (Table I). In contrast, confinement of the crescent of activated Ras that occurs in wild type cells exposed to steep gradients does not occur in cells with a deletion of the four signaling pathways, deletion of myosin II, or depletion of F-actin with LatA. Analysis of single pathway mutants show that cGMP is essential for confinement (the crescent is $13.3 \pm 1.0 \mu m$ in gc-null cells), whereas PIP3, TorC2 and PLA2 play a minor role in confinement (the crescent is $9.4 \pm 1.3 \mu m$ in WT cells in the presence of 50 $\mu$M PI3K inhibitor LY, $9.7 \pm 1.3 \mu m$ in rip3-null and pkbR1-null cells, and $7.9 \pm 2.1 \mu m$ in cells lacking pla2).
DISCUSSION

With a sensitive assay to detect activated Ras at the plasma membrane, we showed here that Dictyostelium cells exhibit patches of activated Ras at the leading edge. Cells in buffer have about 3-fold more active Ras in the front half of the cell than in the rear half. This gradient of active Ras is also detectable in cells lacking $g \beta \gamma$ or $g \alpha 2$, suggesting a mechanism of intrinsic symmetry breaking ((Sasaki et al., 2007), Fig. S1). An external gradient of chemoattractants further activates Ras. With the more sensitive assay to detect active Ras we showed here that chemotactic mediated Ras activation consists of three phases. The first phase consists of activation and adaptation of the chemotactic machinery, and is essentially identical in uniform cAMP and in a cAMP gradient. Application of cAMP induces the translocation of RBD-Raf-GFP to the entire membrane, and the formation of F-actin at the entire cortex. Both in uniform cAMP and in a cAMP gradient, local Ras activation is proportional to the local activation of the receptor. Therefore, the initial Ras activation in a shallow gradient is only slightly stronger at the front than the rear of the cell. The initial activation of Ras is transient; it is maximal after ~6 seconds and declines with a half-life of ~4-6 seconds due to adaptation. This half-life is essentially identical in cells stimulated with uniform cAMP or with a shallow or steep cAMP gradient, and also at the front or the rear of the cell. Activation of Ras requires surface receptors and G$\beta \gamma$, but surprisingly can occur in the absence of G$\alpha 2$. In wild type cells most of the G$\beta \gamma$ is released by cAMP from G$\alpha 2 \beta \gamma$ (Kumagai et al., 1989); in g$\alpha 2$-null cells G$\beta \gamma$ may be released from other cAMP-stimulated G-proteins, such as G$\alpha 1 \beta \gamma$ and G$\alpha 9 \beta \gamma$ (Bominaar and van Haastert, 1994; Brzostowski et al., 2002). Activation of Ras in g$\alpha 2$-null cells is smaller in magnitude and requires higher cAMP concentrations than in wild-type cells. Three non-exclusive mechanisms may explain this reduced response: G$\alpha 2$ contributes to Ras activation, as was suggested by the altered kinetics in g$\alpha 2$-null cells, or less G$\beta \gamma$ is activated in g$\alpha 2$-null cells, or mixtures of wild-type and g$\alpha 2$-null cells do not develop completely normal. However, since cells lacking g$\alpha 4$-null show a similar Ras response to folate as g$\alpha 2$-null cells to cAMP, the later mechanism seems to be unlikely.

The signaling molecules PI3K, cGC, TorC2, and PLA2, as well as the cytoskeleton components F-actin and myosin have little effect on the initial activation and adaptation of Ras. Also deletion of the individual GEFs does not have a very strong effect on activation and
adaptation, suggesting that multiple GEFs contribute to Ras activation. Importantly, at the end of this initial phase of Ras activation cells are in an adapted state.

After the initial transient activation, Ras becomes reactivated exclusively at the upgradient side of the cell. The magnitude of the response depends predominantly on the steepness of the gradient. Thus, in uniform 100 nM cAMP no reactivation of Ras is detectable, but strong activation of Ras is observed at the leading edge in a gradient of 10 nM/µm at a mean concentration of 100 nM cAMP. This symmetry breaking of Ras activation absolutely requires the presence of Ga2; in ga2-null cells a cAMP gradient induces the initial “uniform” Ras response but not Ras activation at the leading edge and no chemotaxis. The signaling molecules PI3K, sGC, TorC2, and PLA2 do not contribute to symmetry breaking of Ras activation in a cAMP gradient, neither does F-actin or myosin. The experiments suggest that symmetry breaking is mediated by Ga2. Since uniform cAMP induces stronger Ras activation in wild-type cells than in ga2-null cells, we propose that Ga2 contributes to Ras activation, presumably by activating additional GEFs or locally inhibiting GAPs. Dictyostelium contains 25 GEFs. Deletion experiments of 9 GEFs reveal that in 8 mutants symmetry breaking is strongly reduced, but not absent. These data suggests that multiple GEFs contribute to symmetry breaking.

During symmetry breaking the downgradient half of the cell remains adapted, whereas Ras activation occurs in a relatively large crescent at the upgradient half of the cell. This crescent of membrane bound RBD-Raf-GFP has the highest intensity at the leading edge and gradually declines further away from the front as a bell-shaped curve with a width at half height of ~15 µm. In wild type cells the crescent of activated Ras becomes more confined to the utmost leading edge, which is the third phase of Ras activation during chemotaxis. Confinement occurs without a change of the total amount of activated Ras as indicated by the constant amount of RBD-Raf-GFP in the cytoplasm or at the entire boundary of the cell. The initial wide bell-shaped curve of membrane-bound RBD-Raf-GFP becomes very narrow, with very steep flanks. This suggests that during confinement of the crescent RBD-Raf-GFP dissociates from the ends of the crescent and binds to the utmost front. The local amount of active Ras-GTP depends on the local activity of GEFs and GAPs. The experiments suggest that during initial symmetry breaking long-range gradients of GEFs at the front and GAPs at the rear lead to the large crescent of active Ras. During subsequent confinement a sharp spatial transition between active and inactive Ras is induced, suggesting that at the utmost front active Ras induces more GEF activity, while further
away from the front GAPs are activated leading to inactivation of Ras. Confinement of Ras activation to the leading edge requires F-actin and myosin, and the signaling molecules that regulate myosin, notably cGMP in Dictyostelium. An attractive model is that myosin filaments that accumulate at the side and rear of the cell during chemotaxis activate or recruit GAPs, whereas actin filaments that accumulate in the front activate or recruit GEFs. Confinement of Ras activation is normal in mutants with a deletion of gefB, C, G, L M and R, but is absent in mutants lacking gef D and E, and nfaA. Interestingly, GEFD contains a putative RhoGAP domain, suggesting a direct link with the actin cytoskeleton (Wilkins et al., 2005).

Expression of dominant negative RasGS17N in rasC-null cells results in a strongly reduced, but significant RBD-Raf-GFP translocation in response to uniform folate. This suggests that in addition to RasC and RasG, other Ras proteins contribute to folate signalling. In the contrary, the current and previous experiments show that either RasC or RasG is necessary for the transduction of the cAMP signal and that RasG is the major Ras protein regulating cAMP mediated symmetry breaking and confinement (Bolourani et al., 2006; Kortholt et al., 2011; Sasaki et al., 2004). Consistently, the strongest defects in symmetry breaking were observed for cells lacking nfaA and gefR, the only so far reported RasG specific GAP and GEF, respectively (Kae et al., 2004; Zhang et al., 2008). Much smaller defects in the chemotactic response were observed in cells lacking the RasC specific gefA (Kae et al., 2007). However, the deletion experiments also show that activation, symmetry breaking, and confinement use a multitude of Ras-GEFs, which are most likely not all directly regulating RasG activity (Kae et al., 2007). Furthermore, during confinement the amplification pathways and cell cortex provide feedback regulation on Ras activity. This suggest that also other Ras proteins, activated downstream of RasG, can contribute to chemotaxis. Consistent with such a model; RapA is activated in a RasG dependent manner, GEFQ activates RasB in an actin dependent manner, and both RasB and RapA are important for myosinII disassembly at the front of chemotaxing cells (Jeon et al., 2007; Mondal et al., 2008).

The combination of symmetry breaking and confinement leads to strong Ras activation at the leading edge. The ratio of active Ras at the front relative to the rear is ~10 in a steep gradient, where the ratio of receptor occupancy is only ~1.2, indicating strong spatial amplification of the cAMP signal. Interestingly, in shallow gradients (< 30 pM/µm) very little amplification of the cAMP gradient is detectable at the level of Ras activation.
From movement in buffer to chemotaxis in shallow and steep gradients

In the absence of chemotactic signals, cells do not move in random directions, but exhibit a persistent random walk (van Haastert and Bosgraaf, 2009). Cells have a high probability to extend a new pseudopod from the same Ras-activated area of the cell and in the same direction as the current pseudopod. This intrinsic pathway for symmetry breaking is independent of receptor or heterotrimeric G-protein signalling. At the lower limit of chemotaxis (~2 pM/µm) the very shallow gradient activates a few additional Ras molecules at the high-gradient side of the cell, which may induce a small gradient-oriented bias of the intrinsic Ras asymmetry thereby changing the probability where actin polymerization occurs and a pseudopod is made. Somewhat steeper gradients (~100 pM/µm) induce more Ras-GTP molecules and therefore a stronger directional bias. Much steeper gradients (~2000 pM/µm) also induce amplification of Ras activation providing full activation of Ras in the utmost leading edge of the cell. In these cells all pseudopods are formed in the direction of the steep gradient.

This cAMP gradient dose-dependent activation of Ras is similar in wild-type cells and in mutant cells lacking four signaling pathways (PI3K, TorC2, PLA2 and sGC) (Kortholt et al., 2011). Interestingly, these mutant cells can chemotax only in steep gradients with strong activation of Ras at the leading edge. Thus, the basal chemotaxis system composed of cAMP receptors, Gα2βγ, RasC/G and Rac/actin is sufficient for chemotaxis, but is relatively insensitive. The few molecules of Ras that are activated by the shallow gradient require the signaling enzymes PI3K, TorC2, PLA2 and sGC to induce a stronger directional bias. Previous experiments (Bosgraaf and van Haastert, 2009) have shown that the signaling molecules PLA2 and cGMP function as memory of direction. Wild-type cells in buffer have the strong tendency to persist in the direction of movement, which is due to the alternatingly left/right extension of pseudopods at a small angle. The persistence of direction has a time constant of ~3 minutes, equivalent to ~10 pseudopods. In the absence of PLA2 and cGMP each new pseudopod is extended in a random direction. Thus, in wild type cells the small directional bias that is imposed by the shallow gradient slowly accumulates at each new pseudopod due to the persistence memory of PLA2 and cGMP. The other signaling molecules PIP3, TorCs, sGC are formed or localized to the place where Ras was activated. They enhance Ras-induced Rac activation and/or formation of F-actin at the leading edge. In concepts from physics, these signaling pathways enhance the signal-to-noise
ratio, because they function as time-averaging and memory device (PLA2 and cGMP) and as amplifier of spatial information (PIP3, TorCs, sGC). Together these signaling pathways allow chemotaxis to occur in cAMP gradients that are ~100-fold more shallow (Fig 4D).

**Conclusion**

The experiments provide a conceptual framework of gradient sensing and chemotaxis. A cAMP gradient induces the activation of the G-protein Go2βγ. The Gβγ subunit induces the uniform activation and adaptation of Ras activation. The Go2 subunit is essential to activate Ras at the side of the cell facing the highest concentration of cAMP. Local and global activities of specific GEFs and GAPs lead to Ras activation in a large area at the front of the cell. As cells start to move in the direction of the cAMP gradient, the rearranged cytoskeleton locally activates additional GEFs and GAPs to confine Ras activation to the utmost leading edge, thereby inducing polarized cells that move persistently towards cAMP. Downstream signaling molecules contribute to chemotaxis as memory of direction and amplifiers of spatial information.
MATERIAL AND METHODS

Cell culture and preparation

The strains used are wild-type AX3, rasC-null (Bolourani et al., 2006), gβ-null (Wu et al., 1995), gα2-null (Kumagai et al., 1991), gc-null (Veltman and van Haastert, 2008), myoII-null (Yumura et al., 2005), gefA-null (Insall et al., 1996), gefB-null (Wilkins et al., 2000a), gefC-null, gefD-null, gefE-null gefG-null, gefL-null (Wilkins et al., 2005), gefM-null (Arigoni et al., 2005), gefR-null (Kae et al., 2007) and nfaA-null (Zhang et al., 2008). RasG activation was inhibited by expressing dominant negative RasG(S17N) from the previously described doxycycline inducible vector pDM310 (Veltman et al., 2009b). Expression of RasG(S17N) from this dox-on system was induced by growing the cells for at least 24 hours in the presence of 10 µM doxycycline. To determine the contribution of the signaling pathways, we used deletion mutants in specific genes in combination with drugs to inhibit one or a combinations of the sGC, PLA2, PI3K and TorC2 pathways as previously described (Kortholt et al., 2011). Actin polymerization was inhibited with 5 µM Latrunculin A (LatA).

To study Ras activation, RBD-Raf-GFP (amino acids 50-134 of RAF1) was co-expressed with cytosolic mRFP from an modified DM318 vector (Veltman et al., 2009a), in which the neomycin cassette was replaced by hygromycin. F-actin formation was visualized by expressing LimEΔcoil-GFP (amino acids 1-145 of LimE) from the previously published LB15B plasmid (Kortholt et al., 2011). Cells were grown in HL5-C medium including glucose (ForMedium) containing 50 µg/ml Hygromycin B (Invitrogen) for selection.

We have taken precautions to obtain mutant cells that exhibit optimal chemotaxis towards cAMP. Many Dictyostelium mutants with deletion of cAMP receptors, G-proteins or signaling enzymes do not acquire good chemotactic responsiveness to cAMP, due to impaired development and reduced expression of other signaling proteins. Development can be improved considerably by exogenous pulsing with cAMP or starving mutants in the presence of wild-type cells (Kortholt et al., 2011). Unlabelled wild-type cells were mixed with equal amounts of GFP/RFP-tagged mutant cells, and starved on agar for 5 to 7 hours till streams were formed. Cells were then harvested, suspended in 10 mM KH2PO4/Na2HPO4, pH 6.5 (PB), and used in chemotaxis experiments.

Chemotaxis assays
To investigate how Ras is locally activated during chemotaxis, cells expressing RBD-Raf-GFP and RFP were stimulated with a micropipette releasing cAMP (Fig. 2). Cells were harvested in PB and incubated on a glass support at a density of ~4x10⁴ cells/cm². The distance between adjacent cells is ~5 cell lengths, by which cells do not form streams, and chemotaxis can be measured in the absence of strong interactions between mutant and wild-type cells. Chemotaxis was observed using a confocal fluorescent microscope, detecting wild type and mutant cells in the phase contrast and fluorescent channel, respectively. Control experiments using the fluorescent dye alexa in the pipette, and diffusion theory, reveal that at a distance of 50 µm from the pipette the spatial gradient is stable at 5 to 10 seconds after application of the pipette (Postma and van Haastert, 2009). Using pipettes with different cAMP concentrations and recordings at different distances from the pipette, cells are exposed to shallow or steep cAMP gradients (in pM/µm) at defined mean background cAMP concentrations (in nM). Confocal images were recorded using a Zeiss LSM 510 META-NLO confocal laser scanning microscope equipped with a Zeiss plan-apochromatic 63x numerical aperture 1.4 objective.

**A sensitive assay for Ras activation at the cell boundary**

In *Dictyostelium* Ras proteins are present at the plasma membrane. Stimulation of cells with cAMP does not change the localization of Ras, but converts Ras from the inactive Ras-GDP state to active Ras-GTP. The RBD domain or mammalian Raf binds specifically to the GTP-form of Ras, mainly RasG. Upon cAMP stimulation RBD-Raf-GFP translocates from the cytoplasm to the cell boundary (Fig. 2). The RBD-Raf-GFP response to cAMP is easy detectable, very reproducible and robust. However, assays measuring the activation of a membrane protein using the translocation of a cytosolic marker to the cell boundary are fundamentally insensitive. Assume a cell with no Ras activation and a fluorescence intensity of RBD-Raf-GFP in the cytosol equal to 100. The boundary pixels are on average half-filled with cytoplasm and have an intensity of 50. When a weak cAMP signal induces little activation of Ras by which ~10% of cytosolic RBD-Raf-GFP translocates from the cytoplasm to the membrane, the intensity in the cytosol decreases to ~90, whereas the intensity in the boundary pixel increases to only 60-70, which is still below the fluorescent intensity of the adjacent cytosolic pixel. Previously we have demonstrated for a PIP3 marker that such small translocations can be easily measured by co-expressing the GFP-detector and cytosolic RFP (Bosgraaf et al., 2008). Here we co-expressed RBD-Raf-GFP and cytosolic-
RFP from one plasmid. The RBD-Raf-GFP minus the RFP signal in the boundary pixels represents $\Psi$, the amount of RBD-Raf-GFP that specifically binds to Ras-GTP at the membrane.

For calculations we used the following steps. First the mean background fluorescence intensity in the red and green channels outside the cells is determined and subtracted from all pixels of the movie. Then individual cells are analyzed. To correct for the difference in expression levels of the two markers within one cell, large areas of the cytoplasm are selected (excluding nucleus and vacuoles), yielding the mean average fluorescent intensity in the cytoplasm of the red channel $<R_c>$ and green channel $<G_c>$, respectively. This provides the correction factor $c = <G_c>/<R_c>$, and all pixels in the red channel are multiplied by $c$. Then for each pixel $(i)$ of that cell we calculated the difference of green and corrected red signal, and this is normalized by dividing by the average fluorescent intensity of GFP in the cytoplasm. Thus, $\Psi(i) = (G_i - cR_i)/<G_c>$. Previous analysis with a PIP3 detector (Bosgraaf et al., 2008) and current analysis with the Ras-GTP detector (Fig. 2) reveal that this method provides a ~10-fold increase of sensitivity to detect local activated Ras. It should be noted that a value of $\Psi = 0.4$ is highly significant and easily detectable using the information from the green and red channels, but is undetectable as an increase RBD-Raf-GFP at the cell boundary in the green channel only. Thus all experiments yielding values of $\Psi$ between 0 and ~0.5 yield new information on Ras activation not presented previously.

**ACKNOWLEDGEMENTS**

We want to thank Dr. R.A. Firtel, Dr. G. Weeks and the *Dictyostelium* stock center for providing the mutant strains used in this study.
References


LEGENDS TO THE FIGURES

Figure 1. Activated Ras-GTP in unstimulated cells. Wild type cells in buffer expressing RBD-Raf-GFP and cytosolic RFP. A. images of a representative cell (GFP, RFP, GFP-RFP [Ψ]). B. Ras activation at the boundary (Ψ); data are the means and standard deviation of 14 cells and are presented at different distances from the front of the extending pseudopod.

Figure 2. Ras activation in cells stimulated with cAMP. Cells expressing RBD-Raf-GFP and cytosolic RFP were exposed to a shallow cAMP gradient (panels A, 28 pM/µm at 2.5 nM midpoint cAMP), and a steep cAMP gradient (Panels B, 5000 pM/µm at 150 nM midpoint cAMP). Presented are images of typical cells at different times after exposure of the cells to these stimuli. Shown are the calculated RBD-Raf-GFP at the membrane (Ψ). (see movies 1 and 2 for the original experiment). Panel C show a schematic of the measurements in the cytoplasm and selected areas of the boundary.

Figure 3. Phases of Ras activation. Cells expressing RBD-Raf-GFP and cytosolic RFP were exposed to uniform cAMP (1 µM cAMP), a steep cAMP gradient or a shallow cAMP gradient as indicated in figure 2. A. Kinetics of Ras-GTP activation presented as the depletion of RBD-Raf-GFP in the cytosol. B. Kinetics of Ras-GTP activation in the membrane (Ψ) at the utmost front and the rear of the cell (defined as a small area at the side of the cell closest to and furthest away from the pipette, respectively); steep gradient. C. Kinetics of Ras-GTP activation presented as the ratio of membrane bound RBD-Raf-GFP (Ψ) at the front half and rear half of the cell. D. Kinetics of confinement of the activated Ras crescent. Measured was the width of the crescent at half-maximal height (see panel E). The data shown in panels A-D are the average of 5 cells. Panels E show that the initial Ras activation at 6 s is directly proportional to the local activation of cAMP receptors. Left E panel, Ras activation at different distances from the front at 6 seconds after application of a steep gradient; the data are from a typical experiment. Right E panel, cells were exposed to cAMP gradients with different steepness and midpoint concentrations. We measured at the front and the rear of the cell the local cAMP concentrations using the dye alexa; we also measured RBD-Raf-GFP at the boundary of the cell (Ψ). Each data point is a different cell, except the data at cAMP = 1 (i.e. uniform cAMP), which is the mean and SD of 5 cells. The linear regression curve giving a slope of 1.06, indicating that the front/rear gradient of initial Ras
activation is directly proportional to the front/rear gradient of receptor activation. F. Ras activation at different distances from the front at 30 and 90 seconds after application of the steep gradient. G. Kinetics of Ras-GTP activation after application of uniform (green), a shallow (red) or steep gradient (blue) of cAMP. Presented are logarithmic transformations of the data of panels A-D. The assumption is that adaptation, symmetry breaking and confinement are first order processes with rate constant $k$ that start a specific time $t_0$, and thus follow the general equation \[ \ln\left(\frac{Y(t)}{Y_{final}}\right) = k(t-t_0), \] where $Y$ is adaptation (decline of RBD-Raf-GFP at the membrane from panel A; $k = 0.2 \text{ s}^{-1}$, $t_0 = 7 \text{ s}$), symmetry breaking (front/rear half ratio from panel C; $k = 0.1 \text{ s}^{-1}$, $t_0 = 16 \text{ s}$), or confinement (the width of the crescent from panel D; $k = 0.03 \text{ s}^{-1}$, $t_0 = 20 \text{ s}$).

**Figure 4. Dose response curves of Ras activation.** Cells expressing RBD-Raf-GFP and cytosolic RFP were exposed to cAMP gradients with different steepness. The actual cAMP gradient was established using the dye alexa that was mixed with cAMP. Ras-GTP activation along the cell boundary ($\Psi$) was measured as in Fig. 3F. These data were used to determine Ras activation in the front half and rear half of the cell (A), in the utmost front area of the cell (B), and the width of the activated Ras crescent at half height (C). Data points with error bars are derived from experiments also presented in Figure 3, and are the average and SD of 5 cells; other data points are deduced from single cells. The chemotaxis index of cells in these gradients is presented in panel D.

**Figure 5. Contribution of RasC and RasG.** Wild-type and the indicated Ras mutants expressing RBD-Raf-GFP and cytosolic RFP were exposed to a steep cAMP gradient. Presented are images of typical cells after exposure of the cells to these stimuli. Shown is the calculated RBD-Raf-GFP at the membrane ($\Psi$). B. Ras activation along the cell boundary ($\Psi$) was measured as in Fig. 3F; data are the means of 6 cells and are presented as degrees distance from the extending pseudopod.

**Figure 6. Ras-GTP activation in Dictyostelium signaling mutants.** Panels A show representative images of RBD-Raf-GFP expressing cells in buffer, 3-6 s after addition of uniform cAMP, or in a cAMP gradient. Panels B show the time course of translocation after uniform stimulation with 1 µM cAMP as means and SEM of 8 cells; Panels C presents the response at 3-6 s after addition of uniform cAMP with different concentrations.
Figure 1

A

\[ G = \text{RBD-Raf-GFP} \quad \text{R = cytosolic-RFP} \]

\[ \Psi_i = (G_i - cR_i) / \langle G_{\text{cyt}} \rangle \]

B

\[ \Psi, \text{RBD-Raf-GFP at membrane} \]

Distance from front (μm)
**Figure 2**

<table>
<thead>
<tr>
<th></th>
<th>before cAMP</th>
<th>&quot;uniform&quot; response</th>
<th>adaptation</th>
<th>symmetry breaking</th>
<th>confinement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**B**

<table>
<thead>
<tr>
<th></th>
<th>-3s</th>
<th>6s</th>
<th>20s</th>
<th>40s</th>
<th>120s</th>
</tr>
</thead>
</table>

**C**

- downgradient half
- upgradient half
- rear
- front

\[ \psi = \frac{(G_i - cR_i)}{<G_{cyt}>} \]
Figure 6

(A) Effect of cAMP gradient on wild-type and mutants in the context of RBD-RAF-GFP (activated Ras).

(B) Time-course of RAF-GFP in cytoplasm for WT and gα₂-null.

(C) RAF-GFP in cytoplasm (% depletion) vs. cAMP concentration (M).
### Table I Ras activation in mutants

<table>
<thead>
<tr>
<th>Cell</th>
<th>Initial “uniform” Response</th>
<th>Symmetry breaking</th>
<th>Width crescent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(% depletion cytoplasm)</td>
<td>(upgradient/downgradient half)</td>
<td>(µm)</td>
</tr>
<tr>
<td>WT</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>rasC-null</td>
<td>21.7*</td>
<td>8.4</td>
<td>4.39*</td>
</tr>
<tr>
<td>rasC-null + RasG(S17N)</td>
<td>2.8*</td>
<td>4.7</td>
<td>1.05*</td>
</tr>
<tr>
<td>gβ-null</td>
<td>2.6*</td>
<td>1.8</td>
<td>0.95*</td>
</tr>
<tr>
<td>gα2-null</td>
<td>17.7*</td>
<td>6.8</td>
<td>1.08*</td>
</tr>
<tr>
<td>gα2-null + RasG(S17N)</td>
<td>1.2*</td>
<td>5.6</td>
<td>nd</td>
</tr>
<tr>
<td>WT + LatA</td>
<td>31.0</td>
<td>6.6</td>
<td>12.71*</td>
</tr>
<tr>
<td>4-p-null</td>
<td>33.0</td>
<td>4.6</td>
<td>6.86</td>
</tr>
<tr>
<td>4-p-null + LatA</td>
<td>34.1</td>
<td>4.6</td>
<td>8.42</td>
</tr>
<tr>
<td>gc-null</td>
<td>28.6</td>
<td>5.8</td>
<td>8.68</td>
</tr>
<tr>
<td>myoII-null</td>
<td>33.0</td>
<td>5.2</td>
<td>7.72</td>
</tr>
<tr>
<td>myo-null + LatA</td>
<td>35.7</td>
<td>2.3</td>
<td>8.12</td>
</tr>
<tr>
<td>gefA-null</td>
<td>27.5*</td>
<td>3.6</td>
<td>4.03*</td>
</tr>
<tr>
<td>gefB-null</td>
<td>32.1</td>
<td>6.0</td>
<td>5.06*</td>
</tr>
<tr>
<td>gefC-null</td>
<td>28.2</td>
<td>2.9</td>
<td>2.97*</td>
</tr>
<tr>
<td>gefD-null</td>
<td>24.2*</td>
<td>2.6</td>
<td>2.96*</td>
</tr>
<tr>
<td>gefE-null</td>
<td>38.1</td>
<td>5.6</td>
<td>3.90*</td>
</tr>
<tr>
<td>gefG-null</td>
<td>35.5</td>
<td>2.8</td>
<td>2.56*</td>
</tr>
<tr>
<td>gefL-null</td>
<td>34.5</td>
<td>4.9</td>
<td>7.55</td>
</tr>
<tr>
<td>gefM-null</td>
<td>23.1*</td>
<td>7.6</td>
<td>2.98*</td>
</tr>
<tr>
<td>gefR-null</td>
<td>20.3*</td>
<td>4.7</td>
<td>2.22*</td>
</tr>
<tr>
<td>nfaA-null</td>
<td>31.4</td>
<td>5.5</td>
<td>3.40*</td>
</tr>
</tbody>
</table>

Cells expressing RBD-Raf-GFP and cytosolic-RFP were exposed to a cAMP gradient (5000 pM/µm, mean concentration 150 nM). The initial “uniform” response is the fluorescence intensity of RBD-Raf-GFP in the cytoplasm at ~6 seconds after application of the cAMP gradient. RBD-Raf-GFP at the cell boundary (Ψ) was calculated at 2 to 5 minutes after stimulation. Symmetry breaking is RBD-Raf-GFP at the cell boundary in the upgradient half of the cell divided by that in the downgradient half of the cell. The crescent of RBD-Raf-GFP at the cell boundary has a bell-shaped form. The width of the crescent at half-maximal height is presented. The data are the means and SD of 8 wild-type or at least 4 mutant cells. WT, wild type; 4-p-null, four pathway null with inhibition of sGC, PLA2, PI3K and TorC2, were generated as previously described (Kortholt et al., 2011); * indicates significantly different from WT at P<0.01; 1), not significantly different from 0; 2), significantly
different from 0; 3), not significantly different from 1.0; nd, not determined because no crescent.
Fig. S1. Intrinsic and gradient-induced symmetry breaking of WT cells, gβ-null cells, gα2-null cells and rasC-null cells expressing RasG(S17N). Cells expressing RBD-Raf-GFP and cytosolic RFP were recorded in buffer and in a steep cAMP gradient. RBD-Raf-GFP at the membrane (Y) was determined in the pseudopod and uropod halves of the cell for intrinsic symmetry breaking in buffer, and in the upgradient and down-gradient halves of the cell for gradient-induced symmetry breaking. The data shown are the means and SD of 8 cells.

Fig. S2. Linear regression analysis of cell elongation versus the initial uniform response, symmetry breaking and crescent width (corresponding values are shown in tableS1). Filled symbol, wild-type; open symbols, Gef-null mutants; no significant correlations are observed.
**Movie 1.** Cell movement in buffer; the frame rate is one frame per 8 seconds.

**Movie 2.** Chemotaxis of wild-type cells in a shallow cAMP gradient (same cell as in figure 2A). The pipette is applied after frame 3; the frame rate is one frame per 8 seconds.
**Movie 3.** Chemotaxis of wild-type cells in a steep cAMP gradient (same cell as in figure 2B). The pipette is applied after frame 3; the frame rate is one frame per 8 seconds.

**Movie 4.** Movement of rasC-null/RasG(S17N) cells in a cAMP gradient; the frame rate is one frame per 8 seconds.
Table S1. Ras activation of gef-null mutants is not correlated with cell shape

<table>
<thead>
<tr>
<th>Cell</th>
<th>Initial “uniform” response (% depletion cytoplasm)</th>
<th>Symmetry breaking (up-/downgradient half)</th>
<th>Width crescent (µm)</th>
<th>Cell elongation (length/width ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>WT</td>
<td>32</td>
<td>3</td>
<td>8.73</td>
<td>0.75</td>
</tr>
<tr>
<td>gefA-null</td>
<td>27.5*</td>
<td>3.6</td>
<td>4.03*</td>
<td>1.36</td>
</tr>
<tr>
<td>gefB-null</td>
<td>32.1</td>
<td>6</td>
<td>5.06*</td>
<td>1.21</td>
</tr>
<tr>
<td>gefC-null</td>
<td>28.2</td>
<td>2.9</td>
<td>2.97*</td>
<td>0.54</td>
</tr>
<tr>
<td>gefD-null</td>
<td>24.2*</td>
<td>2.6</td>
<td>2.96*</td>
<td>0.55</td>
</tr>
<tr>
<td>gefE-null</td>
<td>38.1</td>
<td>5.6</td>
<td>3.90*</td>
<td>0.71</td>
</tr>
<tr>
<td>gefG-null</td>
<td>35.5</td>
<td>2.8</td>
<td>2.56*</td>
<td>0.57</td>
</tr>
<tr>
<td>gefL-null</td>
<td>34.5</td>
<td>4.9</td>
<td>7.55</td>
<td>1.31</td>
</tr>
<tr>
<td>gefM-null</td>
<td>23.1*</td>
<td>7.6</td>
<td>2.98*</td>
<td>0.55</td>
</tr>
<tr>
<td>gefR-null</td>
<td>20.3*</td>
<td>4.7</td>
<td>2.22*</td>
<td>0.22</td>
</tr>
<tr>
<td>nfaA-null</td>
<td>31.4</td>
<td>5.5</td>
<td>3.40*</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Presented are for Ras activation the initial uniform” response, symmetry breaking and confinement of the crescent width from table 1. Also presented is the cell shape as cell elongation defined as the ratio of the length (cell axis for direction of movement) and width (perpendicular to axis of movement); data are the means and SD of 12 cells. * indicates significantly different from WT at P<0.01.
Table S2. Contribution of RasC and RasG to the uniform folate response

<table>
<thead>
<tr>
<th>Cell</th>
<th>Initial “uniform” Response (% depletion cytoplasm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>WT</td>
<td>20.4</td>
</tr>
<tr>
<td><em>rasC</em>-null</td>
<td>14.0*</td>
</tr>
<tr>
<td>WT + RasG(S17N)</td>
<td>14.3*</td>
</tr>
<tr>
<td><em>rasC</em>-null + RasG(S17N)</td>
<td>9.0*</td>
</tr>
</tbody>
</table>

Presented are for Ras activation the initial uniform” folate response; data are the means and SD of 12 cells. * indicates significantly different from WT at P<0.01.